Joint User Pairing and Power Allocation for NOMA-Based GEO and LEO Satellite Network

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\section*{ABSTRACT}
Multi-layer satellite networks (MLSNs) is of great potential for the integrated 5G networks to provide diversified services. However, MLSNs confront frequency interference coordination problem between satellite systems in different orbits. This paper investigates a joint user pairing and power allocation scheme in a non-orthogonal multiple access (NOMA)-based geostationary earth orbit (GEO) and low earth orbit (LEO) satellite network. Specifically, a novel NOMA framework with two uplink receivers, i.e. the GEO and LEO satellites is established where the NOMA groups are formed considering the subcarrier assignment of ground users. To maximize the system capacity, an optimization problem is then introduced subject to the decoding threshold and power consumption. Since the formulated problem is non-convex and mathematically intractable, we decompose it into user pairing and power allocation schemes. In the user pairing scheme, virtual GEO users are generated to transform the multi-user pairing problem into a matching problem and a max-min pairing strategy is adopted to ensure the fairness among NOMA groups. In the power allocation scheme, the non-convex problem is transformed into multiple convex subproblems and solved by iterative algorithm. Simulation results validate the effectiveness and superiority of the proposed schemes when compared with several existing schemes.

\section*{INDEX TERMS}
Multi-layer satellite networks, non-orthogonal multiple access, user pairing, power allocation.

\section*{I. INTRODUCTION}
Future 5G communication networks are envisioned to meet the requirement of higher throughput, lower latency and massive devices connection. Having the ability to provide seamless coverage in wide areas, satellite communication networks are of growing interest to be integrated into the 5G ecosystem [1, 2].

Motivated by the explosive growth of various services, high throughput satellite (HTS) and low earth orbit (LEO) satellite constellations become the future directions of satellite communication networks in 5G era [3, 4]. HTS is geostationary earth orbit (GEO) satellite operating in Ka band with large number of sport beams [5]. HTS systems such as Via-sat and EchoStar are capable of providing total throughput exceeding 200Gbit/s which enable the high throughput requirement [6]. For LEO satellite constellations, miniaturized satellites can provide low latency links with reduced power consumption which are suitable for the delay-sensitive data service [7]. Below the latitude of 600km, Starlink satellites can provide round trip service within tens of milliseconds, even lower than the terrestrial networks in remote areas [8].

To fully utilize the advantages of HTS system and LEO satellite constellations, multi-layer satellite networks (MLSNs) become a promising structure of the satellite communication networks, where satellites in different orbits are constructed as a heterogeneous network [2, 9]. In MLSNs, different terrestrial users are able to communicate with the suitable satellite according to their application requirement,
As shown in the existing researches, the design of user pairing energy efficiency of NOMA system with imperfect CSI. The allocation scheme was presented in [24] to maximize the statistical CSI, respectively. A joint user scheduling and power allocation schemes were investigated with imperfect or statistical information (CSI) also have impact on the system performance. Considering the cooperation with the terrestrial networks, ergodic capacity and outage performances in NOMA-based cognitive hybrid satellite-terrestrial networks were analyzed in [27]–[29]. In addition, to fully utilize the limited onboard resource to serve massive numbers of users, several works have devoted to investigate the beam forming, user pairing and power allocation schemes in NOMA-based satellite communication networks. Two robust beamforming designs were presented in [30] for minimizing the total transmit power in a LEO multi-beam satellite IoT with the NOMA scheme considering the impact of imperfect SIC. User pairing algorithms in NOMA-based satellite networks were proposed in [31]–[33] in order to form optimal NOMA groups in different scenarios. For power allocation schemes, fairness optimization problem of multibeam satellite networks was investigated in [34] and [35] to enhance the quality of service (QoS) of each terminal. Network utility maximization problem was solved in [36] considering the network stability control and power allocation optimization in NOMA-based satellite networks.

As a efficient method for multiple access for 5G communication networks, Non-orthogonal multiple access (NOMA) is deemed as a spectrally efficient way to serve multiple users. By transmitting the superposed signal in same time-frequency resource block and adopting successive interference cancellation (SIC) at the receivers, NOMA has been proved outperform the traditional orthogonal multiple access (OMA) [15], [16].

To fully utilize the frequency resource while ensure the feasibility of the NOMA system, user pairing and power allocation schemes have received considerable interest. In order to enhance the system performance or improve the system fairness, two user pairing algorithms were presented in [17] for fixed power allocation NOMA (F-NOMA) system and the cognitive radio (CR)-inspired NOMA (CR-NOMA) system, respectively. For multiple-input multiple-output (MIMO)-NOMA system, user pairing schemes considering the channel correlation were investigated in [18] and [19] for both downlink and uplink case, and the power allocation schemes were then introduced to maximize the system sum-rate or energy efficiency. To obtain NOMA groups with multiple users, user pairing algorithm in [17] was extended in [20] to obtain a low-complexity sub-optimal pairing scheme. Matching game was introduced in [21] to solve the multi-user pairing problem and the geometric programming was employed to achieve the maximum sum-rate. In addition, the imperfect channel state information (CSI) also have impact on the system performance. In [22] and [23], decoding policy of SIC and resource allocation schemes were investigated with imperfect or statistical CSI, respectively. A joint user scheduling and power allocation scheme was presented in [24] to maximize the energy efficiency of NOMA system with imperfect CSI. As shown in the existing researches, the design of user pairing and power allocation schemes should meet the requirement of high spectral efficiency or energy efficiency, better system fairness and low computational complexity.

Recently, NOMA is widely pursued for performance enhancement in satellite communication networks. Specifically, the effectiveness and superiority of the basic NOMA structure with one satellite and two ground users in GEO land mobile satellite networks [25] and LEO satellite networks [26] were validated by analyzing several key performance merits. Considering the cooperation with the terrestrial networks, ergodic capacity and outage performances in NOMA-based cognitive hybrid satellite-terrestrial networks were analyzed in [27]–[29]. In addition, to fully utilize the limited onboard resource to serve massive numbers of users, several works have devoted to investigate the beam forming, user pairing and power allocation schemes in NOMA-based satellite communication networks. Two robust beamforming designs were presented in [30] for minimizing the total transmit power in a LEO multi-beam satellite IoT with the NOMA scheme considering the impact of imperfect SIC. User pairing algorithms in NOMA-based satellite networks were proposed in [31]–[33] in order to form optimal NOMA groups in different scenarios. For power allocation schemes, fairness optimization problem of multibeam satellite networks was investigated in [34] and [35] to enhance the quality of service (QoS) of each terminal. Network utility maximization problem was solved in [36] considering the network stability control and power allocation optimization in NOMA-based satellite networks.

It can be observed from the existing researches that the NOMA scheme is only employed with conventional single satellite systems. Noticing that ground users experience significant channel condition difference from the GEO and LEO satellites due to the different latitude, the NOMA scheme can be employed among satellite systems with different orbits to reuse the limited frequency resource. Motivated by these observations, this paper investigates a joint user pairing and power allocation scheme in a NOMA-based GEO and LEO satellite network. The main contributions are as follows.

- A novel heterogeneous framework combining GEO and LEO systems in the uplink case is presented where two satellites receive signal simultaneously from the ground users. The NOMA scheme is employed to reuse the frequency resource and improve the spectral efficiency. To make full use of the frequency resource, a novel structure of NOMA group considering the subcarrier requirement of different ground terminals is introduced. Subsequently, the end-to-end signal-to-interference-plus-noise ratios (SINRs) of the ground terminals are derived following the NOMA principle. An optimization problem is then introduced to maximize the sum rate of the considered network subject to the constraints of the decoding SINRs at each satellite node and the maximum transmission power at the ground terminals.
The proposed non-convex optimization problem is decomposed and solved into two parts: user pairing scheme and power allocation scheme. For the user pairing scheme, we first divide each GEO user into several virtual users and transform the multi-user pairing problem into a matching problem in bipartite graph to reduce the computational complexity. Then, an iterative bisection method with Hungarian algorithm is presented to form the NOMA groups and maximize the minimum channel difference among all the user pairs.

For the power allocation scheme, the method of successive convex approximation (SCA) is adopted to transform the original non-convex problem into a series of convex subproblems through logarithmic approximation and Lagrangian dual method is employed to solve the subproblem in an iterative way.

The performance of the proposed user pairing and power allocation schemes are evaluated through numerical simulations. Simulation results validate that the NOMA scheme can achieve higher capacity than other existing schemes and the user pairing scheme is able to obtain an enhanced fairness performance when compared with other user pairing schemes.

The rest of the paper is organized as follows. Section II presents the system model and then formulates the optimization problem. In section III, the user pairing scheme is investigated to form NOMA groups with multiple users. Based on the pairing result, the power allocation problem is solved in section IV. Section V provides the simulation results to demonstrate the performance of the proposed architecture and algorithms. Finally, Section VI draws the conclusion of this paper.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. SYSTEM MODEL

Consider a two-layer GEO and LEO satellite network in the uplink case, as shown in Fig. 1, there are $N$ users with high throughput requirement accessing the GEO system (e.g., Internet access terminals) $G = \{G_1, G_2, \ldots, G_N\}$ and $M$ delay-sensitive users with smaller throughput requirement accessing the LEO system (e.g., satellite IoT users) $L = \{L_1, L_2, \ldots, L_M\}$. Each user in $L$ and $G$ is equipped with a single antenna pointing at its target satellite and both satellites use single transponder to gather the uplink information. Due to the relative movement between the ground users and the LEO satellite, the NOMA scheme is employed only in a certain time period when the LEO satellite falls into the LOS path between the GEO satellite and the ground user. Under the overlapped beam coverage, the frequency reuse urgency becomes the motivation of the NOMA scheme.

Following the transmission principle of DVB-S2 [37], the available bandwidth $B_{tot}$ of the network is divided into $K$ subcarriers and the bandwidth of each subcarrier is $B_{sc}$. We assume that only one subcarrier is assigned to each LEO user due to the limited transmission demand and transceiving ability. And for the $i$th GEO user $G_i$, the number of assigned subcarriers $\tau_i$ is determined by its transmission demand. It is assumed that the total bandwidth of LEO users is smaller than that of GEO users and the system bandwidth is sufficient for terminals access, i.e., $K > \sum_{i=1}^{N} \tau_i > M$.

As shown in Fig. 2, a novel structure of NOMA user group is introduced to pair GEO and LEO users into $N$ NOMA groups $\{U_1, U_2, U_3, \ldots, U_N\}$. The NOMA group $U_i$ occupying $\tau_i$ subcarriers consists of one GEO user $u_{i,1}$ and $W_i$ (where $W_i \leq \tau_i$) LEO users $(u_{i,2}, u_{i,3}, \ldots, u_{i,W_i+1})$. Different from the classical multi-user NOMA group where all the NOMA users share the same frequency resource, the proposed structure is able to reduce the interference between the LEO users while making full use of the frequency resource.
The total observation at each satellite nodes can be expressed as:

\[
y_{\text{geo}} = \sum_{i=1}^{N} \left( h_{g,i1} \sqrt{P_{i1} x_{i1}} + \sum_{j=2}^{W_i+1} h_{g,ij} \sqrt{P_{ij} x_{ij}} \right) + n_g,
\]

\[
y_{\text{leo}} = \sum_{i=1}^{N} \left( h_{l,i1} \sqrt{P_{i1} x_{i1}} + \sum_{j=2}^{W_i+1} h_{l,ij} \sqrt{P_{ij} x_{ij}} \right) + n_l,
\]

where \( h_{g,ij} \) and \( h_{l,ij} \) denote the channel coefficients between user \( u_{ij} \) (\( i = 1, 2, \ldots, W_i + 1 \)) and the satellite nodes, which include free space path loss, shadow fading loss and antenna gain at the satellites, and the impact of Doppler effect of LEO satellite on \( h_{l,ij} \) should also be considered. \( P_{ij} \) denotes the transmit power allocated at \( u_{ij} \), \( x_{ij} \) is the data symbol transmitted from \( u_{ij} \) to the satellite satisfying \( E \left[ |x_{ij}|^2 \right] = 1 \). \( n_g \) and \( n_l \) is the background additive white Gaussian noise (AWGN) at the satellite nodes with \( E \left[ |n_g|^2 \right] = \sigma_g^2 \), \( E \left[ |n_l|^2 \right] = \sigma_l^2 \).

In the proposed network, the LEO satellite is operating in the orbit with a lower altitude (<1500km) when compared with the GEO satellite (35800km), which lead to a significant free space path loss difference between the two satellites. In most cases, the antenna gain difference on the satellite nodes and the different shadow fading condition can not compensate the free space path loss difference in the link budget. Thus, the LEO satellite experience better channel condition than the GEO satellite when communicating with the ground users.

Following the principle of NOMA, in each user group, the GEO satellite with worse channel condition directly decode the GEO user’s information without SIC, the SINR is

\[
\gamma_{i1} = \frac{P_{i1} |h_{g,i1}|^2}{\sum_{j=2}^{W_i+1} P_{ij} |h_{g,ij}|^2 \tau_{i1}^{-1} + \sigma_g^2}.
\]

Correspondingly, the LEO satellite with better channel condition first removes the interference of the GEO user utilizing SIC technique and then decodes the information of the LEO users. The SINRs of GEO user and LEO users at the LEO satellite can be written as

\[
\gamma_{ij \rightarrow g} = \frac{P_{ij} |h_{l,ij}|^2 \tau_{ij}^{-1}}{P_{i1} |h_{g,i1}|^2 + \sigma_l^2}, \quad j = 2, 3, \ldots, W_i + 1.
\]

\[
\gamma_{ij} = \frac{P_{ij} |h_{l,ij}|^2}{\tau_i \sigma_l^2}, \quad j = 2, 3, \ldots, W_i + 1.
\]

From the SINR expressions, we can find that in the \( j \)th NOMA group, the GEO user \( u_{i1} \) occupying \( \tau_i \) subcarriers is interfered by all the LEO users in the same group while the LEO users \( u_{ij} \) (\( j = 2, 3, \ldots, W_i + 1 \)) only receive interference from the GEO user \( u_{i1} \). Compared with the NOMA scheme with two user group, paring multiple users in one NOMA group can further enhance the spectral efficiency of the considered network. In addition, different from the classical multi-user NOMA group, assigning individual subcarrier to each LEO user can reduce the intra-group interference among LEO users and the computation complexity of SIC at the LEO satellite.

Subsequently, the total system capacity of considered network can be written as

\[
C_{\text{tot}} = \sum_{i=1}^{N} \sum_{j=1}^{W_i+1} \log_2(1 + \gamma_{ij}).
\]

**B. PROBLEM FORMULATION**

In this paper, we aim to maximize the achievable capacity of the considered network subject to the decoding SINRs requirements at each satellite node and the power constrains of the ground users. Let \( \gamma_{g,h} \) and \( \gamma_{l,h} \) be the decoding SINRs thresholds of the GEO and LEO satellites which are different due to the detection ability, \( P_{g,\text{max}} \) and \( P_{l,\text{max}} \) be the maximal transmission power of GEO and LEO users, respectively. The optimization problem can be formulated as

\[
\max_{W_i, P_i} C_{\text{tot}}
\]

s.t. \( W_i \leq \tau_i, \; \forall i \),

\( \gamma_{i1} \geq \gamma_{g,h}, \; \forall i \),

\( \gamma_{ij} \geq \gamma_{l,h}, \; \forall i, j \in \{2, 3, \ldots, W_i+1\} \),

\( 0 < P_{i1} \leq P_{g,\text{max}}, \; \forall i \),

\( 0 < P_{ij} \leq P_{l,\text{max}}, \forall i, j \in \{2, 3, \ldots, W_i+1\}. \)

where the optimization objective is to maximize the achievable system capacity and the optimization variables are user pairing scheme and the transmit power \( P_i = [P_{i1}, P_{i2}, \ldots, P_{iW_i+1}] \). Obviously, the problem in (5) is non-convex and mathematically intractable which cannot be solved directly. Therefore, we decompose the problem into two parts: the user paring and power allocation schemes to achieve optimal capacity performance in the following sections.

**III. USER PAIRING SCHEME**

In this section, we investigate the user paring scheme as the basis of the power allocation scheme. From the analysis above, the aim of the user pairing scheme is to divide the ground users into \( N \) NOMA groups with one GEO user and multiple LEO users in each group.

Firstly, in order to reduce the computational complexity of multi-user pairing, each GEO user \( G_i \in \mathbf{G} \) is divided into \( \tau_i \) virtual GEO users with same channel coefficients \( h_{G_i} \) and \( h_{l_i,G_i} \). Giving the user set of virtual GEO users as

\[2\text{In this paper, it is assumed that both GEO and LEO satellite are able to obtain the perfect CSI through the public signaling channel in order to perform the NOMA scheme.}\]

\[3\text{In this paper, we assume that } P_{g,\text{max}} \text{ and } P_{l,\text{max}} \text{ are liner related as } P_{g,\text{max}} = 10 \log_{10} P_{l,\text{max}} \text{ due to the limited transceiving requirement of the LEO users.}\]
**G* = \{G_1^*, G_2^*, \ldots, G_\xi^*\} and \xi = \sum_{i=1}^{N} \tau_i*, the original multiple users pairing problem in G and L is transformed into a pairing problem between \(G^*\) and L.**

Secondly, it is worth mentioning that in the two user pairing problem between \(G^*\) and L, there remains \(\sum_{i=1}^{N} \tau_i - M\) virtual GEO users unpaired after the pairing stage. To achieve the optimal capacity performance of the considered network, we present the following theorem.

**Theorem 1:** N virtual GEO users with best channel condition in \(G^*\) are unpaired in the optimum pairing scheme \(P_{opt}\).

**Proof:** Considering a contrary situation, i.e. in the optimum pairing scheme \(P_{opt}\), there exist at least one unpaired virtual GEO users \(G_\beta^*\) has a worse channel condition than one paired virtual GEO user \(G_\beta^*\).

Change the pair mate of LEO user \(L_\gamma\) from \(G_\beta^*\) to \(G_\alpha^*\) in \(P_{opt}\) to form a new pairing scheme \(P^*\). The capacity gain can be expressed as

\[
\Delta C = C_{P_{opt}} - C_{P^*} = \log_2 \left(1 + \frac{P_\beta |h_{g,\beta}|^2}{P_{\gamma} |h_{g,\gamma}|^2 + I_\beta}\right) + \log_2 \left(1 + \frac{P_\alpha |h_{g,\alpha}|^2}{I_\alpha}\right) - \log_2 \left(1 + \frac{P_\beta |h_{g,\beta}|^2}{P_{\gamma} |h_{g,\gamma}|^2 + I_\gamma}\right) - \log_2 \left(1 + \frac{P_\alpha |h_{g,\alpha}|^2}{I_\alpha}\right),
\]

where \(h_{g,\alpha}, h_{g,\beta}\) and \(h_{g,\gamma}\) (\(|h_{g,\alpha}|^2 < |h_{g,\beta}|^2\)) denote the channel coefficients of \(G_\alpha^*, G_\beta^*\) and \(L_\gamma\), respectively. \(I_\alpha\) and \(I_\gamma\) are the remaining interference at the GEO satellite receiver excluding the interference from user \(L_\gamma\).

It can be proved that \(\Delta C > 0\) when \(G_\alpha^*\) and \(G_\beta^*\) are allocated with the same power and interference condition, which means \(P_{opt}\) is not the optimal pairing scheme. This proves the theorem 1.

Lastly, after \(\sum_{i=1}^{N} \tau_i - M\) virtual GEO users with best channel condition are selected and excluded, set \(G^*\) turns into \(G_\xi^*\) with M virtual GEO users. The user pairing problem is then transformed into a matching problem aims to find M pairs in 2M users from two individual sets.

Existing researches proved that the NOMA systems with fixed power allocation scheme can achieve better performance when two users in distinct channel conditions are paired [17]. In addition, considering the fairness of the pairing scheme, optimizing the channel difference in one NOMA group may deteriorate the performance in other groups. Therefore, we introduce a max-min pairing strategy to maximize the minimum channel difference among all the user pairs

\[
\max_{G_{pair} \in G^*_\xi} \min_{L_{pair} \in L} |h_{g, G_{pair}}|^2 - |h_{g, L_{pair}}|^2, \quad (7)
\]

where \(|h_{g, G_{pair}}|^2 - |h_{g, L_{pair}}|^2\) denotes the channel difference between the paired users. It is worth noticing that the users are paired according to the channel coefficients towards the GEO satellite without considering the LEO satellite, this is because the capacities of LEO users on the LEO satellite are only determined by the transmit power of LEO users according the expression in (3), which are not related to the pairing scheme.

To solve the max-min problem in (7), we equivalently transformed it into a maximize problem by introducing an auxiliary variable \(\Omega\).

\[
\max \quad \Omega \\
\text{s.t.} \quad |h_{g, G_{pair}}|^2 - |h_{g, L_{pair}}|^2 \geq \Omega, \quad G_{pair} \in G^*_\xi, \quad L_{pair} \in L. \quad (8)
\]

The transformed problem can be solved by iterative bisection method to maximize the variable \(\Omega\). In each iteration, the pairing scheme can be viewed as a matching problem in bipartite graph \(G(V, E)\), where \(V\) is the set of ground users consists of two subsets \(G_\alpha^*\) and \(L_\gamma\), \(E\) is the edge with vertexes from both subsets. By employing the Hungarian algorithm, we can find the maximum match [38] of the bipartite graph \(G(V, E)\) with the given channel difference threshold \(\Omega\). The iteration is converged when the maximum match turns into a perfect match and the difference between the upper bound \(\Omega_{U}\) and lower bound \(\Omega_{L}\) falls below the iteration accuracy \(\varepsilon\).

The proposed user pairing algorithm is described in Algorithm 1.

Furthermore, we analyze the computational complexity of the proposed user pairing algorithm. For the iterative bisection method, the computational complexity to reach the accuracy \(\varepsilon\) is \(O(\log_2(\varepsilon^{-1}))\), and in each iteration, the computational complexity of Hungarian method is \(O(M^3)\). Thus, the computational complexity of Algorithm 1 is \(O(\log_2(\varepsilon^{-1})M^3)\).

**IV. POWER ALLOCATION SCHEME**

Base on the multi-user pairing result obtained in the previous section, this section studies the power allocation scheme to achieve the optimal capacity performance in the proposed network. Noticing that the inter-group interference is eliminated by assigning different subcarriers to each NOMA group, the optimization problem in (5) can be simplified as a series of power allocation problems in each NOMA group with the given pairing scheme. For the \(i\)th NOMA group, the power allocation problem is written as

\[
\max_{P_i} \sum_{j=1}^{W_i+1} \log_2(1 + \gamma_{ij}) \\
\text{s.t.} \quad \gamma_{1i} \geq \gamma_{gth},
\]
Algorithm 1 User Pairing Algorithm

Input: GEO user set $G$ and LEO user set $L$, all the CSI of the users in $G$ and $L$

Initialization: Randomly select a user in set $L$, set $\Omega_U = |h_{g,L_\text{max}}|^2$ and $\Omega_L = -|h_{g,L_\text{max}}|^2$, $\lambda = 0$
1: Generate virtual GEO users set $G^*$ according to the subcarrier requirement and channel state information of the GEO users in $G$;
2: Sort the virtual GEO users in $G^*$ by channel coefficients $|h_{g,G^*}|^2$, select $\sum_{i=1}^{N} t_i - M$ users with best channel condition as unpaired users, generate set $G^\ast$;
3: Calculate the channel difference $\Delta h_{mn} = |h_{g,G^\ast}|^2 - |h_{g,L_m}|^2$ between the virtual GEO users and LEO users for all $G_n \in G^\ast$ and $L_m \in L$;
4: while
5: $\Omega_U - \Omega_L < \varepsilon$ or $\lambda$ reaches the maximal iteration number
6: $\Omega_{\lambda} = 0.5(\Omega_U + \Omega_L)$;
7: Build edge $v_{mn}$ between user $G_n$ and $L_m$ if $\Delta h_{mn} \geq \Omega$. generate bipartite graph $G_{\lambda}$ ($V$, $E$);
8: Obtain the maximum match $G_{\lambda}$ of $G_{\lambda}$ ($V$, $E$) employing the Hungarian algorithm;
9: if $G_{\lambda}$ is not a perfect match then
10: $\Omega_U = \Omega_{\lambda}$;
11: else
12: $\Omega_L = \Omega_{\lambda}$;
13: end if
14: $\lambda = \lambda + 1$;
15: end while
16: Combine the virtual GEO users with the paired LEO users to obtain the NOMA groups with multiple users;

Output: User pairing scheme.

It has been proved in [39] that SCA method is convergent and satisfies Karush-Kuhn-Tucher (KKT) conditions in each iteration. In this paper, we introduce a SCA algorithm with two loops. In the first loop with iteration variable $\rho$, we introduce logarithmic approximation to approximate the non-convex function and upgrade the approximation variables to generate a convex subproblem around the feasible point. In the second loop with the iteration variable $\rho^\ast$, we solve the transformed subproblem Lagrangian dual method and obtain the optimal solution $\hat{P}_i[\rho^\ast]$. For logarithmic approximation, the lower bound of the original function $\log_2(1 + \gamma_{ij})$ is given as

$$
\log_2(1 + \gamma_{ij}) \geq \frac{1}{\ln 2} \left( \theta_{ij} \ln(\gamma_{ij}) + \eta_{ij} \right),
$$

where $\theta_{ij} = \frac{\gamma_{ij}^*}{1 + \gamma_{ij}^*}$, $\eta_{ij} = \ln(1 + \gamma_{ij}^*) - \frac{\gamma_{ij}^*}{1 + \gamma_{ij}^*}$ $\ln \gamma_{ij}^*$ are the approximation variables, the approximation is tight when $\gamma_{ij}^* = \gamma_{ij}$.

Substituting (10) into (9), the optimization problem in each iteration is written as

$$
\max_{P_{ij}} \frac{1}{\ln 2} \sum_{j=1}^{W_{i+1}} \left( \theta_{ij} \ln(\gamma_{ij}) + \eta_{ij} \right)
$$

s.t. $\gamma_{ij} \geq \gamma_{ij}^\ast$, $\gamma_{ij} \geq \gamma_{ij}^\ast$, $\forall j \in \{2, 3, \ldots, W_{i+1}\}$
0 $< P_{i1} \leq P_{g,\text{max}}$
0 $< P_{ij} \leq P_{l,\text{max}}$, $\forall j \in \{2, 3, \ldots, W_{i+1}\}$

Theorem 2: Let $\hat{P}_{ij} = \ln P_{ij}$, the transformed optimization problem of (11) is a convex problem.
Proof: Please refer to Appendix A.

The transformed optimization problem in (22) in the appendix A can be solved applying Lagrangian dual method. The Lagrangian function $L \left( \hat{P}_i, \mu_i, v_i \right)$ is written as

$$
L = f \left( \hat{P}_i \right) + \upsilon_i \left( P_{g,\text{max}} - e^{\hat{P}_{i1}} \right) + \sum_{j=2}^{W_{i+1}} \upsilon_j \left( P_{l,\text{max}} - e^{\hat{P}_{ij}} \right)
$$

+ $\mu_i \left[ e^{\hat{P}_{i1}} |h_{g,i1}|^2 - \gamma_{i1} \left( \sum_{j=2}^{W_{i+1}} e^{\hat{P}_{ij}} |h_{g,ij}|^2 - \tau_l^{-1} + \sigma_g^2 \right) \right]

+ \sum_{j=2}^{W_{i+1}} \mu_{ij} \left( e^{\hat{P}_{ij}} |h_{l,ij}|^2 - \tau_g^{-1} \gamma_{ij} \right).
$$

where $\mu_i = \{\mu_{i1}, \mu_{i2}, \ldots, \mu_{iW_{i+1}}\}$, $\upsilon_i = \{\upsilon_{i1}, \upsilon_{i2}, \ldots, \upsilon_{iW_{i+1}}\}$ are the Lagrange multipliers. The standard Lagrangian dual function is expressed as

$$
D \left( \mu_i, v_i \right) = \inf_{P_{ij}} L \left( \hat{P}_i, \mu_i, v_i \right).
$$

The optimal solution in each iteration should satisfy the stationary condition $\frac{\partial L}{\partial P_{ij}} = 0$. Substituting (23) into (12), we can obtain the equations as (14), as shown at the bottom of the next page by solving $\frac{\partial L}{\partial P_{ij}} = 0$. 

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It is difficult to obtain closed-form solutions for $e^{\hat{h}_{ij}}$, $(j = 2, 3, \ldots, W_i + 1)$ directly from (14). Therefore, we replace the variables in $\sum_{j=2}^{W_i+1} e^{\hat{h}_{ij}}|h_{g,i}|^2$ with the solutions form the last iteration $P_i[\rho^{*} - 1]$, $(j = 2, 3, \ldots, W_i + 1)$, the optimal solutions in the $j$th iteration can be then derived in (15), as shown at the bottom of the page, where $\Psi_j = \frac{\theta_1}{\ln 2} \left( \sum_{j=2}^{W_i+1} \frac{P_i[\rho^{*} - 1]|h_{g,i}|^2 + \tau_i \sigma_i^2}{W_i + 1} \right)$, and $\{P_i[^*]\}^+ = \max\{0, P\}$.

Then, according to the complementary slackness condition, the Lagrange factors $\mu_i$ and $\nu_i$ can be upgraded by

$$
\mu_i \left[ \rho^{*} \right] = \left[ \mu_i \left[ \rho^{*} \right] - \delta_\mu \left[ \rho^{*} \right] \left( \hat{P}_{i1} |h_{g,i}|^2 \right) \right]^{+} - \gamma_{gth} \left( \sum_{j=2}^{W_i+1} e^{\hat{P}_{ij}}|h_{g,i}|^2 \tau_i^{-1} + \sigma_g^2 \right), \quad j = 2, 3, \ldots, W_i + 1,
$$

$$
\mu_{ij} \left[ \rho^{*} \right] = \left[ \mu_{ij} \left[ \rho^{*} \right] - \delta_\mu \left[ \rho^{*} \right] \left( e^{\hat{P}_{ij}}|h_{g,i}|^2 \right) \right]^{+} - \tau_i \sigma_i^2 \gamma_{hth}, \quad i = j = 2, 3, \ldots, W_i + 1,
$$

$$
\nu_{ij} \left[ \rho^{*} \right] = \left[ \nu_{ij} \left[ \rho^{*} \right] - \delta_\nu \left[ \rho^{*} \right] \left( P_{i,\text{max}} - e^{\hat{P}_{ij}} \right) \right]^{+}, \quad j = 2, 3, \ldots, W_i + 1,
$$

where $\delta_\mu$ and $\delta_\nu$ are the step size to upgrade $\mu_i$ and $\nu_i$ in each iteration, respectively.

The power allocation scheme of the considered network is proposed in Algorithm 2 according to the analysis above.

The computational complexity of algorithm 2 is analyzed as follows. In each NOMA group, the computational complexity to upgrade parameters $\mu_i, \nu_i$ and $P_i$ in the second loop are $O(\rho^{*} (W_i + 1))$ and the computational complexity to obtain the optimal $P_i$ in the first loop is $O(\rho^{*} (W_i + 1))$. Since there exist $N$ NOMA groups in the pairing scheme, the computational complexity of algorithm 2 is $O(N \rho^{*} \sum W_i)$. Moreover, the computational complexity of the joint scheme can be obtained by adding the computational complexity of algorithm 1 and algorithm 2.

$$
\begin{align*}
\theta_{i1} + \frac{e^{\hat{h}_{i1}}}{} & = 0, \\
\theta_{ij} - \frac{\theta_{i1}}{} & = 0, \\
\frac{P_{i1}[\rho]}{} & = \frac{\theta_{i1}}{} , \\
P_{ij}[\rho] & = \frac{\theta_{ij}}{} , \\
\end{align*}
$$

\[\text{(15)}\]

V. NUMERICAL RESULTS

In this section, representative simulation results are provided to evaluate the performance of the proposed NOMA network as well as the proposed user pairing and power allocation schemes. The simulation scenario consists of one GEO satellite, one LEO satellite, 20 GEO users and 70 LEO users, the maximum number of subcarriers assigned to GEO users is set as 4. The satellite-terrestrial channels are assumed to undergo shadowed-Rician fading distribution [41]. The other system parameters are given in Table 1. In the simulation, the user pairing scheme proposed in section III is compared with the other two pairing schemes:

1) Greedy pairing scheme. This pairing scheme is employed to form NOMA groups with multiple users in [33], where users are selected into a NOMA group if their channel differences are maximum at current. Following the greedy pairing algorithm, each GEO user
$G_i$ is paired with $\tau_j$ LEO users in a given order until all the terminals are paired.

2) **Random pairing scheme.** In this scheme, the channel differences between the users are not considered, the GEO users and LEO users are randomly paired into NOMA groups only following the constraint of $(W_i \leq \tau_i)$ given in section II.

Moreover, we provide two more conventional schemes with different power allocation criteria for further comparison with the power allocation algorithm proposed in section IV:

1) **Traditional OMA scheme.** Giving the time division multiple access (TDMA) as an example of the traditional OMA scheme, where the GEO and LEO users occupy orthogonal time resources to transmit the information with the maximum power $P_{g,\text{max}}$ and $P_{l,\text{max}}$.

2) **Adaptive power control scheme.** The adaptive power control (APC) scheme is proposed in [10] to maximize the transmission rate of non-geostationary earth orbit (NGEO) satellite while ensuring the service quality of the GEO satellite. Different from the NOMA scheme, both GEO and NGEO satellites in the APC scheme directly decode its own information without employing the SIC technique. The power allocation problem in the uplink case is given as

$$\max_{P_{NGEO}} C_{NGEO} = \log_2(1 + \gamma_{NGEO})$$

s.t. $I_{GEO} \leq I_{GEOth},$  \hspace{1cm} (20)

where $\gamma_{NGEO}$ is the SINR at the NGEO satellite node, $I_{GEO}$ is the interference from the NGEO ground terminal towards the GEO satellite and $I_{GEOth}$ is the tolerable interference threshold at the GEO satellite.

In Fig. 3, the convergence process of the proposed user pairing algorithm and power allocation algorithm are illustrated, respectively. Fig. 3(a) shows the ratio of $\Omega_2$ and $\Omega_0$ in each iteration and Fig. 3(b) shows the minimal channel difference $\Delta h_{\text{min}}$ among all the NOMA groups after each iteration. It can be observed that the algorithm converges rapidly in the simulation scenario and the $\lambda/\lambda_0$ falls below the value of 0.1. For the power allocation algorithm, giving the transmit power $P_{l,\text{max}} = 0\text{dBW}$ and the decoding SINRs thresholds $\gamma_{gth} = \gamma_{lth} = \gamma_{th} = 0\text{dB}$. Fig. 3(c) depicts the average transmission rate of both GEO and LEO users in each iteration. As shown in the figure, the average transmission rate for GEO and LEO users both converge after less than 6 iterations. The simulation results validate the effectiveness of the proposed user pairing and power allocation schemes.
The values of $\gamma_{th}$ are considered as $-3$dB, 0dB, and 3dB, and $I_{GEOth}$ is set as 0dB in APC scheme. The curves indicate the increase of system sum rate with the growth of $\gamma_{th}$ for all three schemes, and the rate of NOMA scheme is superior to that of the other two schemes with the given SINRs thresholds. This result demonstrates that the NOMA scheme is able to reuse the time and frequency resource by employing the SIC technique to achieve higher capacity and spectral efficiency. In addition, we can find that the sum rate of the NOMA schemes increases with the decrease of $\gamma_{th}$. This is because the GEO users have higher transmission ability and occupy more subcarrier resource than the LEO users in the considered network, the decrease of $\gamma_{th}$ enables the GEO users to transmit information with higher power.

To derive further insight of the system capacity performance, the average transmission rate per user for GEO and LEO users are analyzed in Fig. 5, where the system parameters are set the same as in Fig. 4. For the NOMA scheme, both GEO and LEO users can achieve higher average rate when compared with the OMA scheme in most cases. Besides, it can be find that the capacity performance of GEO users is improved with the rise of $\gamma_{th}$, while the capacity performance of LEO users is getting worse at the same time. This observation indicates that the power allocated to the LEO-IoT terminals will decrease to ensure the SINRs at GEO satellite fall below the threshold $\gamma_{th}$ while more power can be allocated to the GEO users to achieve the maximum system capacity when the $\gamma_{th}$ increases. For the APC scheme, the GEO users can achieve highest average transmission rate among all the schemes while the LEO users’ average transmission rate is the lowest. This is because power allocation criteria of the APC scheme first ensure the transmission quality of the GEO users before maximize the capacity of the LEO users. In addition, without SIC technique, the LEO satellite will receive interference from the GEO users when decoding its own information, thus the capacity performance of LEO system will degrade in turn.

To evaluate the fairness performance of user pairing scheme, we introduce the Jains fairness index $J$, which is continuous with the range of $[\frac{1}{N}, 1]$

\[
J = \frac{\left( \frac{1}{N} \sum_{i=1}^{N} C_i \right)^2}{N \times \left( \frac{1}{N} \sum_{i=1}^{N} C_i \right)^2}, \quad (21)
\]

where $C_i$ is the transmission rate of the $i$th NOMA group and $C_{\text{min}}$ is the minimum transmission rate among all the NOMA groups. The user pairing scheme can achieve higher index value when the fairness of transmission rate among the NOMA groups is improved.

Fig. 6 illustrates the Jains fairness index for different user pairing schemes with respect to different maximum transmit power $P_{l,max}$, where $\gamma_{th}$ is considered as 0dB. For all three schemes, the system fairness is improved with the increase of maximum transmit power, and the Max-min pairing scheme
always outperforms the other two schemes. This is because in the Max-min pairing scheme, the minimum channel difference among all the NOMA group is maximized through the iterative bisection method with Hungarian algorithm. Moreover, the gap of fairness index between the Max-min pairing scheme and the other two schemes also increase with higher $P_{t,\text{max}}$, indicating that the proposed Max-min scheme can achieve better fairness performance at higher SINRs.

In Fig. 7, comparisons of Jains fairness index are provided among three user pairing schemes with different decoding SINR threshold $\gamma_{th}$, where the maximum transmit power $P_{t,\text{max}} = 10\text{dBW}$. For greedy pairing scheme and random pairing scheme, the fairness index increases with the growth of $\gamma_{th}$. This phenomenon can be explained by the fact that the NOMA group experience a higher transmission rate with smaller $\gamma_{th}$, thus enlarge the capacity difference between different NOMA group and in turn decrease the fairness index. For the Max-min pairing scheme, the fairness index undergoes a slight growth when compared with the other two schemes, showing that the NOMA groups in the Max-min scheme shall receive a rather balanced benefit from the decrease of $\gamma_{th}$ and achieve a stable fairness performance.

VI. CONCLUSION

This paper investigates a joint user pairing and power allocation scheme in a NOMA-based satellite network with GEO and LEO systems. First, we proposed a optimization problem to maximize the sum rate of considered network base on the NOMA scheme. Then, user pairing scheme is investigated to from the NOMA groups with multiple users. The fairness among NOMA groups is ensured by employing the max-min pairing strategy. To achieve the optimal throughput, the power allocation scheme is introduced base on the pairing result. The non-convex problem is equivalently transformed into a series of convex subproblem utilizing SCA method and the optimal solution is obtained though iterative algorithm. Finally, simulation results demonstrate that the proposed schemes are enabled to achieve higher capacity and fairness performance which can be potentially extended into multi-layered satellite scenarios and scenarios with multiple antennas.

APPENDIX A

PROOF OF THEOREM 2

Substituting (2), (3) along with $\hat{\mathbf{P}}_i = \ln \mathbf{P}_i$ into (11), the optimization problem is written as

$$\max_{\mathbf{P}_i} \frac{\theta_{11}}{2} \ln \left( e^{\hat{P}_{i1}} |h_{g,i}|^2 \right)$$

$$- \frac{\theta_{11}}{2} \ln \left( \sum_{j=2}^{W_i+1} e^{\hat{P}_{ij}} |h_{g,j}|^2 \tau_j^{-1} + \sigma_g^2 \right)$$

$$+ \frac{\theta_{ij}}{2} \ln \left( \frac{e^{\hat{P}_{ij}} |h_{l,j}|^2}{\tau_j \sigma_{l,j}^2} \right) + \eta_{ij}$$

subject to

$$\sum_{j=2}^{W_i+1} e^{\hat{P}_{ij}} |h_{g,j}|^2 \tau_j^{-1} + \sigma_g^2 \geq \gamma_{\text{th}}$$

$$0 < e^{\hat{P}_{ij}} \leq P_{r,\text{max}}$$

$$0 < e^{\hat{P}_{ij}} \leq P_{t,\text{max}}$$

Denote $f(\hat{\mathbf{P}}_i)$ as the objective function, $-f(\hat{\mathbf{P}}_i)$ can be expressed as a liner combination of log-sum-exp function $[40]$ and affine function,

$$-f(\hat{\mathbf{P}}_i) = \frac{\theta_{11}}{2} \ln \left( \sum_{j=2}^{W_i+1} e^{\hat{P}_{ij}} |h_{g,j}|^2 \tau_j^{-1} + \sigma_g^2 \right)$$

$$- \left( \frac{1}{2} \ln \theta_{ij}\hat{\mathbf{P}}_i^T + \zeta \right),$$

where

$$\zeta = \sum_{j=1}^{W_i+1} \left( \frac{\theta_{11}}{2} \ln \left( |h_{g,j}|^2 \right) + \eta_{ij} \right) - \log_{2} \left( \tau_j \sigma_{l,j}^2 \right) \sum_{j=2}^{W_i+1} \theta_{ij}$$

is a constant.

Since the log-sum-exp function is proved to be convex $[40]$, the objective function $f(\hat{\mathbf{P}}_i)$ is a concave function.

For the constraints in (12b)-(12e), it is obvious that (12c)-(12e) are convex with exponential functions. And (12b) can be equivalently transformed into (14) by taking logarithm on both sides of the inequality.

$$\ln \left( \sum_{j=2}^{W_i+1} e^{\hat{P}_{ij}} |h_{g,j}|^2 \tau_j^{-1} + \sigma_g^2 \right) - \hat{P}_{i1}$$

$$+ \ln \left( \gamma_{\text{th}} - |h_{g,i}|^2 \right) \leq 0.$$  (24)

It can be easily proved that the transformed inequality (24) is a convex constraint. Therefore, the optimization problem in (11) is proved as a convex problem.
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