An Efficient Energy Efficiency Power Allocation Algorithm for Space-Terrestrial Satellite NOMA Networks

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Abstract. Due to the shortage of spectrum resources, Non-orthogonal multiple access (NOMA) has been considered as a forward-looking technology to enhance the performance for space-terrestrial satellite networks. In this paper, the power allocation algorithm is proposed on account of Stackelberg game to apply in the space-terrestrial satellite NOMA networks. The terrestrial base stations (BSs) and satellites are leaders and followers, respectively. The alternative direction method of multipliers (ADMM) algorithm is applied in BSs layer and satellites layer to acquire optimal power allocation scheme. The results indicate that the system energy efficiency has great promotion by the proposed algorithm.

Keywords: NOMA · Stacklberg · ADMM · Energy efficiency

1 Introduction

In the wake of the promotion and application of massive mobile terminal devices, it is expected that the whole number of devices linked to the global mobile communication network will reach 100 billion in the future. In order to carry more than 100 billion mobile data in the future, mobile communication technology is faced with enormous challenges. Satellite networks can be used to supplement terrestrial networks access, pool satellite and terrestrial network resources to provide faster broadband services. The terrestrial network and satellite network are integrated to supply services for terminals [1]. NOMA has been proposed as a forward-looking multiple access mechanism for future wireless communication network [2,3].

This work was supported by the Scientific and Technological Innovation Foundation of Shunde Graduate School, USTB under Grant No. BK19BF009 and the National Natural Science Foundation of China under Grant No. 61701020.

S. Shi et al. (Eds.): AICON 2020, LNICST 356, pp. 217–226, 2021.
https://doi.org/10.1007/978-3-030-69066-3_19

In NOMA system, the channel resource can be shared by multi-users to obtain higher spectral efficiency. [2] evaluated the NOMA system performance and pointed out that the total throughput and user capacity are superior to OMA system. The proposed fixed power allocation and user grouping algorithm can enhance system performance. Z. Xiao, etc. [4] studied the sum rate problem of maximized two user NOMA system, and proposed a suboptimal scheme to resolve this problem. The authors find the beamforming vector to two users simultaneously subject to an analog beamforming structure, meanwhile, allocate corresponding power to them. In the future, the satellite will be investivaged to ensure ubiquitous coverage. In [1], the downlink transmission of NOMA on account of terrestrial-satellite networks was studied. Based on the matching of ground users and satellite users, the power allocation schemes of two different types of users are developed by using Lagrange multiplier method. By contrast with the suboptimal allocation algorithm and the average power algorithm, the results indicated that the proposed algorithm can enhance the system capacity. As far as we know, many researchers have assumed a single-tier NOMA network model, and research on terrestrial satellite NOMA network model is also scarce. Inspired by this, we investigate the power allocation algorithm of space-terrestrial satellite NOMA networks.

In this paper, the power allocation algorithm on account of Stackelberg game is studied in the space-terrestrial satellite networks. Section 2 presents the NOMA based space-terrestrial satellite networks model and shows the problem formulation scheme. In Sect. 3, The problem for energy efficiency optimization is proposed, in which Stackelberg game model is applied to resolve power allocation scheme. The Dinkelbach-style algorithm is applied to transform the non-convex optimal function into convex-form to resolve the proposed problem, and ADMM technology is introduced to reduce the time delay and reduce the number of iterations. Performance of the proposed algorithms is evaluated in Sect. 4 by many simulations. In the end, Sect. 5 summarizes the paper.

2 System Model and Problem Formulation Scheme

2.1 System Model

A communication scenario for space-terrestrial satellite networks is proposed, where S satellites and R terrestrial base stations (BSs) provide services together for ground users. Symbol s and r represent sth satellite and rth terrestrial BS, respectively, in which $s \in \{1, 2, \cdots, S\}$ and $r \in \{1, 2, \cdots, R\}$. The satellite is LEO satellite and equipped with M antennas to serve terrestrial users under its coverage and each BS is equipped with N antennas to serve users under coverage. Symbol m and n represent mth sunchannel of the satellite and n subchannel of a BS, respectively, in which $m \in \{1, 2, \cdots, M\}$, $n \in \{1, 2, \cdots, N\}$. In the terrestrial networks, NOMA is applied for multi-users and multi-users can be applied to the same subchannel with SIC technology, and each BS services T users on each subchannel. However, the research of NOMA technology in satellite networks is still in its infancy, and many problems need to be solved and studied urgently. Therefore, NOMA isn't implemented in satellite network, and each satellite services a user on each subchannel. In this paper, we believe that all users are either served by the BSs or served by the satellite (Fig. 1).

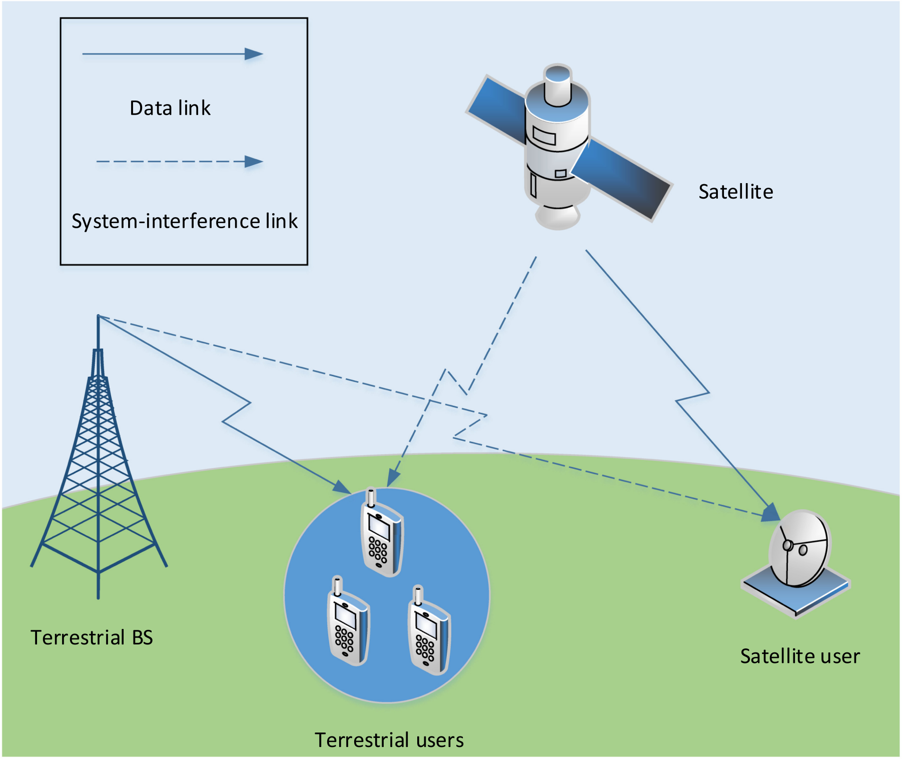

Fig. 1. System model.

2.2 Problem Formulation Scheme

Just as indicated from the above system model, the transmit signal for BS r represents as follows

$$x_r = \sum_{i=1}^{N} \sum_{j=1}^{T} \sqrt{p^r_{B,i,j}} s^r_{B,i,j} \tag{1}$$

in which $p^r_{B,i,j}$ denotes the allocated powers for the j-th user of BS r on subchannel i, and $s^r_{B,i,j}$ represents the messages for the j-th user of BS r over subchannel i.

In the same way, The transmit signal for satellite s represents as follows

$$x_s = \sum_{i=1}^{M} \sqrt{p_{S,i}^{s}} s_{S,i}^{s} \tag{2}$$

Therefore, the received signal for BS r of the t-th user on subchannel n is

$$\begin{aligned} y_{n,t}^{r} &= g_{B,n,t}^{r} x_r + g_{S,n,t}^{s} x_s + Zn \\ &= g_{B,n,t}^{r} \sum_{i=1}^{N} \sum_{j=1}^{T} \sqrt{p_{B,i,j}^{r}} s_{B,i,j}^{r} + g_{S,n,t}^{s} \sum_{i=1}^{M} \sqrt{p_{S,i}^{s}} s_{S,i}^{s} + Z_n \end{aligned} \tag{3}$$

We denote $g_{B,n,t}^{r}$ and $g_{S,n,t}$ as the subchannel gain between BS r and its t-th user in subchannel n and from the t-th user of BS r in subchannel n to satellite s, respectively. The Z_n indicates the additive white Gaussian noise (AWGN). In addition, the major interference of heterogeneous networks is inter-system interference. Therefore, in this paper, interference of terrestrial users is mainly considered from satellites. Meanwhile, inter-cell interference is regarded as a part of AWGN.

The received signal of the user of satellite s in subchannel m is

$$\begin{aligned} y_{m}^{s} &= g_{S,m}^{s} x_s + g_{B,m}^{r} x_r + Zn \\ &= g_{S,m}^{s} \sum_{i=1}^{M} \sqrt{p_{S,i}^{s}} s_{S,i}^{s} + g_{B,m}^{r} \sum_{i=1}^{N} \sum_{j=1}^{T} \sqrt{p_{B,i,j}^{r}} s_{B,i,j}^{r} + Zn \end{aligned} \tag{4}$$

When multiple users share a subchannel, other users will have great interference to target user. The successive interference elimination (SIC) technology is implemented to reduce irrelevant interference. And, the specific order is as follows:

$$\begin{aligned} &\frac{\left|g_{B,n,1}^{r}\right|^2}{I_{B,n,1}^{CR} + Z_n} \le \frac{\left|g_{B,n,2}^{r}\right|^2}{I_{B,n,2}^{CR} + Z_n} \le \cdots \le \frac{\left|g_{B,n,t}^{r}\right|^2}{I_{B,n,t}^{CR} + Z_n} \\ &\le \frac{\left|g_{B,n,t+1}^{r}\right|^2}{I_{B,n,t+1}^{CR} + Z_n} \le \cdots \le \frac{\left|g_{B,n,T}^{r}\right|^2}{I_{B,n,T}^{CR} + Z_n} \end{aligned} \tag{5}$$

in which $I_{B,n,t}^{CR} = \left|g_{S,n,t}^{s}\right|^2 \sum_{i=1}^{M} p_{S,i}^{s}$ is the inter-system interference. The t-th user can decode and eliminate the data for user k $(k < t)$ according to the SIC, and the signal for user k $(k > t)$ is considered as interference. Hence, $I_{B,n,t}^{N} = \left|g_{B,n,t}^{r}\right|^2 \sum_{i=t+1}^{T} p_{B,n,i}^{r}$ is called superposition interference.

The SINR of the t-th user of BS r in subchannel n is given by

$$SINR_{n,t}^{r} = \frac{\left|g_{B,n,t}^{r}\right|^2 p_{B,n,t}^{r}}{I_{B,n,t}^{N} + I_{B,n,t}^{CR} + Z_n} \tag{6}$$

Correspondingly, the SINR of the user of satellite s in subchannel m is given by

$$SINR_m^s = \frac{\left|g_{S,m}^s\right|^2 p_{S,m}^s}{I_{S,m}^{CR} + Z_n} \tag{7}$$

in which $I_{S,m}^{CR} = \left|g_{B,m}^r\right|^2 \sum_i^N \sum_j^T p_{B,i,j}^r$ indicates the inter-system interference, and denotes inter-system interference from the terrestrial BSs for the satellite users.

On the subchannel n, the capacity for the t-th user served by the BS r is indicated by

$$C_{n,t}^r = \frac{B}{N} \log_2(1 + SINR_{n,t}^r) \tag{8}$$

similarly,

$$C_m^s = \frac{B}{M} \log_2(1 + SINR_m^s) \tag{9}$$

The energy efficiency of the BS r is indicated as the ratio of the total capacity and the power consumed by the BSs, and is denoted by

$$\eta_{EE}^r = \frac{C_B^r}{P_B^r} \tag{10}$$

in which $C_B^r = \sum_{n=1}^N \sum_{t=1}^T C_{B,n,t}^r$, and $P_B^r = \sum_{n=1}^N \sum_{t=1}^T p_{B,n,t}^r + p_{B,static}$. $p_{B,static}$ is the circuit consumption at every BS. Similarly,

$$\eta_{EE}^s = \frac{C_S^s}{P_S^s} \tag{11}$$

in which $C_S^s = \sum_{m=1}^M C_{S,m}^s$, and $P_S^s = \sum_{m=1}^M P_{S,m}^s + p_{S,static}$. The $p_{S,static}$ is similar to $p_{B,static}$, which is a constant value. Optimizing the energy efficiency based NOMA of the space-terrestrial satellite networks is our target. The energy efficiency maximization of BS r can be formulated as follows:

$$\begin{gathered} \max_{p_{B,n,t}^r > 0} \eta_{EE}^r \\ s.t. C1: \sum_{n=1}^N \sum_{t=1}^T p_{B,n,t}^r \le P_{MAX}^R, \forall r \\ C2: C_{B,n,t}^r \ge C_{\min}^r, \forall r, n, t \end{gathered} \tag{12}$$

where the capacity of each user has a lowest limit $C_{\min}^r$. P_{MAX}^R is the power upper limit of BSs. Similarly, the energy efficiency maximization problem of the s-th satellite is equivalent to

$$\begin{gathered} \max_{p_{S,m}^s > 0} \eta_{EE}^s \\ s.t. C1: \sum_{m=1}^M P_{S,m}^s \le P_{MAX}^S, \forall s \\ C2: C_{S,m}^s \ge C_{\min}^s, \forall s, m \end{gathered} \tag{13}$$

where P^S_{MAX} is the satellite s's power upper limit, and the $C^s_{\min}$ is lowest limit capacity of every satellite user. However, in space-terrestrial satellite networks, power allocations for BSs and satellites is interactive with each other to obtain maximum system energy efficiency.

3 Stacklberg Game Formulation and Energy Efficiency Optimization

3.1 Stacklberg Game

In this paper, the Stackelberg game aims to achieve a balance between BSs and satellite. Stacklberg was originally proposed in the field of economics [5]. Game is made up of two parts, namely the leader and the follower. Followers will follow the leader's decision and change their own decision, and the decision between them is influenced by each other. In this paper, the leaders and followers of the system for competition is regarded as the maximization of the system's energy efficiency [10], in which BSs are followers, and satellites are leaders. In the Stacklberg game, each base station tries to maximize its own energy efficiency. After the base stations make the decisions, the satellite makes a strategy to maximize each satellite's energy efficiency. The iterative calculation between the base stations and the satellite will attain the equilibrium point of Stackelberg game.

3.2 Problem Optimization

We first try to solve the optimal solution of the follower subgame, and the optimal power allocation scheme of BSs should be obtained. The process of solving (12) or (13) is complicated. In order to make the solution more efficient, the original fractional non-convex function is transformed into a convex-form function to get the optimal solution for the proposed problem by Dinkelbach-style algorithm [6]. Where we could convert the optimization problem of (12) in the non-convex form as

$$\begin{aligned} F(\lambda) = & \max_{p^s_{S,m}>0, p^r_{B,n,t}>0} C^r_B(P^R, P^S) - \lambda P^r_B \\ s.t. & C1, C2, C3, C4 \end{aligned} \tag{14}$$

When the solution of the equation $\mathrm{F}(\lambda) = 0$ is obtained, the optimal solution of the function (14) is also obtained, where the parameter λ is set as an adjective variable. Therefore, the power allocation scheme will be formulated on the basis of $\mathrm{F}(\lambda)$. Where we could convert the optimization problem of (14) in the non-convex form as

$$\min_{p^s_{S,m}>0, p^r_{B,n,t}>0} \lambda P^r_B - C^r_B(P^R, P^S) \tag{15}$$

For the sake of solving the optimal power allocation scheme, we introduce the ADMM algorithm. A more detailed introduction to the ADMM method is available in [7]. And we introduce the adjective vectors of U_{BS} and V_{BS}, while the elements for BS constitute U_{BS} and V_{BS} are global adjective vectors where each one corresponds to each in X_{BS}. The Γ is defined to satisfy constraint $C2'$. Then, the target function is imported by $g(V_{BS}) = 0$ if $V_{BS} \in \Gamma$, otherwise $g(V_{BS}) = +\infty$. On the account of the above description, the power optimization function (15) is rewritten to

$$\min_{U_{BS}, V_{BS}} \lambda P_B^r - C_B^r(P^R, P^S) + g(V_{BS}) \tag{16}$$

The transformation is as follows

$$F_\rho^{BS} = f(U_{BS}) + g(V_{BS}) - \frac{\rho_{BS}}{2} \|\phi_{BS}\|_2^2 + \frac{\rho_{BS}}{2} \left\|U_{BS} - V_{BS}^t + \phi_{BS}\right\|_2^2, \tag{17}$$

in which ρ_{BS} represents the constant penalty parameter, and μ_{BS} is the dual variable. The optimization problem should be solved by following steps

$$\begin{aligned} U_{BS}^{t+1} &:= \arg\min_{U_{BS}} \left\{ f(U_{BS}) + \tfrac{\rho}{2} \|U_{BS} - V_{BS}^t + \phi_{BS}\|_2^2 \right\} \\ V_{BS}^{t+1} &:= \arg\min_{V_{BS}} \left\{ \left\|U_{BS}^{t+1} - V_{BS} + \phi_{BS}^t\right\|_2^2 \right\} \\ \phi_{BS}^{t+1} &:= \phi_{BS}^t + (U_{BS}^{t+1} - V_{BS}^{t+1}) \end{aligned} \tag{18}$$

The power allocation algorithm based ADMM for BS is concluded in the following Algorithms 1, and the satellite users power allocation algorithm has same scheme:

Algorithm 1. Power Allocation algorithm based ADMM for BS users

```
Initialize $U_{BS}^0$, $V_{BS}^0 \in C2$ and $\phi_{BS}^0 > 0$, iteration index $t = 0$, penalty parameter $\rho_{BS} = 0$, stop criteria $\xi > 0$;
while $f(U_{BS}) > \xi$ do
    Updates $U_{BS}^{t+1}$
    Updates $V_{BS}^{t+1}$
    Updates $\phi_{BS}^{t+1}$
    $t := t + 1$;
end while
```

The optimal energy efficiency of the BSs obtained by controlling the power allocation is in Algorithm 1, that is, the followers make their own decision. According to the characteristics of stacklberg game process, the leader will make decisions accordingly. Algorithm 2 shows the game between the leader and the follower. On the wake of the game progresses and both will attain an equilibrium point, then, the power distribution scheme will be acquired.

4 Simulation Results and Analysis

We assume the space-terrestrial satellite NOMA networks including $S = 2$ satellites with $NS = 8$ orthogonal subchannels and $R = 2$ BSs with $NR = 4$ subchannels. And each BS subchannel is shared by $T = 4$ users. The bandwidth $B = 30$ MHz and the carrier frequency indicates 2 GHz, and the noise power is -174 dBm/Hz. It is assumed that the coverage radius of the satellite is 500 km, and the remaining parameters about the satellite are defined on account of [8]. The maximum transmit power is indicated as $P^R_{MAX} = 30$ W, and $P^S_{MAX} = 90$ W. Considering the great difference between satellite channel and BS channel, satellite channel is simulated as Rician channel [8], BS channel is simulated as Rayleigh channel [9].

Algorithm 2. Obtaining the Equilibrium Point Algorithm of a Stackelberg Game.

```
Initialization: $k = 0$, given the maximum iterative number $K_{\max}$ of the Stacklberg game
Initialize the value of BSs $P^R(k)$, satellites $P^S(k)$ at iteration $k = 0$.
repeat
    Obtaining the power allocation scheme of BSs $P^R(k+1), P^S(k)$ by Algorithm 1.
    Given the above $P^R(k+1), P^S(k)$, calculate $P^R(k+1), P^S(k+1)$ of satellite users power allocations scheme from Algorithm 1.
until $k = K_{\max}$.
```

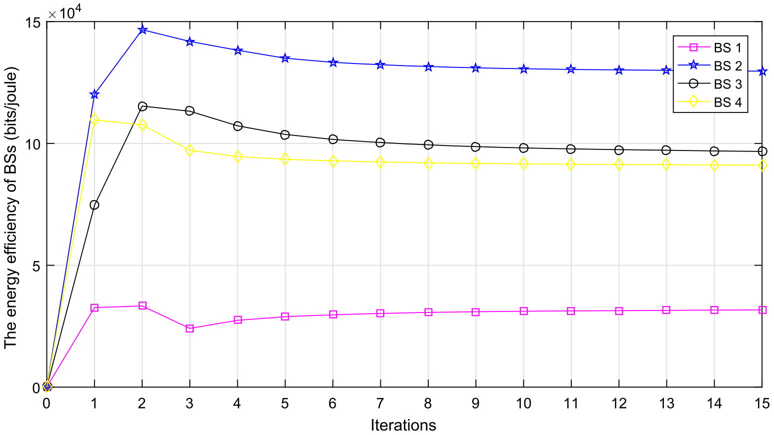

Fig. 2. The energy efficiency of different followers at each iteration.

Figure 2 indicates the energy efficiency of different followers under each of iteration. The energy efficiency of each follower increases with the iterations, and the curve converges when the number of iterations is about 5. It can be seen that iterative Algorithm 1 can remarkably improve the energy efficiency for followers in the sub-game. Similarly, this algorithm is also applicable to the leader subgame.

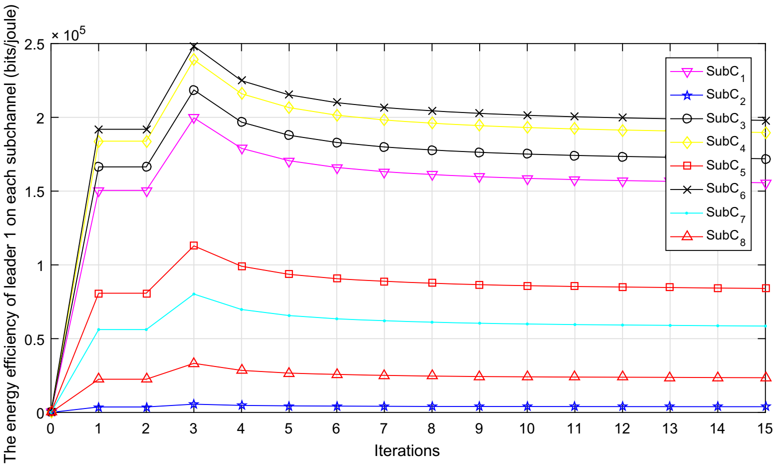

Fig. 3. The energy efficiency for satellite 1 on each subchannel at each iteration.

Figure 3 shows the energy efficiency in each subchannel for 1st satellite (leader 1) under each of iteration. The energy efficiency of the satellites (leaders) is increasing and reaching the equilibrium point. The figure indicates the proposed algorithm can improve the energy efficiency of leaders. Because of the different allocation of each user on each subchannelthe, the energy efficiency of each subchannel is different. The energy efficiency in the Stackelberg game is obviously perfect.

5 Conclusion

In this paper, the space-terrestrial satellite NOMA network was investigated to maximize system energy efficiency by introducing Stackelberg game. The leaders (BSs) and followers (satellites) make corresponding strategys according to the other party's strategys to obtain the maximum system energy efficiency, respectively. The ADMM algorithm is applied to obtain power allocation scheme in BSs layer and satellites layer, respectively. At the same time, the balance between BSs and satellite is achieved by Stackelberg game. Significantly improve the energy efficiency of the proposed network.

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