Transmission Quality Improvement Algorithms for Multicast Terrestrial-Satellite Cooperation System

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Abstract. In this paper, we investigate a terrestrial-satellite multicast beamforming cooperative system to optimize the problem of low expenses and high capacity requirements of ground users. Different from the point-to-point link-based terrestrial network, we design the terrestrial and satellite beamforming vectors cooperatively based on the required contents of users in order to realize more reasonable resource allocation. The satellite and base stations provide service cooperatively for ground users within coverage, and during transmission, both the satellite and the base stations use the multicast beamforming technique to improve the system performance, and the user group scheduling, resource allocation and beamforming design are considered jointly. Based on this architecture, we first formulate a joint optimization problem to maximize the system capacity performance, and we design the beamforming vectors of the base stations and the satellite cooperatively on the basis of user group scheduling and power constraints. Then we extend the problem into a more realistic scene that the link delay of satellite is larger than it of base stations, this may influence the joint optimization timeliness of condition changes. So we propose a two phases optimization algorithm that we optimize terrestrial-satellite system jointly in the first phase and optimize terrestrial part independently in the second phase. The simulation results show that, the proposed algorithm gains more than 38% of capacity improvement compared with maximum ratio transmission (MRT) method.

Keywords: Terrestrial-satellite cooperation system · Multicast · Beamforming design · Resource allocation · User group scheduling

This work was supported by the National Natural Science Foundation of China (NSFC, 91538203 and 61871257), the new strategic industries development projects of Shenzhen City (JCYJ20170307145820484), the Joint Research Foundation of the General Armaments Department and the Ministry of Education (6141A02033322), and the Beijing Innovation Center for Future Chips, Tsinghua University.

S. Han et al. (Eds.): AICON 2019, LNICST 286, pp. 308–326, 2019.
https://doi.org/10.1007/978-3-030-22968-9_27

1 Introduction

In recent years, the number of smart mobile terminals shows a trend of rapid growth, especially mobile phones and mobile tablets. The market statistics in [1] represents that the global smart mobile phones account for 55% in all kinds of mobile terminals, and nearly 2.75 billion people have more than one phone. Meanwhile, other reports indicate that, with the increasing number of mobile terminal users, the requirement of mobile service such as music, video, mobile TV etc. develop rapidly [2]. In [2], it is estimated that, by 2019, the video service ratio will ascend to 72% of total mobile service, which was only 55% in 2014. The consequent situation of mobile service increment is the explosive growth of mobile data flow. In 2014, the mobile data flow was about 2.5EB and it was predicted to reach 24.3EB in 2019. It can be noticed that the wireless communication and wireless service nowadays present a new trend and challenge the traditional service techniques. On the one hand, the traditional communication is connection centric but the developing trend of communication is content centric. Compared with the content centric communication, the basis requirement of connection centric communication is the connection link that the efficiency and resource utilization ratio are low. The current communication system cannot satisfy the demand of date traffic. On the other hand, for the content centric requirement, the user-desired contents may be requested by many users at the same time such as famous video clips, live sports competitions, focus news and so on. So how to satisfy the complex content requirement and the communication link requirement simultaneously is the principal problem [3]. Compared with the traditional point-to-point transmission method, the point-to-multipoint transmission using multicast technique could provide services of the same contents for more users in the same time without extra resource and improve the system performance and network capacity [4]. Furthermore, under the multicast transmission condition, how to consume the cost of power, frequency, bandwidth etc. and obtain more communication efficiency and higher quality of service (QoS) is another focus problem [5]. Thus, the low expenses high capability multigroup multicast beamforming transmission technique plays a more important role in content centric wireless communication gradually.

In the previous literatures, the multicast beamforming technique was first proposed in wireless communication networks in [6]. The researchers designed an adaptive transmit antenna array to solve the multicast problem of system performance, but they assumed the channel information of transmitter was perfect that ignored many constraints in actual scene. Later in [7], an optimization problem of multicast beamforming for one group was first proposed. In this literature, beamforming design problem was considered to improve the performance of the system. The authors proved the relations between the max-min-fair (MMF) problem and the quality of service (QoS) problem. But the single group scene didn't consider the interference. The literature [8] extended the problem in [7] to multigroup scene. The optimization problem based on the relation between MMF problem and QoS problem was solved. In [9] the authors built a multiuser multichannel multiple-input-single-output (MISO) cognitive radio network model, they proposed two explicit searching algorithm based method to solve the suboptimal channel allocation problem and obtained significant improvement in achievable sum rate. But this method solved problem with dividing it into subproblems, that might influence the result. In [10] a non-orthogonal multiple access (NOMA) based multimedia multicast beamforming Terrestrial-Satellite Network model was built. The users in the model was divided into base station users and satellite users, meanwhile the satellite and the base stations were equipped with multi-antennas and could serve group users based on their required content. This work improved the scene from ground network to the satellite, but the division of users was simple. So, these works were meaningful that brought a new area of wireless communication and improved the performance, but they still have some small defects that could not afford the requirement recently.

To enhance these weaknesses, two stage cooperative multicast transmission was proposed in [11], in which the method aimed to guarantee a practical coverage ratio with the minimum base station power. Later, in [12], a joint beamforming design problem was considered to maximize signal-to-interference plus noise ratio in multiple multicast groups. Although these works optimized different objective functions, the limitations were similar. Optimization goal in [11] was limited by the power rate of base stations, and in [12] it was constrained by per-cell power. And to make the optimization problem more realistic, the researchers discussed better user access and more efficiency resource allocation to improve the system ability. In [13], a three-tier heterogeneous cellular network was proposed. The users were assumed to access more than one base station. However, the paper finally solved the problem of the single base station, and optimized user association and power allocation separately. The performance might not be the best. Later in [14], the authors focused on a joint beamforming, user scheduling and power allocation method. They improved the system ability in optimizing the limitations cooperatively, but they only considered the intercell interference. The researchers in [15] separated the operation of wireless powered communication networks into two phases that namely the wireless energy transfer (WET) phase and wireless information transfer (WIT) phase. And in [14], a two phases cooperative NOMA system was proposed. Based on the time division, the users could combines the signals that received from the two phases by using the maximal-ration combining (MRC) technology. These papers gave new thinking that the user scheduling and resource allocation efficiency of time division were two important concerns in improving communication ability.

Motivated by this, in this paper, we consider a downlink multicast beamforming terrestrial-satellite cooperative system in which satellite and base stations provide service corporately for ground users within coverage. In this model, during the transmission, the users are divided into groups based on their requirement, and the system optimize the user group scheduling jointly with the resource allocation. The satellite and the base stations are all equipped with multi-antennas and reuse the same bandwidth, so they could provide the multicast service for ground users. We first formulate the problem to optimize the system capacity performance under the constraints of power allocation and user group scheduling. Then we design the beamforming vectors and solve the optimization problem by using the max-min-fair problem. Later we extend the problem into a more realistic scene that we consider the influence of the satellite and base station link delay, in order to decrease the influence for the joint optimization of base stations and satellite, and we propose an iterative algorithm to improve the system capacity performance based on two optimization phases.

The rest of the paper is organized as follows. In Sect. 2, the system model and the problem formulation are presented. In Sect. 3, the relaxation of user group scheduling and max-min-fair function, and the Lagrange Dual Method are adopted to solve the joint optimization problem. Finally the numerical results and simulation results are discussed in Sect. 4 and the conclusions are presented in Sect. 5.

2 System Model and Problem Formulation

2.1 System Model

Figure 1 shows a Terrestrial-Satellite Cooperative System model of multicast multigroup downlink architecture. In this system a satellite and I_B base stations serve ground users cooperatively. All users are under coverage of the satellite, and could access more than one base stations according to their requirement. Then we divide these users into J_G groups totally based on their desired contents. Under this circumstance, the satellite not only provides the desired contents to the users but also promotes the quality of service of the bottleneck users. In this paper, we assume the satellite to be a low earth orbit (LEO) satellite. Further more, we assume that each base station has A_B antennas, the satellite has A_S antennas, the maximum user number is M_U, the satellite and the base stations use the same spectrum during entire transmission, so the interference appears in different groups of one base station, different groups of different base stations and satellite.

It is denoted that $\omega_{i,j}$ is the beamforming vector for base station i group j, and $\|\omega_{i,j}\|^2 = P_{B,i,j}$ which is the transmission power of group j in base station i. $x_{B,i,j}$ is the multicast signal serving group j, and $E[|x_{B,i,j}|^2] = 1$. Therefore, the transmission signal of base station i can be written as

$$s_{B,i} = \sum_{j=1}^{J_B} \omega_{i,j} x_{B,i,j} \tag{1}$$

For the satellite, the transmission signal can be written similarly as

$$s_S = \sum_{j=1}^{J_S} \nu_j x_{S,j} \tag{2}$$

where ν_j is the beamforming vector for group j, and $\|\nu_j\|^2 = P_{S,j}$ which is the transmission power of group j. $x_{S,j}$ is multicast signal serving group j, and $E[|x_{S,j}|^2] = 1$.

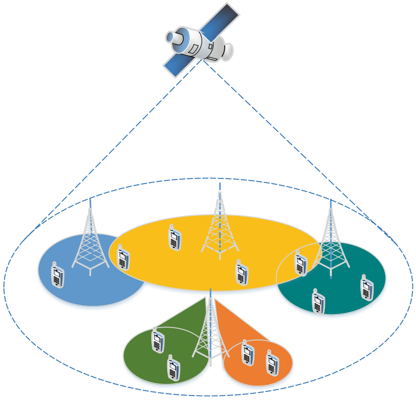

Fig. 1. The terrestrial-satellite cooperate network.

Then the received signal of base station user K in group J of base station I is

$$y_{I,J,K} = \sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} x_J + g_{I,J,K}^H \nu_J x_J + \sum_{\substack{j=1 \\ j \neq J}}^{J_G} \left(\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,j} x_j + g_{I,J,K}^H \nu_j x_j \right) + n_{I,J,K} \quad (3)$$

where $h_{i,I,J,K}$ is the channel from base station i to the user K in base station I group J, $g_{I,J,K}$ is the channel from satellite to the user K in base station I group J. $\omega_{i,I,J}$ is the beamforming vector from base station i to group J of base station I, and ν_j is the beamforming vector from satellite to group j. $n_{I,J,K}$ is the AWGN noise. x_j is the required multicast signal of group j that $E[|x_j|^2] = 1$.

So the SINR of user K of group J in base station I is

$$\gamma_{I,J,K} = \frac{|\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} + g_{I,J,K}^H \nu_J|^2}{\sum_{\substack{j=1 \\ j \neq J}}^{J_G} |\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,j} + g_{I,J,K}^H \nu_j|^2 + \sigma_n^2} \quad (4)$$

Based on Shannon's Theorem, the capacity can be calculated by

$$R_{I,J,K} = \log_2(1 + \gamma_{I,J,K}) \quad (5)$$

where $R_{I,J,K}$ is the capacity of user K in group J from base station I including the signal from base stations, and the satellite.

Although, the user group scheduling should be considered in multicast transmission. So the SINR of user K of group J in base station I could be rewritten as

$$\gamma_{I,J,K_u} = \frac{u_J|\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} + g_{I,J,K}^H \nu_J|^2}{\sum_{\substack{j=1 \\ j \neq J}}^{J_G} u_j|\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,j} + g_{I,J,K}^H \nu_j|^2 + \sigma_n^2} \quad (6)$$

where the group J is served if $u_J = 1$, otherwise $u_J = 0$.

Then the capacity could be written as

$$R_{I,J,K} = \log_2(1 + \gamma_{I,J,K_u}) \tag{7}$$

2.2 Problem Formulation

Expression (7) gives the formulation of the capacity, but in wireless communication that the channel condition of different users relate to many reasons such as place, time, environment, weather, and so on. So we should notice that the SINR of each group is decided by the user who under the poorest channel condition. Considering the power limit, we can formulate the optimization problem (OP) as

$$\begin{aligned} (OP) \quad & \max_{\{\omega_j\}_{j=1}^{J_G}, \{\nu_j\}_{j=1}^{J_G}, u} \quad \log(1 + \min_{I,J,K} \gamma_{I,J,K_u}) \\ s.t.\ & C1 : P_{B,I} = \textstyle\sum_{j=1}^{J_G} u_j ||\omega_{i,I,J}||^2 \leq P_{B,i,I,max} \ I \in [1, I_B] \\ & C2 : P_S = \textstyle\sum_{j=1}^{J_G} u_j ||\nu_j||^2 \leq P_{S,max} \\ & C3 : u_j \in \{0, 1\}, j = 1, \ldots, J_G \end{aligned}$$

where $C1$ and $C2$ are the maximum transmission power constraints for the base stations and the satellite, and $C3$ is the user group scheduling constraints.

3 Algorithm Development

We formulate the optimization problem in Sect. 2 based on the power constraints, but the optimization problem cannot be solved directly. Firstly, the function of the optimization problem is non-convex because of the γ_{I,J,K_u} in $R_{I,J,K}$. Secondly, the constraints $C3$ is a $0 - 1$ variable which is non-convex. So in this section, we first relax the optimization problem into the convex form, and then we expand the solution into a complex scenario to improve the system performance under the scenario that the link delay of satellite optimization is larger than it in base station optimization.

3.1 Relaxation and Solution of the Optimization Problem (OP)

The user group scheduling factor $u_j = 1$ when the group is under served and $u_j = 0$ otherwise, so combining the property of the beamforming vector ω and ν we could say that $u_j = 0$ if and only if $\omega = 0$ and $\nu = 0$. That means if the group is under service, the beamforming vector is absolutely non-zero. This lead to the reformulation of (OP):

$$\begin{aligned} (OP') \quad & \max_{\{\omega_j\}_{j=1}^{J_G}, \{\nu_j\}_{j=1}^{J_G}} \quad \log(1 + \min_{I,J,K} \gamma_{I,J,K}) \\ s.t.\ & C1 : P_{B,I} = \textstyle\sum_{j=1}^{J_G} ||\omega_{i,I,J}||^2 \leq P_{B,i,I,max} \ I \in [1, I_B] \\ & C2 : P_S = \textstyle\sum_{j=1}^{J_G} ||\nu_j||^2 \leq P_{S,max} \end{aligned}$$

We suppose (u^*, Ω^*) and Ω^* as the optimal solutions of the problem (OP) and (OP'), in which $\Omega^* = [\omega^*, \nu^*]$. So the relationship between them is

$$u^* = \mathcal{F}(\Omega^*); \qquad u^*\Omega^* = \Omega^* \tag{8}$$

where $\mathcal{F}x$ indicates that the value of it is one if $x \neq 0$ and zero otherwise. Referring to [13], we could prove the relation between (OP) and (OP').

Proof. Necessity part:
We assume Φ_1 and Φ_2 as the feasible sets of (OP) and (OP'). Using (8) we have

$$\begin{aligned}\log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(u^*, \Omega^*)) &= \log(1 + \min_{I,J,K} \gamma_{I,J,K}(\Omega^*)) \\ &\geq \log(1 + \min_{I,J,K} \gamma_{I,J,K}(\Omega)), (u^*, \Omega^*) \in \Phi_1 \Omega^* \in \Phi_2\end{aligned}$$

So for any $(\hat{u}, \hat{\Omega}) \in \Phi_1$ there exists $\bar{\Omega} \in \Phi_2$ that satisfies

$$\log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(\hat{u}, \hat{\Omega})) = \log(1 + \min_{I,J,K} \gamma_{I,J,K}(\bar{\Omega}))$$

Then we obtain

$$\log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(u^*, \Omega^*)) \geq \log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(\hat{u}, \hat{\Omega}))$$

Proof. Sufficiency part:
Similarly, using (8) we have

$$\begin{aligned}\log(1 + \min_{I,J,K} \gamma_{I,J,K}(\Omega^*)) &= \log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(u^*, \Omega^*)) \\ &\geq \log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(u, \Omega))\end{aligned}$$

For any $\bar{\Omega} \in \Phi_2$ there exists $(\hat{u}, \hat{\Omega}) \in \Phi_1$ that satisfies

$$\log(1 + \min_{I,J,K} \gamma_{I,J,K}(\bar{\Omega})) = \log(1 + \min_{I,J,K} \gamma_{I,J,K_u}(\hat{u}, \hat{\Omega}))$$

Then we obtain

$$\log(1 + \min_{I,J,K} \gamma_{I,J,K}(\Omega^*)) \geq \log(1 + \min_{I,J,K} \gamma_{I,J,K}(\bar{\Omega}))$$

So we know that, the Eq. (8) and the relation between (OP) and (OP') are valid.

After relaxing the user group scheduling factors, by the monotonicity of logarithm function referring to [6], the problem could be rewritten as

$$\begin{aligned}(DOP) \quad &\max_{\{\omega_j\}_{j=1}^{J_G}, \{\nu_j\}_{j=1}^{J_G}} \min_{I,J,K} \gamma_{I,J,K} \\ s.t.\ &C1: P_{B,I} = \textstyle\sum_{j=1}^{J_G} ||\omega_{i,I,J}||^2 \leq P_{B,i,I,max} \ I \in [1, I_B] \\ &C2: P_S = \textstyle\sum_{j=1}^{J_G} ||\nu_j||^2 \leq P_{S,max}\end{aligned}$$

But according to [17] it is still non-convex, so we couldn't solve it in a direct and simple way. We introduce an auxiliary variable t into (DOP), the problem can be written as the equivalent formulation below.

$$\begin{aligned}(DOP_t) \quad & \max_{\{\omega_j\}_{j=1}^{J_G},\{\nu_j\}_{j=1}^{J_G},t} \; t \\ s.t.\; & C1: \gamma_{I,J,K} \geq t \\ & C2: P_{B,I} = \textstyle\sum_{j=1}^{J_G} ||\omega_{i,I,J}||^2 \leq P_{B,i,I,max} \; I \in [1, I_B] \\ & C3: P_S = \textstyle\sum_{j=1}^{J_G} ||\nu_j||^2 \leq P_{S,max}\end{aligned}$$

Then we use the trace matrix $|h^H\omega|^2 = tr(hh^H\omega\omega^H)$ and $||\omega||^2 = tr(\omega\omega^H)$ to reformulate (DOP_t) as follow,

$$\begin{aligned}(DOP_X) \quad & \max_{\{X_j\}_{j=1}^{J_G},t} \; t \\ s.t.\; & C1: t(\textstyle\sum_{\substack{j'=1\\ j\neq j}}^{J_G} tr(Q_{I,J,K}X_j) + \delta_N^2) - tr(Q_{I,J,K}X_J) \leq 0 \\ & C2: X_J \geq 0 \; J \in [1, J_G] \\ & C3: P_{B,I} = \textstyle\sum_{j=1}^{J_G} tr(A_{B,i}X_j) \leq P_{B,i,I,max} \; I \in [1, I_B] \\ & C4: P_S = \textstyle\sum_{j=1}^{J_G} tr(A_{SX_j}) \leq P_{S,max} \\ & C5: rank(X_J) = 1 \; J \in [1, J_G]\end{aligned}$$

where

$$\Omega_{joint,J} = \left[\omega_{1,I,J}^H, \omega_{2,I,J}^H, \ldots, \omega_{I_B,I,J}^H, \nu_J^H\right]^H, \; X_J = \left[\Omega_{joint,J}\Omega_{joint,J}^H\right]$$

$$h_{joint,I,J,K} = \left[h_{1,I,J,K}^H, \ldots, h_{I_B,I,J,K}^H, g_{I,J,K}^H\right]^H, \; Q_{I,J,K} = h_{joint,I,J,K}h_{joint,I,J,K}^H$$

$$A_{B,I} = Diag\{Z_B, Z_S\}, Z_B = I_{A_B \times A_B}, Z_S = 0_{A_S \times A_S}$$

$$A_S = Diag\{Z_B, Z_S\}, Z_B = 0_{A_B \times A_B}, Z_S = I_{A_S \times A_S}$$

and $X_J \geq 0$ means the matrix X_J is positive semi-definite. It is obviously that if we want to optimize ω and ν, we should satisfy $X_J \geq 0$ and $rank(X_J) = 1$.

In (DOP_X), the power constrains could be rewrite as $\sum_{i=1}^{I_B} P_{B,i} + P_S = \sum_{j=1}^{J_G} tr(X_j) \leq \sum_{i=1}^{I_B} P_{B,i,I,max} + P_{S,max}$. It is clearly that if the power constrains of base stations and satellite are all satisfied, the inequation above is obviously satisfied. So we introduce another auxiliary parameter $\Delta_P \geq 0$ and a total power auxiliary variable P_{AUX} into the total power constrain as $\sum_{j=1}^{J_G} tr(X_j) + \Delta_P = P_{AUX}$. Then we can relax (DOP_X) without rank-1 constrains as

$$
\begin{aligned}
&(DOP_{X_{\Delta_P}}) \max_{\{X_j\}_{j=1}^{J_G}, t, \Delta_P} t \\
&s.t.\ C1: t(\sum_{\substack{j'=1 \\ j\neq j}}^{J_G} tr(Q_{I,J,K}X_j)+\delta_N^2)-tr(Q_{I,J,K}X_J)\leq 0 \\
&\quad C2: X_J \geq 0\ J\in[1,J_G] \\
&\quad C3: P_{B,I}=\sum_{j=1}^{J_G} tr(A_{B,i}X_j)\leq P_{B,i,I,max}\ I\in[1,I_B] \\
&\quad C4: P_S=\sum_{j=1}^{J_G} tr(A_S X_j)\leq P_{S,max} \\
&\quad C5: \sum_{j=1}^{J_G} tr(X_j)+\Delta_P = P_{AUX} \\
&\quad C6: \Delta_P \geq 0
\end{aligned}
$$

It is proved or quoted in [17] that if $P_{AUX} \geq \sum_{i=1}^{I_B} P_{B,i,I,max} + P_{S,max}$, the optimization problem $(DOP_{X_{\Delta_P}})$ is equal to (DOP_X) because the constrains $C5$ and $C6$ in $(DOP_{X_{\Delta_P}})$ is invalid under this condition. In multicast beamforming scene, references [4] and [8] considered max-min fare problem and QoS problem are two main problems. In QoS problem, the beamforming vectors ω and ν are optimized to minimum the total power for all served users. Same as the relaxation above, the QoS problem can be written as

$$
\begin{aligned}
&(DOP_Q) \min_{\{X_j\}_{j=1}^{J_G}} \sum_{j=1}^{J_G} tr(X_j) \\
&s.t.\ C1: (\sum_{\substack{j'=1 \\ j\neq j}}^{J_G} tr(Q_{I,J,K}X_j)+\delta_N^2)-tr(Q_{I,J,K}X_J)\leq 0 \\
&\quad C2: X_J \geq 0\ J\in[1,J_G] \\
&\quad C3: P_{B,I}=\sum_{j=1}^{J_G} tr(A_{B,i}X_j)\leq P_{B,i,I,max}\ I\in[1,I_B] \\
&\quad C4: P_S=\sum_{j=1}^{J_G} tr(A_S X_j)\leq P_{S,max}
\end{aligned}
$$

Here we define $DOP_{X_{\Delta_P}}(P_{B,i,I,max}, P_{S,max}, P_{AUX})$ to represent optimization problem $DOP_{X_{\Delta_P}}$, and we know that (X_J^*, t^*, Δ_P^*) is the solution of the optimization problem. Same as the definition above, the QoS problem can be written as $DOP_Q(P_{B,i,I,max}, P_{S,max})$, and the solution is (X_J^*). According to the $C5$ in $(DOP_{X_{\Delta_P}})$, the constraint could be rewritten as $DOP_{X_{\Delta_P}}(P_{B,i,I,max}, P_{S,max}, DOP_Q(P_{B,i,I,max}, P_{S,max}) + \Delta_P^*)$, so we could establish relationship between the relaxed problem $DOP_{X_{\Delta_P}}$ and the relaxed problem DOP_Q as follow:

$$
t^* = DOP_{X_{\Delta_P}}\Big(P_{B,i,I,max}, P_{S,max}, DOP_Q\Big(t, P_{B,i,I,max}, P_{S,max}\Big) + \Delta_P^*\Big)
$$

$$
P_{AUX} - \Delta_P^* = DOP_Q\Big(DOP_{X_{\Delta_P}}\Big(P_{B,i,I,max}, P_{S,max}, P_{AUX}\Big), P_{B,i,I,max}, P_{S,max}\Big)
$$

to simplify the equation, we use P to represent $(P_{B,i,I,max}, P_{S,max})$:

$$
t^* = DOP_{X_{\Delta_P}}\Big(P, DOP_Q\Big(t, P\Big) + \Delta_P^*\Big),
$$

$$P_{AUX} - \Delta_P^* = DOP_Q\Big(DOP_{X_{\Delta_P}}\Big(P, P_{AUX}\Big), P\Big) \tag{9}$$

which is proved in [16].

The optimization problem DOP_Q is a standard SDP problem [7]. Previous researchers solved standard SDP problems with SeDuMi, CVX and so on. Here we choose SeDuMi [18] to calculate the SDP function. From [7] we know that, since $DOP_{X_{\Delta_P}}$ and DOP_Q are monotonically nondecreasing in t and P_{AUX}, optimization problem $DOP_{X_{\Delta_P}}$ could be solved based on the relation in Eq. (9). So we can use the bisection search over t with given P as follow:

Initialize: $[t_L, t_U]$, end condition ϵ

Step 1: Set $t = \frac{t_L+t_U}{2}$, solve the opitmization problem $DOP_Q(t, P_{B,i,I,J}, P_{S,I,J})$.

Step 2: If problem $DOP_Q(t, P_{B,i,I,J}, P_{S,I,J})$ is infeasible, or the optimum solution is greater than P_{AUX}, set $t_U = t$; otherwise $t_L = t$.

Step 3: If $|t_U - t_L| \leq \epsilon$, terminate. If not, repeat previous steps.

First, we set two initial values t_L and t_U that the solution of $t = DOP_{X_{\Delta_P}}$ $(P_{B,i,I,max}, P_{S,max}, P_{AUX})$ is located in $[t_L, t_U]$. Then, let $t = \frac{t_L+t_U}{2}$ and try to solve the optimization problem $DOP_Q(P_{B,i,I,max}, P_{S,max})$ with SeDuMi function tools. Next, if problem $DOP_Q(P_{B,i,I,max}, P_{S,max})$ is infeasible, or the optimum solution is greater than P_{AUX}, set $t_U = t$; if not, set $t_L = t$. Finally, if $|t_U - t_L| \leq \epsilon$, terminate the repetition and output the calculation results. If not, repeat previous steps until satisfying the end conditions.

As for the values of t_L and t_U, because of the physical meaning of the optimization problem, the lower bound $t_L = 0$ is obviously. By analysing the problem $t = DOP_{X_{\Delta_P}}$, we could find that when the system only serves one user in one group, the interference is zero and the t reaches t_U. Under this condition, the optimization problem could be written as

$$\max_{\{\omega_j\}_{j=1}^{J_G}, \{\nu_j\}_{j=1}^{J_G}} \frac{|h_{joint,I,J,K}^H \Omega_{joint,J}|^2}{\delta^2} \tag{10}$$

which we consider the only served user is $u_{I,J,K}$. Then we use the Cauchy-Schwartz inequality, the optimal beamforming vector could be written as

$$\Omega_{joint,J} = \sqrt{P_{AUX}} \frac{h_{joint,I,I,K}}{||h_{joint,I,I,K}||} \tag{11}$$

so the SINR $\gamma_{I,J,K}$ equal to $\frac{P_{AUX}||h_{joint,I,I,K}||^2}{\delta^2}$. The only one user $u_{I,J,K}$ condition could be extend to more users condition, then the SINR could be written as

$$\min_{I,J,K} \frac{P_{AUX}||h_{joint,I,I,K}||^2}{\delta^2} \tag{12}$$

and it equals to the upper bound t_U. By confirming the lower bound and upper bound t_L and t_U, we could calculate the optimal solution with a small enough ϵ.

After calculating the optimization problem $DOP_{X_{\Delta_P}}$ and DOP_Q, we notice that these two problems are constrain-relaxed. To ensure the beamforming vectors ω and ν are existent and the solution of X_J is valid, we constraint X_J as a positive semi-definite matrix and $rank(X_J) = 1$. But in problem $DOP_{X_{\Delta_P}}$ and DOP_Q, we drop the rank-1 constraint and relaxed them, it means that when we optimize $DOP_{X_{\Delta_P}}$ and DOP_Q, the result cannot always satisfy the constraint of rank-1. Previous researchers discussed these questions in [19]. They found that the Gaussian randomization method could give the highest accuracy in multicast beamforming system conditions [20]. In this case, we generate candidate beamforming vectors and choose the best performance beamforming vectors to solve the relaxed optimization problem. We know from [19] that we can generate a Gaussian random vector μ with zero-mean and unit-variance, which $\mu \sim CN(0, I)$. So based on the solution X_J, we perform the eigenvalue decomposition that $X_J = U_J \Sigma_J U_J^H$. For the beamforming vector, assumed in group J, can be calculated by $\Omega_{joint,J} = U_J \Sigma_J^{\frac{1}{2}} \mu_J$, where $\mu_J \sim CN(0, I)$ and $E[\Omega_{joint,J} \Omega_{joint,J}^H] = X_J$. But we should notice, when we choose the best performance beamforming vector for the optimization problem, the corresponding power constraints should be adjusted. Because not all the original power constraints satisfy the new method and there may exist some original available power constraints unused. To solve this question, we introduce a new optimal power scaling factor p_F into total power constraints. Accordingly, the original optimization problem $DOP_{X_{\Delta_P}}$ and DOP_Q could be reformulated as following:

$$
\begin{aligned}
&(DOP_{p_F}) \max_{\{p_{F,j}\}_{j=1}^{J_G}, t, \Delta_P} \quad t \\
&s.t.\ C1: t \le \frac{p_{F,j} |\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} + g_{I,J,K}^H \nu_J|^2}{\sum_{\substack{j=1 \\ j \ne J}}^{J_G} p_{F,j} |\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} + g_{I,J,K}^H \nu_J|^2 + \sigma_N^2} \\
&\quad C2: P_{B,I} = \textstyle\sum_{j=1}^{N_G} p_{F,j} ||\omega_{i,I,J}||^2 \le P_{B,i,I,max} \qquad I \in [1, I_B] \\
&\quad C3: P_S = \textstyle\sum_{j=1}^{J_G} p_{F,j} ||\nu_j||^2 \le P_{S,max} \\
&\quad C4: \textstyle\sum_{j=1}^{J_G} p_{F,j} ||\Omega_{joint,j}||^2 + \Delta_P = P_{AUX} \\
&\quad C5: p_{F,J} \ge 0 \qquad J \in [1, J_G]
\end{aligned}
$$

Then, the optimization problem DOP_Q could be reformulated as

$$
\begin{aligned}
&(DOP_{Q_F}) \min_{\{p_{F,j}\}_{j=1}^{J_G}} \sum_{j=1}^{J_G} p_{F,j} ||\Omega_{joint,j}||^2 \\
&s.t.\ C1: \textstyle\sum_{\substack{j=1 \\ j \ne J}}^{J_G} p_{F,j} |\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} + g_{I,J,K}^H \nu_J|^2 + \sigma_N^2 \\
&\qquad\qquad \le p_{F,j} |\textstyle\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J} + g_{I,J,K}^H \nu_J|^2 \\
&\quad C2: P_{B,I} = \textstyle\sum_{j=1}^{N_G} p_{F,j} ||\omega_{i,I,J}||^2 \le P_{B,i,I,max} \qquad I \in [1, I_B] \\
&\quad C3: P_S = \textstyle\sum_{j=1}^{J_G} p_{F,j} ||\nu_j||^2 \le P_{S,max} \\
&\quad C4: p_{F,J} \ge 0 \qquad J \in [1, J_G]
\end{aligned}
$$

Same as the relation of (9), we have

$$t^* = DOP_{p_F}\Big(P, DOP_{Q_F}\big(t, P\big) + \Delta_P^*\Big),$$

$$P_{AUX} - \Delta_P^* = DOP_{Q_F}\Big(DOP_{p_F}\big(P, P_{AUX}\big), P\Big) \tag{13}$$

which the constraint $C1$ in DOP_{p_F} is nonconvex, so we cannot solve the optimization problem DOP_{p_F} directly. Observing the optimization problem DOP_{Q_F}, we know that it is a standard linear formulation. So we could refer the method above to solve the optimization problem using the relation between DOP_{p_F} and DOP_{Q_F}. Similarly, the optimal beamforming vector is $p_{F,J}\Omega_{joint,J}$ and the upper bound of optimum solution t_U could be calculate as $\min\limits_{I,J,K} \frac{P_{AUX}||h_{joint,I,I,K}||^2}{\delta^2}$. Finally, we summarize the optimization algorithm as Algorithm 1.

Algorithm 1. Joint Terrestrial-Satellite Beamforming Design Algorithm

Initialization: $[t_L, t_U]$, end condition ϵ.
while $|t_U - t_L| \geq \epsilon$ **do**
    Set $t = \frac{t_L+t_U}{2}$ and solve the optimization problem $DOP_{Q_F}(\mathbf{P})$.
    if $DOP_{Q_F}(\mathbf{P})$ infeasible **or** $DOP_{Q_F}(\mathbf{P}) \geq P_{AUX}$ **then**
        set $t_U = t$
    else
        set $t_L = t$
    End If
End While
Generate candidate beamforming vectors and choose the best performance beamforming vector to solve the optimization problem DOP_{p_F}.

3.2 Expand Power Optimization of Base Stations

In the last subsection, we relax the (OP) into convex form and solve it. But in the actual scene, we cannot always optimize the base stations and satellite jointly. Because the link delay of satellite is much larger than that of base stations, when the channel condition or the requirement of users change, the optimization of base stations could match it in time but the satellite may not. That means joint optimization of satellite and base stations might not always match up to the changes. Considering this, we divide the optimization of transmission into two phases. The joint optimization of satellite and base stations is in the first phase, and in the second phase we optimize the power of base stations to better satisfy the need of users.

The first phase is illustrate in the last subsection. We notice that $\omega = \omega_0 P$ where $||\omega_0|| = 1$, so we could rewrite the extend optimization problem (EP) as

$$\begin{aligned} &(EP) \max_{P_{B,I}} \min_{I,J,K} \gamma_{I,J,K} \\ &s.t.\ C1 : P_{B,I} = \textstyle\sum_{j=1}^{N_G} ||\omega_{i,I,J_0} \sqrt{P_{B,i,I,J}}||^2 \leq P_{B,i,I,max}\ I \in [1, I_B] \end{aligned}$$

in which $\omega_{i,I,J_0} \sqrt{P_{B,i,I,J}} = \omega_{i,I,J}$. Same as the method before, we can get:

$$\begin{aligned} &(EP_t) \max_{P_{B,I},t} t \\ &s.t.\ C1 : \gamma_{I,J,K} \geq t \\ &\quad\ \ C2 : P_{B,I} = \textstyle\sum_{j=1}^{N_G} ||\omega_{i,I,J_0} \sqrt{P_{B,i,I,J}}||^2 \leq P_{B,i,I,max}\ I \in [1, I_B] \end{aligned}$$

To solve this problem, we use the Lagrange Dual Method to transmit (EP_t) into the dual problem. Then the Lagrange function of the (EP_t) is:

$$\mathcal{L}(P_{B,I}, t, \eta) = t - \eta_1(t - \gamma_{I,J,K}) - \eta_2(\sum_{j=1}^{N_G} ||\omega_{i,I,J_0} \sqrt{P_{B,i,I,J}}||^2 - P_{B,i,I,max}) \quad (14)$$

the dual function is

$$\theta(\eta) = \mathbf{sup}\mathcal{L}(P_{B,I}, t, \eta) \quad (15)$$

Then the corresponding dual optimization of (EP_t) is

$$\begin{aligned} &(EP_{DUAL}) \min \theta(\eta) \\ &s.t.\ C1 : \eta_l \geq 0 \qquad\qquad l = \{1, 2\} \\ &\quad\ \ C2 : \textstyle\sum_{l=\{1,2\}} \eta_l = 1 \end{aligned}$$

The optimal solutions must satisfy the Karush-Kuhn-Tucher (KKT) condition, we have

$$\frac{\partial \mathcal{L}}{\partial P_{B,I}} = 0 \quad (16)$$

So, the optimal solution of base station transmission power allocation could be calculated as

$$P_{B,i,I,J} = \Big(\frac{4(1-\eta_1)\sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,J_0} g_{I,J,K}^H \nu_J}{2\eta_2 \sum_{\substack{j=1 \\ j\neq J}}^{J_G} |\mathcal{I}|^2 - 4(1-\eta_1)\sum_{i=1}^{I_B} {h_{i,I,J,K}^H}^2 \omega_{i,I,J_0}^2}\Big)^2 \quad (17)$$

where $\mathcal{I} = \sum_{i=1}^{I_B} h_{i,I,J,K}^H \omega_{i,I,j} + g_{I,J,K}^H \nu_j$.

Then we put the optimal solution into the dual problem (EP_{DUAL}), and use the subgradient method to update the Lagrange multipliers iteratively.

$$\eta_1[t+1] = \max\Big\{\eta_1[t] - \delta_{\eta_1}[t+1]\big(t - \gamma_{I,J,K}\big), 0\Big\} \quad (18)$$

$$\eta_2[t+2] = \max\left\{\eta_2[t] - \delta_{\eta_2}[t+1]\Big(\sum_{j=1}^{N_G} ||\omega_{i,I,J_0}\sqrt{P_{B,i,I,J}}||^2 - P_{B,i,I,max}\Big), 0\right\} \quad (19)$$

where we denote t as the iteration step, and δ is the step length for the iteration. So we obtain all the factors we need. And the expand power optimization of base stations algorithm is exhibited below.

Initialize: $\eta_l[0]$, $l = 1, 2$

Repeat: 1. Update SINR according to (4)

2. For $I = [1, I_B]$, $J = [1, J_G]$, update $P_{B,i,I,J}$ according to (17)

3. Update η_l according to (18) and (19)

4. If $P_{B,I}$ converge, end.

So the complete joint optimization algorithm of phase division under the consideration of link delay is described in Algorithm 2.

Algorithm 2. Phase Division Joint Optimization Algorithm

```
Initialize:η_l[0], l = 1, 2
Design the beamforming vectors according to Algorithm 1
while P_{B,I} converge do
    Update SINR according to (4)
    for I =1 to I_B do
        for J =1 to J_G do
            Update P_{B,i,I,J} according to (17)
        End For
    End For
    Update η_l according to (18) and (19)
    t = t + 1
End While
```

4 Performance Evaluation

In this section, we use the MATLAB software to simulate and evaluate the proposed algorithm and then present the result. The proposed system model is a downlink communication network that the satellite, base stations and ground mobile terminals work cooperatively. The satellite is a LEO with 1000 km from the ground, the maximum power is 40 W, and the carrier frequency is set as 2 GHz, the AWGN power σ_n is set as -134 dBm. The maximum constraint power of the base stations $P_{B,i,I,max}$ is set as 43 dBm. The gain of mobile terminal is 0 dbi. The transmission gain of the satellite and the base station are 50 dBi and 18 dBi. The terrestrial channel is set as Rayleigh channel, the satellite channel is set as Rician channel.

Figures 2, 3 and 4 shows the influence of base station number, group size and group number. The blue lines in these figures represent the optimal capacity of Algorithm 1, the purple lines represent the capacity that only served by the base

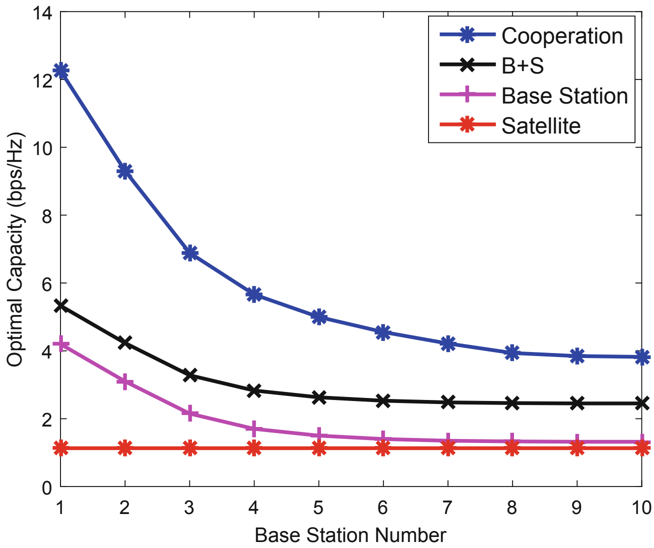

Fig. 2. Influence of base station number on optimal capacity. (Color figure online)

stations, the red lines represent the capacity that only served by the satellite, and the black lines are the sum capacity of base stations and satellite.

In Fig. 2, we set $A_B = 2$, $A_S = 5$, $M_U = 5$ and $J_G = 2$. We could observe from Fig. 2 that when the base station number rises, the optimal capacity decreases. When there is only one base station, the capacity of blue line is about 2.9 times to the purple line and about 2.3 times to the black line. When the number of base station comes to 10, the capacity of blue line declines to 150% of the black line. This is because when the number of base station increases, the interference between base stations has a greater impact on the SINR and capacity, but the positive effect of the Algorithm 1 is notable.

In Fig. 3 we set $A_B = 2$, $A_S = 5$, $I_B = 2$ and $J_G = 2$. And in Fig. 4 we set $A_B = 2$, $A_S = 5$, $I_B = 2$ and $M_U = 5$. It is obviously that the speed of decrease of the capacity in Fig. 3 is much slower than it in Fig. 4. That means the influence of the interference that brought by the group number is greater than by the group size. In Fig. 3 the capacity of algorithm 1 nearly keeps the 60% increment to the capacity in black line, so we find that the group size influence the capacity but play a minor role in our proposed algorithm. In Fig. 4 when the group number raises from 1 to 3, not only the cooperative capacity decreases about 77%, but also the capacity of purple line and red line decrease very fast. Combining the Figs. 2, 3 and 4, the problem that how to design the number of base station, the group size and group number according to the requirement of users is a complex but important question. But it is beyond the scope of this paper.

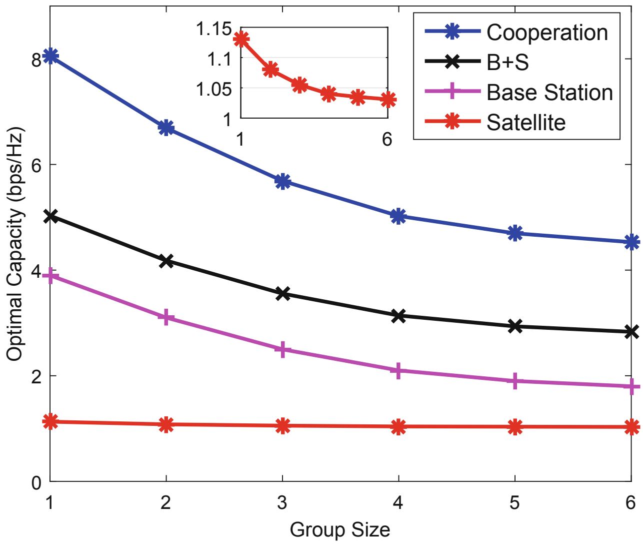

Fig. 3. Influence of group size on optimal capacity. (Color figure online)

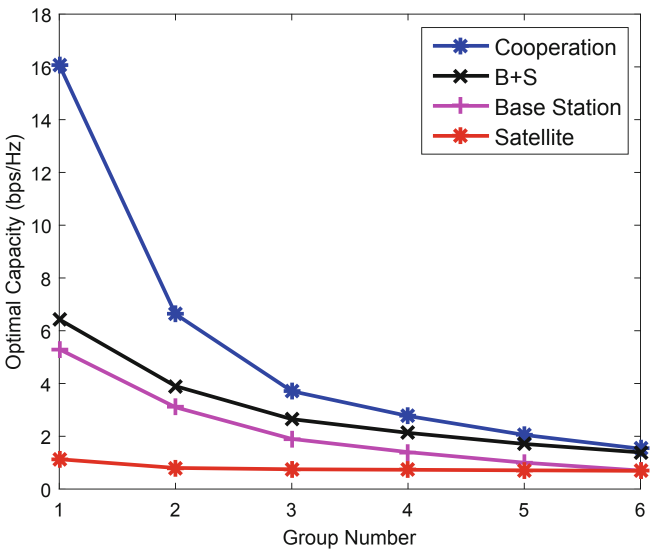

Fig. 4. Influence of group number on optimal capacity. (Color figure online)

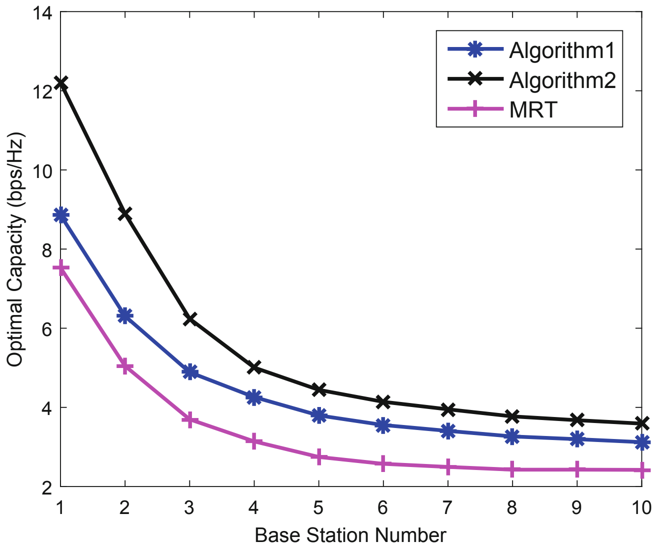

Fig. 5. Compare of Algorithms 1 and 2 and other method. (Color figure online)

In Fig. 5 we compare the capacity of Algorithms 1 and 2 and other method in [21] that the beamforming vectors is calculated by maximum ratio transmission (MRT). We set $A_B = 2$, $A_S = 5$, $M_U = 5$ and $J_G = 2$. And we divide the program into two phases that the user condition in the second phase is different from the first phase. This simulate the real scene that the link delay of satellite is larger than it of base station, so the optimization of satellite may not catch up with the change of users. So in the first phase we design the beamforming vectors of base stations and satellite jointly, in second phase we optimize the capacity under the power constraints of base stations only. The results show that when the number of base station is 1 and 2, the capacity increment of algorithm 2 is 41% and 37% compared with Algorithm 1. When the number of base station gets higher, the percent of capacity keeps nearly 15%. Because when the interference is not very complex with a small base station number, the improvement in the second phase play an important role in optimization. As the number of base station raises, the influences of interference get higher, the improvement of second phase optimization decreases but still important. The purple line in Fig. 5 is the MRT method that we could find that, our joint optimization algorithm of beamforming design effect the capacity of system more markable than MRT. And the simulation results show that when the base station number is 1, 2 or bigger than 7, the improvement of blue line is about 29%, but when the number is 6, the capacity improvement of Algorithm 1 is 38%. And the improvement of Algorithm 2 is about 60% compared with MRT method. So the suitable base station number could improve the capacity markable.

5 Conclusion

In this paper, we proposed a multicast beamforming terrestrial-satellite cooperation system, in which satellite and base stations provide service cooperatively for ground users. By formulating and solving optimization problem under the constraints of user group scheduling, resource allocation and beamforming design, we improved the system capacity performance. When the scene is more realistic, we optimized the problem in two phases that we designed the beamforming vectors of base station and satellite jointly in the first phase, obtained the power allocation result in the second phase because of the optimization link delay of satellite is larger than it of base station. The simulation results showed that, comparing with other methods, the proposed algorithm in this paper was better in performance especially when the factors such as base station number, group size and group number were suitable for the hole system. The proposed algorithm of beamforming design, optimization of resource allocation and user group scheduling in this paper gained more than 38% of capacity improvement.

References

1. Ericsson mobility report (2018). https://www.ericsson.com/en/mobility-report
2. Cisco.: Cisco visual networking index: global mobile data traffic forecast update 2014–2019. Whitepaper (2015)
3. Sinky, H., Khalfi, B., Hamdaoui, B., Rayes, A.: Responsive content-centric delivery in large urban communication networks: a LinkNYC use-case. IEEE Trans. Wirel. Commun. **17**(3), 1688–1699 (2018)
4. Xiao, L., Dai, H., Ning, P.: Jamming-resistant collaborative broadcast using uncoordinated frequency hopping. IEEE Trans. Inf. Forensics Secur. **7**(1), 297C–309 (2012)
5. Lin, B., Fei, Z., Zhang, Y.: UAV communications for 5G and beyond: recent advances and future trends. IEEE Internet Things J. **6**(2), 2241–2263 (2019)
6. Sun, Y., Liu, K.: Transmit diversity techniques for multicasting over wireless networks. In: 2004 IEEE Wireless Communications and Networking Conference, Atlanta, GA, USA (2004)
7. Sidiropoulos, N., Davidson, T., Luo, Z.: Transmit beamforming for physical-layer multicasting. IEEE Trans. Signal Process. **54**(6), 2239–2251 (2006)
8. Karipidis, E., Sidiropoulos, N., Luo, Z.: Convex transmit beamforming for downlink multicasting to multiple co-channel groups. In: 2006 IEEE International Conference on Acoustics Speech and Signal Processing Proceedings, Toulouse (2006)
9. Dadallage, S., Yi, C., Cai, J.: Joint beamforming, power, and channel allocation in multiuser and multichannel underlay MISO cognitive radio networks. IEEE Trans. Veh. Technol. **65**(5), 3349–3359 (2016)
10. Zhu, X., Jiang, C., Kuang, L., Ge, N., Lu, J.: Non-orthogonal multiple access based integrated terrestrial-satellite networks. IEEE J. Sel. Areas Commun. **35**(10), 2253–2267 (2017)
11. Zhou, Y., Liu, H., Pan, Z., Tian, L., Shi, J., Yang, G.: Two-stage cooperative multicast transmission with optimized power consumption and guaranteed coverage. IEEE J. Sel. Areas Commun. **32**(2), 274–284 (2014)

12. Hsu, G., Liu, B., Wang, H., Su, H.: Joint beamforming for multicell multigroup multicast with per-cell power constraints. IEEE Trans. Veh. Technol. **66**(5), 4044–4058 (2017)
13. Ye, Q., Rong, B., Chen, Y., Al-Shalash, M., Caramanis, C., Andrews, J.: User association for load balancing in heterogeneous cellular networks. IEEE Trans. Wirel. Commun. **12**(6), 2706–2716 (2013)
14. Ku, M., Wang, L., Liu, Y.: Joint antenna beamforming, multiuser scheduling, and power allocation for hierarchical cellular systems. IEEE J. Sel. Areas Commun. **33**(5), 896–909 (2015)
15. Yang, K., Yu, Q., Leng, S., Fan, B., Wu, F.: Data and energy integrated communication networks for wireless big data. IEEE Access **4**, 713C–723 (2016)
16. Liu, Y., Ding, Z., Elkashlan, M., Poor, H.: Cooperative nonorthogonal multiple access with simultaneous wireless information and power transfer. IEEE J. Sel. Areas Commun. **34**(4), 938C–953 (2016)
17. Karipidis, E., Sidiropoulos, N., Luo, Z.: Quality of service and max-min fair transmit beamforming to multiple cochannel multicast groups. IEEE Trans. Signal Process. **56**(3), 1268–1279 (2008)
18. Sturm, J.: Using SeDuMi 1.02, a MATLAB toolbox for optimization over symmetric cones. Optim. Methods Softw. **11–12**, 625–C653 (1999)
19. Pennanen, H., Christopoulos, D., Chatzinotas, S., Ottersten, B.: Distributed coordinated beamforming for multi-cell multigroup multicast systems. In: 2016 IEEE International Conference on Communications (ICC), Kuala Lumpur (2016)
20. Jiang, C., Chen, Y., Gao, Y., Liu, K.: Joint spectrum sensing and access evolutionary game in cognitive radio networks. IEEE Trans. Wirel. Commun. **12**(5), 2470C–2483 (2013)
21. Zhao, Z., Chen, W.: An adaptive switching method for sum rate maximization in downlink MISO-NOMA systems. In: GLOBECOM 2017 IEEE Global Communications Conference, Singapore (2017)