Interference Management in Terrestrial-Satellite Networks Using Stackelberg Game

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Abstract. The terrestrial-satellite network (TSN) has been recognized a potential network realizing wide-seamless coverage and high transmission rate. In this paper, a Stackelberg game model for the interference management problem is studied in spectrum sharing TSNs, where the competition between the leaders and followers is recognized as the utility maximization between the satellite user (SU) and terrestrial users (TUs). In the leader sub-game, the utility function of SU is constructed of transmission rate and cross-tier interference reacting to the followers, and the optimal strategy is acquired by mathematical derivation. Taking account to the fairness among TUs, the maximization of the minimum worst-case transmission rate is established in the follower sub-game by optimizing the cooperative scheduling and power allocation strategy jointly. Then we propose an evolutionary gale-shapley algorithm to solve the cooperative scheduling problem. And the closed-form expression of TU power is derived by the Lagrangian dual decomposition approach. By the Stackelberg iteration of the leader strategy and follower strategy, the Stackelberg equilibrium point is ultimately obtained. We give the performance simulation to verify the convergence and effectiveness of the proposed algorithm.

Keywords: Terrestrial-satellite network · Interference management · Stackelberg game · User fairness · Cooperative scheduling

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1 Introduction

The terrestrial-satellite network (TSN) plays a prominent role in the 5G networks and beyond for supporting the ubiquitous wireless services with wide coverage and large-capacity [1–3]. In the TSN, the users can choose the satellite or the traditional terrestrial base stations (BSs) based on their demand, which improves the network capacity and flexibility. However, co-existing satellite, terrestrial BS, and users make the wireless resource management more complicated [4]. And the shortage of spectrum resources has also brought pressure to performance improvement in the TSN [5]. The researchers have done a lot work to deal with these challenges. In [6], the authors considered the spectrum sharing between the satellite-tier and terrestrial-tier, and proposed an energy efficient power allocation approach to satisfy the diverse delay quality-of-service (QoS) requirements. The paper [7] investigated the spectrum access problem in terrestrial-satellite heterogeneous networks by nonorthogonal multiple access (NOMA) for each beam, where satellite users (SUs) and terrestrial users (TUs) used the same spectrum in the underlay mode to improve spectrum utilization. The user scheduling and resource allocation problem was studied for the spectrum coexisting based TSN in [8], and the authors proposed a joint optimization scheme to improve system sum rate and energy efficiency.

Although spectrum sharing and NOMA can increase spectral efficiency of TSN, the serious co-channel interference is inevitablec [9], especially in the multiple BSs based TSNs. Resource allocation and interference management has been considered to coordinate the user access and allocation of resource blocks, so as to achieve desirable performance [10–13]. In [10], the authors studied interference efficiency maximization problem in a two-tier heterogeneous network and proposed a robust resource allocation scheme to achieve the rate-interference tradeoff. In [11], the authors proposed to mitigate the cross-tier interference in the cloud based TSN by using the channel information at the cloud, a two-tier Stackelberg game between cloud and users was then established to obtain the optimal pricing and resource allocation strategy. The minimization problem of the beam usage and power consumption while ensuring the user demand was investigated in [12], where the optimized user interference was within a tolerable range. Also in [13], a coordinated multi-point (CoMP) transmission and NOMA based resource allocation model was designed to mitigate the inter-cell interference, in which the authors discussed the different CoMP strategy and derived the optimal power solutions among the coordinating BSs to improve the spectral efficiency.

However, the cross-tier interference problem by jointly considering the QoS guarantee, user fairness, cooperative scheduling, and inter-cell interference mitigation has not been studied systematically in multiple BSs based two-tier TSN. In this paper, the joint resource management problem for utility maximization is investigated in the terrestrial-satellite two-tier networks. With the consideration of the QoS, cross-tier interference, and the user fairness, we model the optimization problems of satellite-tier and terrestrial-tier, respectively. The two-tier joint optimization problem is then formulated as a Stackelberg game between

the SUs and TUs, where SUs are the leaders and TUs are the followers. In the satellite-tier optimization problem, the leaders choose the optimal power strategy to guarantee their high transmission rate without serious cross-tier interference to the followers. Based on the strategy of the leaders, the terrestrial-tier maximizes the minimum worst-case transmission rate among the followers to achieve the fairness of the TUs. The optimization problem of follower sub-game includes two nested problems: cooperative scheduling problem and power allocation problem. An evolutionary gale-shapley algorithm is proposed to solve the cooperative scheduling problem. The power allocation problem is then transformed into a convex optimization problem, and we derive the closed-form expression of the optimal power strategy of followers. By the Stackelberg iteration of the leader strategy and follower strategy, the Stackelberg equilibrium point is ultimately obtained.

2 System Model and Stackelberg Game Formulation

2.1 System Model

The considered downlink TSNs consist of a LEO, K terrestrial BS with $\mathbb{K} = \{1, 2, \ldots, K\}$, U^T TUs with $\mathbb{U}^T = \{1, 2, \ldots, U^T\}$, and U^S SUs with $\mathbb{U}^S = \{1, 2, \ldots, U^S\}$. The system bandwidth is B, which is divided to N orthogonal subchannels (SC) and each SC is identical for a SU and a terrestrial cell for spectrum sharing. To guarantee the QoS of satellite-tier, each SU communicates with LEO in different SC. And the NOMA is adopted in the terrestrial-tier to improve the spectrum utilization.

Thus, in a terrestrial-satellite system, the signal received of the SU u is

$$y_u^S = \underbrace{g_u^S \sqrt{p_u^S} s_u^S}_{\text{Desired Signal}} + \underbrace{\sum_{k \in \mathbb{K}} \left(g_{k,u}^T \sum_{j \in \mathbb{K}^T} x_{k,j}^T \sqrt{p_{k,j}^T} s_{k,j}^T \right)}_{\text{Cross-tier Interference}} + n_u^S, \tag{1}$$

where g_u^S, $g_{k,u}^T$, p_u^S, and $p_{k,j}^T$ are the channel coefficient from the LEO to SU u, the channel coefficient from the terrestrial BS k to SU u, the transmission power from the LEO to SU u, and the transmission power from the terrestrial BS k to SU j, respectively. s_u^S and $s_{k,j}^T$ denote the transmission signal from the LEO to the SU u, and the transmission signal from the BS k to the TU j. n_u^S is the additive white Gaussian noise (AWGN) of the satellite-tier. Denote that $E[|s_u^S|^2] = 1$, $E[|s_{k,j}^T|^2] = 1$, and $E[n_u^S] = \sigma^{S^2}$. We define the cooperative factor $x_{k,u}^T$, where $x_{k,u}^T = 1$ indicates the TU u is served by BS k, $x_{k,u}^T = 0$, otherwise.

Assume that BS k and SU u communicate with the same SC, then the signal to interference noise ratio (SINR) of the SU u is

$$\gamma_u^S = \frac{|g_u^S|^2 p_u^S}{|g_{k,u}^T|^2 \sum\limits_{j \in \mathbb{M}_k} x_{k,j}^T p_{k,j}^T + \sigma^{S^2}}, \tag{2}$$

where $\mathbb{M}_k = \{x_{k,u}^T = 1 | u \in \mathbb{U}^T\}$ represents the set of users served by BS k. Let $B_{sc} = B/N$ denote the bandwidth of each SC, N_0^S denote the noise power spectral density of the satellite-tier, and we have $\sigma^{S^2} = B_{sc} N_0^S$. Based on the Shannon theorem, the transmission rate of the SU u is

$$C_u^S = \log_2(1 + \gamma_u^S). \tag{3}$$

For terrestrial system, the users served by the same BS form a NOMA cluster, thus the intra-cluster interference caused by NOMA mechanism should be considered. The received signal of the TU u includes desired signal, intra-cluster interference, cross-tier interference, and noise, which is

$$y_u^T = \underbrace{\sum_{k \in \mathbb{K}} x_{k,u}^T h_{k,u}^T \sqrt{p_{k,u}^T} s_{k,u}^T}_{\text{Desired Signal}} + \underbrace{\sum_{k \in \mathbb{K}} \left(x_{k,u}^T h_{k,u}^T \sum_{j \in \mathbb{U}^T, j \neq u} x_{k,j}^T \sqrt{p_{k,j}^T} s_{k,j}^T \right)}_{\text{Intra-cluster Interference}} + \underbrace{\sum_{j \in \mathbb{U}^S} h_u^S \sqrt{p_j^S} s_j^S}_{\text{Cross-tier Interference}} + n_u^T, \tag{4}$$

where $h_{k,u}^T$ and h_u^S represent the channel coefficient from the BS k to the TU u and the channel coefficient from the LEO to the TU u. $n_{k,u}^T$ is the AWGN of the terrestrial system with $E[n_u^T] = \sigma_u^{T^2}$. For the TUs of $\mathbb{M}_k$ with $\forall k \in \mathbb{K}$, we assume that the channel gains are sort as $|h_{k,1}^T|^2 \leq \cdots \leq |h_{k,u}^T|^2 \leq \cdots \leq |h_{k,U^T}^T|^2$. Let $\{s_u^k\}$ denote the set from 1st TU to the uth TU served by BS k, and k' denote the SU that use the same SC with BS K. The SINR of the TU u is

$$\gamma_u^T = \frac{\sum\limits_{k \in \mathbb{K}} x_{k,u}^T |h_{k,u}^T|^2 p_{k,u}^T}{\sum\limits_{k \in \mathbb{K}} x_{k,u}^T |h_{k,u}^T|^2 \sum\limits_{j \in \mathbb{M}_k \setminus \{s_u^k\}} p_{k,j}^T + \sum\limits_{k \in \mathbb{K}} x_{k,u}^T |h_u^S|^2 p_{k'}^S + \sigma_u^{T^2}}, \tag{5}$$

where $\sigma_u^{T^2} = B_{sc} N_0^T$. Thus, the transmission rate of the TU u is

$$C_u^T = \log_2(1 + \gamma_u^T). \tag{6}$$

2.2 Stackelberg Game Formulation

In the terrestrial-satellite networks, the resource optimization problem can be formulated as the primary problem for satellite system and the secondary problem for the terrestrial system.

The SUs as the primary user, the QoS should be guaranteed first. On the other hand, the power consumption of the satellite system is considered to reduce waste of limited resources and minimize cross-tier interference. Accordingly, we construct the utility function of each SU as

$$v_u^S = C_u^S - \omega_u^S p_u^S, \tag{7}$$

where ω_u^S is a weighting factor in bits/s/(Hz·W). The sum utility of the satellite system is $V^S = \sum_{v \in \mathbb{U}^S} u_u^S$. Thus, the primary optimization problem for satellite system can be modeled as

$$\begin{aligned} \mathcal{P}1: \quad & \max_{\{p_u^S\}} V^S \\ s.t. \quad & C1: C_u^S \geq C^{th}, \forall u \in \mathbb{U}^S, \\ & C2: \sum_{u \in \mathbb{U}^S} p_u^S \leq P_{\max}^S, \\ & C3: p_u^S \geq 0, \forall u \in \mathbb{U}^S, \end{aligned} \tag{8}$$

where C1 guarantees the QoS of SUs with the rate threshold. C2 and C3 denote the power constraint of SUs.

According to the power optimization strategy of the satellite-tier, the TU selects the access points and transmission power to maximize its utility function. To achieve the fairness of TUs, we regard the minimum worst-case transmission rate among TUs as the utility function in the terrestrial-tier, i.e., $z = \min_{\forall u \in \mathbb{U}^T} C_u^T$. The secondary problem can be formulated as

$$\begin{aligned} \mathcal{P}2: \quad & \max_{\{x_{k,u}^T, p_{k,u}^T\}} z \\ s.t. \quad & C1: C_u^T \geq z, \forall u \in \mathbb{U}^T, \\ & C2: \sum_{i \in \mathbb{M}_k} p_{k,i}^T \leq P_{\max}^T, \forall k \in \mathbb{K}, \\ & C3: p_{k,u}^T \geq 0, \forall k \in \mathbb{K}, \forall u \in \mathbb{U}^T, \\ & C4: |g_{k,k'}^T|^2 \sum_{i \in_k} p_{k,i}^T \leq I^{th}, \forall k \in \mathbb{K}, \\ & C5: x_{k,u}^T \in \{0,1\}, \forall k \in \mathbb{K}, \forall u \in \mathbb{U}^T, \\ & C6: \mathbb{M}_k = \{x_{k,i}^T = 1 | i \in \mathbb{U}^T\}, \ |\mathbb{M}_k| \leq M^{BS}, \forall k \in \mathbb{K}, \\ & C7: \sum_{k \in \mathbb{K}} x_{k,u}^T \leq M^{UE}, \forall u \in \mathbb{U}^T, \end{aligned} \tag{9}$$

where C1 is the minimum rate guarantee. C2 and C3 are the power constraint of the TUs. C4 ensures the SU's QoS. C5, C6, and C7 denote that the cooperative factor $x_{k,u}^T$ is a binary variable, and restrict the maximum number for cooperative transmission of BSs and TUs, respectively.

The aforementioned two-tier resource allocation problem can be modeled as a Stackelberg game model, where the competition between leaders and followers is recognized as the utility maximization between SUs and TUs. SUs as the leaders have the strategy space $\mathbf{P}^{\mathrm{L}} = \{\mathbf{P}^{\mathrm{S}}\}$, and TUs as the followers have the strategy space $\mathbf{P}^{\mathrm{F}} = \{\mathbf{X}^{\mathrm{T}}, \mathbf{P}^{\mathrm{T}}\}$, that construct the strategy space $\{\mathbf{P}^{\mathrm{L}}, \mathbf{P}^{\mathrm{F}}\}$ of the game. Leaders choose strategy $\mathbf{P}^{\mathrm{S}}$ firstly in the game. In the follower sub-game, each TU as a player of the non-cooperative game, tries to choose the

strategy $\mathbf{P}^{\mathrm{F}}$ to maximize their transmission rate. Afterwards, the leaders update their strategies based on the strategies of followers and vice versa. According to the Schauder fixed point theory [14] and the theorem that there must be a Nash equilibrium point in finite strategic game. It is easy to prove that both leader game and follower game can reach Nash equilibrium, so the existence of Stackelberg equilibrium point can be achieved.

3 Optimization Solutions of the Stackelberg Game

In this section, we firstly optimize the leader sub-game problem and follower sub-game problem, respectively. Then the joint iterative optimization algorithm is proposed to achieve Stackelberg equilibrium. Furthermore, the corresponding algorithm design is introduced.

3.1 Optimization Strategy of the Leader Sub-Game

The optimization problem $\mathcal{P}1$ is a single-cell power allocation problem. And with the fixed follower strategy of the terrestrial-tier, $\mathcal{P}1$ is strictly convex where the optimal strategy can be obtained by using the KKT optimality conditions. Let $\frac{\partial U^S}{\partial p_u^S}\Big|_{\hat{p}_u^S} = 0$, we obtain the extreme point $\hat{p}_u^S = \frac{1}{\ln 2\omega_u^S} - \frac{I_u^S}{|g_u^S|^2}$, where $I_u^S = |g_{k,u}^T|^2 \sum_{j \in \mathbb{M}_k} x_{k,j}^T p_{k,j}^T + {\sigma^S}^2$. In the meanwhile, C1 of $\mathcal{P}1$ is equivalently converted into

$$p_u^S \geq \frac{(2^{C^{th}} - 1) I_u^S}{|g_u^S|^2}. \tag{10}$$

Defining $\Phi_u = \frac{(2^{C^{th}} - 1) I_u^S}{|g_u^S|^2}$. Then the optimal strategy of leader sub-game $\mathcal{P}1$ can be expressed as

$$\tilde{p}_u^S = \begin{cases} \Phi_u, & \hat{p}_u^S \leq \Phi_u \\ \frac{\Phi_u}{\sum_{u \in \mathbb{U}^S} \Phi_u} P_{\max}^S, & \hat{p}_u^S \geq \frac{\Phi_u}{\sum_{u \in S} \Phi_u} P_{\max}^S \\ \hat{p}_u^S, & \text{else} \end{cases}. \tag{11}$$

By the optimal strategy of the leader sub-game, the followers in terrestrial system decides and adjusts resource allocation to achieve its maximum utility.

3.2 Optimization Strategy of the Follower Sub-Game

The follower sub-game $\mathcal{P}2$ is a highly non-convex mixed integer programming (MIP) problem, because of the binary factor $x_{k,u}^T$, and the non-convexity constraint of C1, which cannot be solved directly in a polynomial time. In this part, we divide the follower optimization problem into two sub-problems: cooperative scheduling problem and power allocation problem.

The cooperative transmission problem is essentially a two-sided matching problem between TUs and BSs. An evolutionary gale-shapley algorithm is considered in this paper to solve the cooperative transmission problem. Firstly, we introduce a cooperative threshold h^{th} and calculate $w_{k,n}^T = \text{sgn}\left(\left\lfloor \frac{|h_{k,u}^T|^2}{h^{th}} \right\rfloor\right)$, where $w_{k,n}^T = 0$ means that the BS k cannot serve TU u due to the poor channel condition. $\lfloor \cdot \rfloor$ is the rounding down function.

In the evolutionary gale-shapley algorithm, each TU selects the BS in turn according to the preference sequence based on channel coefficient. The BS makes a decision by the value of $|\mathbb{M}_k|$ and the cluster rate. If the BS k rejects the TU u, the TU u will no longer send the request to BS k in the following cycles. The detailed description can be found in **Algorithm** 1.

With the optimization cooperative scheduling strategy $\mathbf{X}^{\mathrm{T}}$, the max-min problem of user rate optimization is convex with respect to the power allocation $\{p_{k,u}^T\}$. The Lagrangian dual decomposition approach is used to obtain the power solutions. The corresponding Lagrangian function is

$$\begin{aligned} L(p_{k,u}^T, \lambda_u, \mu_k, \nu_k) = & D(p_{k,u}^T, \lambda_u, \mu_u, \nu_k) \\ & + z(1 - \sum_{u \in \mathbb{U}^T} \lambda_u) + I^{th} \sum_{k \in \mathbb{K}} \mu_k + P_{\max}^T \sum_{k \in \mathbb{K}} \nu_k, \end{aligned} \tag{12}$$

where

$$\begin{aligned} D(p_{k,u}^T, \lambda_u, \mu_k, \nu_k) = & \sum_{u \in \mathbb{U}^T} \lambda_u \log_2 (1 + \frac{\sum\limits_{k \in \mathbb{K}} x_{k,u}^T |h_{k,u}^T|^2 p_{k,u}^T}{\sum\limits_{k \in \mathbb{K}} |h_{k,u}^T|^2 \sum\limits_{j \in \mathbb{M}_k \setminus \{s_u^k\}} p_{k,j}^T + I_u^T}) \\ & - \sum_{k \in \mathbb{K}} \mu_k |g_{k,k'}^T|^2 \sum_{u \in \mathbb{M}_k} p_{k,u}^T - \sum_{k \in \mathbb{K}} \nu_k \sum_{u \in \mathbb{M}_k} p_{k,u}^T, \end{aligned} \tag{13}$$

where $I_u^T = \sum\limits_{k \in \mathbb{K}} x_{k,u}^T |h_u^S|^2 p_{k'}^S + {\sigma_u^T}^2$. The optimal power $p_{k,u}^{T*}$ can be derived by $\frac{\partial L(p_{k,u}^T, \lambda_u, \mu_u, \nu_k)}{\partial p_{k,u}^T} = 0$, which is

$$p_{k,u}^{T*} = \left[\frac{\lambda_u x_{k,u}^T}{(\mu_u |g_{k,k'}^T|^2 + \nu_k) \ln 2} - \frac{\sum\limits_{k \in \mathbb{K}} x_{k,u}^T |h_{k,u}^T|^2 \sum\limits_{j \in \mathbb{M}_k \setminus \{s_u\}} p_{k,j}^T + I_u^T}{|h_{k,u}^T|^2} \right]^+, \tag{14}$$

where $[y]^+ = \max(y, 0)$. Let σ_{λ_u}, σ_{μ_k}, and σ_{ν_k} be the positive step size at the lth iteration, the updated expressions of the dual variables are

$$\lambda_u(l+1) = \left[\lambda_u(l) - \sigma_{\lambda_u} \left(C_u^T - z\right)\right]^+, \tag{15}$$

$$\mu_k(l+1) = \left[\mu_k(l) - \sigma_{\mu_k} (I^{th} - |g_{k,k'}^T|^2 \sum_{u \in \mathbb{M}_k} p_{k,u}^T)\right]^+, \tag{16}$$

$$\nu_k(l+1) = \left[\nu_k(l) - \sigma_{\nu_k}(P_{\max}^T - \sum_{u\in\mathbb{M}_k} p_{k,u}^T)\right]^+. \tag{17}$$

3.3 An Joint Iterative Algorithm to Achieve Stackelberg Equilibrium

According to the aforementioned leader and follower strategies, a joint iterative algorithm is proposed in this section. At each iteration, the SUs choose the optimization strategy by (11), the TUs then find the follower optimization strategy based on the leader strategy. The Stackelberg equilibrium solutions eventually can be obtained when the algorithm reaches convergence. The detailed process is described in **Algorithm** 1.

Algorithm 1. The Stackelberg Equilibrium point for the two-tier TSNs

Input:
Channel coefficient $\{g_u^S\}$, $\{g_{k,u}^T\}$, $\{h_u^S\}$, and $\{h_{k,u}^T\}$;
Maximum satellite power $P_{\max}^S$ and BS power $P_{\max}^T$;
Rate threshold C^{th} and tolerable interference temperature I^{th} of SUs.

Output:
$\mathbf{P}^{\mathrm{S}}$, $\mathbf{X}^{\mathrm{T}}$, $\mathbf{P}^{\mathrm{T}}$.

Initialize maximum Stackelberg iterative number $T_{\max}$ and maximum Lagrangian iterative number $L_{\max}$; Let $t = 0$;
Initialize $F_{unmatch} = \mathbb{U}^t$, $w_{k,n}^T$, n_u, and m_k; Set preference sequence $\{PF\_TU_u\}$.
repeat
  Leader Strategy for Satellite-Tier
  for $u \in \mathbb{U}^S$ **do**
    Calculate and update leader power strategy p_u^S by (11);
  end for
  Follower Strategy for Terrestrial-Tier
  while $F_{unmatch} \neq \emptyset$ **do**
    for $u \in F_{unmatch}$ **do**
      TU u sends matching request to BS k with $w_{k,n}^T = 1$ according to $\{PF\_TU_u\}$;
      if $m_k < M^{BS}$ **then**
        Update $\mathbf{X}^{\mathrm{T}}$, $n_u = n_u + 1$.
      else
        BS k choose the user cluster with the highest cluster rate, update $\mathbf{X}^{\mathrm{T}}$;
        $n_u = n_u + 1$ and replaced TU $\tilde{u}$ with $n_{\tilde{u}} = n_{\tilde{u}} - 1$;
        $F_{unmatch} = F_{unmatch} \cup \{\tilde{u}\}$.
      end if
      if $n_u = M^{UE}$ **then**
        $F_{unmatch} = F_{unmatch} \backslash \{u\}$.
      end if
    end for
  end while
  $l = 0$;
  while $l < L_{\max}$ **do**
    for $u \in \mathbb{U}^T$, $k \in \mathbb{K}$ **do**

27: Calculate and update follower power strategy $p_{k,u}^{T}$ by (14);
28: Calculate and update Lagrangian dual variables λ_u, μ_k, and ν_k by (15), (16), and (17), respectively.
29: **end for**
30: $l = l + 1$;
31: **end while**
32: $t = t + 1$;
33: **until** Covergence or $t = T_{\max}$

4 Simulation Results and Discussion

In this section, performance of the proposed algorithm is evaluated. The satellite altitude is 36000 km covering an urban area with 20 terrestrial BSs, and the radius of each cell is 1 km. The carrier frequency of TSN is 3 GHz and the system bandwidth is 10 MHz. The number of SUs and TUs are 20 and 100. The maximum transmission power of satellite $P_{\max}^{S} = 53$ dBm and the terrestrial BS $P_{\max}^{T} = 43$ dBm. The terrestrial channel is based on the UMa_A model [15] and Rayleigh fading. And the satellite channel is consider as the shadowed-Rician model [6]. The other transmission parameters are set referring to [16,17].

Figure 1 shows the convergence of several SUs for the proposed algorithm with $C^{th} = 5$ bits/s/Hz and $I^{th} = -60$ dBm. From the Fig. 1, we can see that the curves converge to stable solutions at about 5 Stackelberg iterations. This is because that the solutions of the two sub-games are convergent, thus the joint iteration has a good convergence, which verifies conversely the previous analysis.

Figure 2 shows the convergence of follower sub-game for the proposed algorithm with different C^{th}, where $I^{th} = -60$ dBm. Similar to Fig. 1, the follower strategy converges at about 6 iterations under different C^{th}. With the increase of C^{th}, the followers obtain the lower transmission rate z, because more stringent QoS of SUs shrinks the feasible region of the follower strategy $\mathbf{P}^{\mathrm{t}}$ to reduce cross-tier interference, resulting in the low transmission rate of TUs.

Figure 3(a) and Fig. 3(b) show the minimum transmission rate of TUs and system sum rate when the number of TUs increases from 10 to 60, respectively, where $C^{th} = 5$ bits/s/Hz and $I^{th} = -40$ dBm. It can be seen that the system sum rate of TSN increases along with an increase in the number of TUs, while the minimum transmission rate of terrestrial-tier decreases accordingly. The reason for this trend is that the lower power ratio is achieved for each TUs with the limited $P_{\max}^{T}$ as the number of TUs increases, that results to a decreased transmission rate.

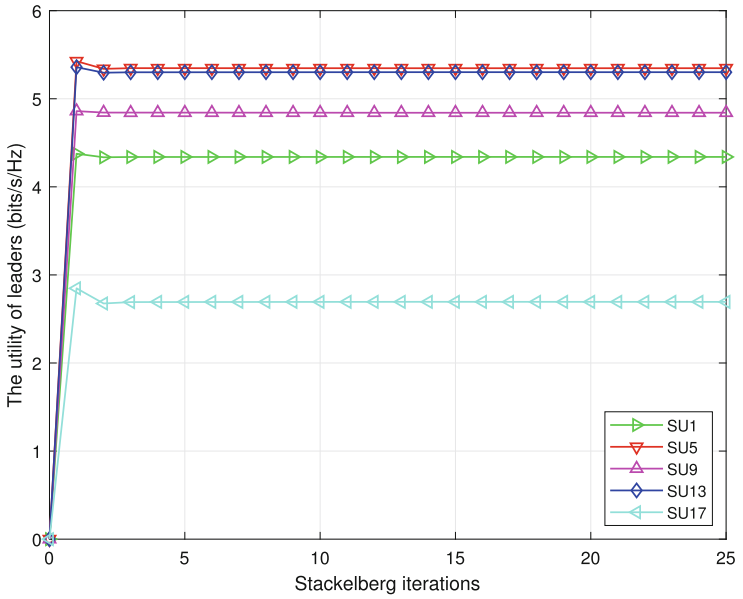

Fig. 1. Utility of leaders versus the number of Stackelberg iteration.

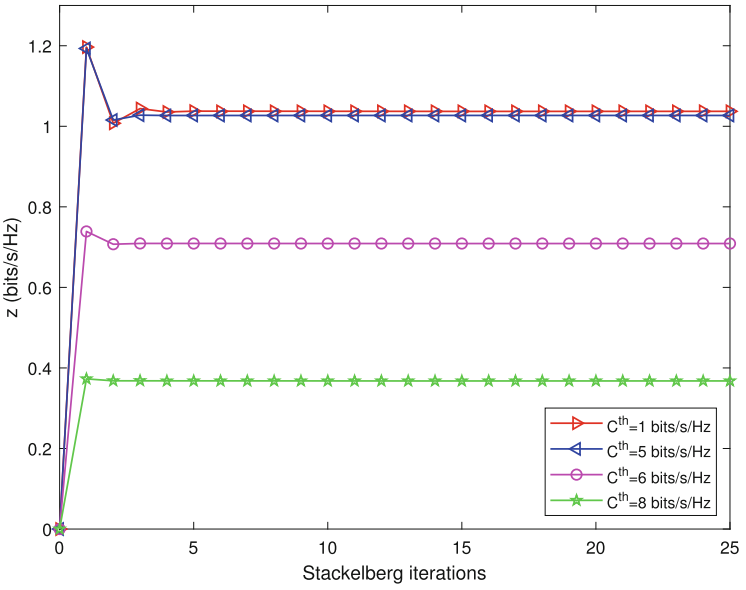

Fig. 2. Minimum rate z versus the number of Stackelberg iterations with different C^{th}.

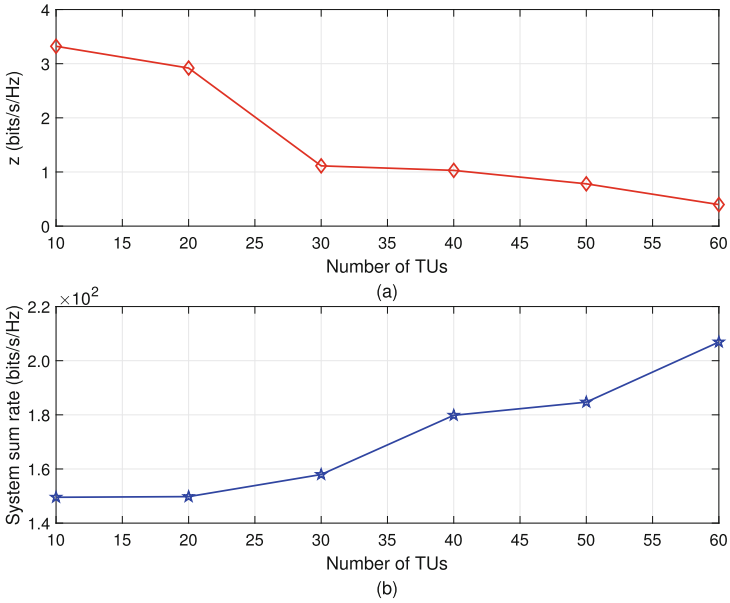

Fig. 3. (a) Minimum rate z versus the number of TUs. (b) System sum rate versus the number of TUs.

5 Conclusion

In this paper, we discussed the interference management problem of the two-tier TSNs by considering QoS guarantee, user fairness, cooperative scheduling, and power allocation. The two-tier optimization problem can be formulated as a Stackelberg game model where the SUs were the leaders and the TUs were the followers. The leader strategy was obtained by maximizing the SU utility. The followers aimed to the minimum transmission rate maximization problem to achieve the fairness among the TUs. To solve this highly non-convex MIP problem, we divided it into the cooperative scheduling problem and power allocation problem. An evolutionary gale-shapley algorithm was proposed to solve the cooperative scheduling problem. Accordingly, the power allocation problem can be transformed as a convex one, and the closed-form expression was derived. Finally, a joint iterative algorithm was proposed to achieve Stackelberg Equilibrium between the leader strategy and the follower strategy. The simulation results showed that the proposed algorithm has a good convergence and performance improvement.

References

1. Takahashi, M., Kawamoto, Y., Kato, N., Miura, A., Toyoshima, M.: DBF-based fusion control of transmit power and beam directivity for flexible resource alloca-

tion in HTS communication system toward B5G. IEEE Trans. Wireless Commun. **21**(1), 95–105 (2022)
2. Fu, S., Gao, J., Zhao, L.: Collaborative multi-resource allocation in terrestrial-satellite network towards 6G. IEEE Trans. Wirel. Commun. **20**(11), 7057–7071 (2021)
3. Wu, B., Fang, F., Fu, S.: Improving the system performance in terrestrial-satellite relay networks by configuring aerial relay. IEEE Trans. Veh. Technol. **70**(12), 13139–13148 (2021)
4. Shi, Y., Liu, J., Fadlullah, Z.M., Kato, N.: Cross-layer data delivery in satellite-aerial-terrestrial communication. IEEE Wirel. Commun. **25**(3), 138–143 (2018)
5. Zhang, Y., Zhang, H., Zhou, H., Long, K., Karagiannidis, G.K.: Resource allocation in terrestrial-satellite based next generation multiple access networks with interference cooperation. IEEE J. Sel. Areas Commun. **40**(4), 1210–1221 (2022)
6. Ruan, Y., Li, Y., Wang, C.-X., Zhang, R., Zhang, H.: Energy efficient power allocation for delay constrained cognitive satellite terrestrial networks under interference constraints. IEEE Trans. Wireless Commun. **18**(10), 4957–4969 (2019)
7. Liu, X., Zhai, X.B., Lu, W., Wu, C.: QoS-guarantee resource allocation for multibeam satellite industrial internet of things with NOMA. IEEE Trans. Industr. Inf. **17**(3), 2052–2061 (2021)
8. Peng, D., Bandi, A., Li, Y., Chatzinotas, S., Ottersten, B.: Hybrid beamforming, user scheduling, and resource allocation for integrated terrestrial-satellite communication. IEEE Trans. Veh. Technol. **70**(9), 8868–8882 (2021)
9. Fang, F., Xu, Y., Ding, Z., Shen, C., Peng, M., Karagiannidis, G.K.: Optimal resource allocation for delay minimization in NOMA-MEC networks. IEEE Trans. Commun. **68**(12), 7867–7881 (2020)
10. Xu, Y., et al.: Robust resource allocation for two-tier HetNets: an interference-efficiency perspective. IEEE Trans. Green Commun. Netw. **5**(3), 1514–1528 (2021)
11. Zhu, X., Jiang, C., Kuang, L., Zhao, Z., Guo, S.: Two-layer game based resource allocation in cloud based integrated terrestrial-satellite networks. IEEE Trans. Cogn. Commun. Netw. **6**(2), 509–522 (2020)
12. Abdu, T.S., Kisseleff, S., Lagunas, E., Chatzinotas, S.: Flexible resource optimization for GEO multibeam satellite communication system. IEEE Trans. Wireless Commun. **20**(12), 7888–7902 (2021)
13. Ali, M.S., Hossain, E., Al-Dweik, A., Kim, D.I.: Downlink power allocation for CoMP-NOMA in multi-cell networks. IEEE Trans. Commun. **66**(9), 3982–3998 (2018)
14. Talman, A.J.J.: Variable dimension fixed point algorithms and triangulations. Stat. Neerl. **35**(1), 1 (1981)
15. Guidelines for evaluation of radio interface technologies for IMT-2020, Report ITU-R M.2412-0, ITU (2017)
16. Li, J., Xue, K., Wei, D.S.L., Liu, J., Zhang, Y.: Energy efficiency and traffic offloading optimization in integrated satellite/terrestrial radio access networks. IEEE Trans. Wireless Commun. **19**(4), 2367–2381 (2020)
17. Miller, M.J., Vucetic, B., Berry, L.: Satellite Communications: Mobile and Fixed Services. Springer, Berlin (1993)