Auction-based Multi-Channel Cooperative Spectrum Sharing in Hybrid Satellite-Terrestrial IoT Networks

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***Abstract*—In this paper, we investigate the multi-channel cooperative spectrum sharing in hybrid satellite-terrestrial internet of things (IoT) networks with the auction mechanism, which is designed to reduce the operational expenditure of the satellite-based IoT (S-IoT) network while alleviating the spectrum scarcity issues of terrestrial-based IoT (T-IoT) network. The cluster heads of selected T-IoT networks assist the primary satellite users transmission through cooperative relaying techniques in exchange for spectrum access. We propose an auction-based optimization problem to maximize the sum transmission rate of all primary S-IoT receivers with the appropriate secondary network selection and corresponding radio resource allocation profile by the distributed implementation while meeting the minimum transmission rate of secondary receivers of each T-IoT network. Specifically, the one-shot Vickrey-Clarke-Groves (VCG) auction is introduced to obtain the maximum social welfare, where the winner determination problem is transformed into an assignment problem and solved by the Hungarian algorithm. To further reduce the primary satellite network decision complexity, the sequential Vickrey auction is implemented by sequential fashion until all channels are auctioned. Due to incentive compatibility with those two auction mechanisms, the secondary T-IoT cluster yields the true bids of each channel, where both the non-orthogonal multiple access (NOMA) and time division multiple access (TDMA) schemes are implemented in cooperative communication. Finally, simulation results validate the effectiveness and fairness of the proposed auction-based approach as well as the superiority of the NOMA scheme in secondary relays selection. Moreover, the influence of key factors on the performance of the proposed scheme is analyzed in detail.**

***Index Terms*—Hybrid Satellite-Terrestrial IoT Networks, VCG auction, sequential Vickrey auction, NOMA, multiple relay selection.**

I. Introduction

A. Backgrounds and Motivations

OVER the recent years, internet of things (IoT) have become worldwide networks based on standard communication protocols, helping to realize communication *anything, anyone, anytime, anyplace* [1], which greatly facilitate our daily life and provide more intelligent services, such as smart home, transportation, health-care, manufacture and factory [2]. However, the number of IoT devices would reach more than 24.1 billion by 2030, and most of them are connected by the wireless links [3]. With such a huge volume of IoT devices anticipated to be connected into the wireless network, it is foreseeable that spectrum scarcity is a critical design constraint in massive IoT deployments [4], [5]. IoT devices in the industrial, scientific, and medical domains are working on the crowded free band, coexisting with the wireless technologies operating in this band, e.g., ZigBee, Wi-Fi, and Bluetooth, which cannot provide seamless connectivity with the desired quality of service (QoS) [6]. Therefore, it is preferred for the pre-existing primary network to share the licensed frequency band with IoT networks by cognitive radio (CR), which has emerged as an intelligent technology to address the spectrum scarcity issues. The emerging CR-based IoT network provides a novel paradigm solution for the sensor nodes to efficiently utilize spectrum resources [7].

Thanks to improvements in the launch technologies as well as miniaturization of the satellites themselves, a recent feasibility study has shown that low earth orbit (LEO) satellite could be effectively used for distributed control and automation in a smart grid scenario, meeting the stringent latency requirements [8]. The satellite-based IoT (S-IoT) system offers truly global coverage, which serves a huge number of devices, users, and/or objects [9]–[12]. Over the past few years, LEO satellite-based constellation networks have been launched, e.g., Starlink, Kuiper, and OneWeb announced to provide global Internet-access services. Within the fully covered global access networks, LEO satellites provide great opportunities to the geo-distributed IoT networks. Riot research reports expect that the number of S-IoT devices will see a major jump in 2021, and there will be some 30.3 million S-IoT devices deployed globally by 2050 [13]. With growing requirements of S-IoT services and limited availability of L-band and S-band spectral resources, higher frequency bands (above 10 GHz) like Ku and Ka have also been assigned for mobile satellite services [14]–[17]. Furthermore, the line-of-sight (LoS) S-IoT systems are vulnerable to be blocked by heavy shadowing or obstacles for the high frequency band in the cases of urban, populated environments [18]. Deployment of terrestrial relays in hybrid satellite-terrestrial relay networks (HSTRNs) has been pro-

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posed to enhance coverage and high data rate services [19]–[21]. To reduce capital and operational expenditure, sharing infrastructure and radio resources between S-IoT networks and terrestrial-based IoT (T-IoT) networks is also an inevitable trend [22], [23].

B. Related Works

In CR, the secondary users are authorized to utilize the licensed spectrum assigned to a primary network, provided that the secondary spectrum access will not deteriorate the QoS of the primary user [21]. In an underlay paradigm [24], the transmit power of the secondary user is strictly constrained to satisfy an interference criterion at the primary user. The Underlay paradigm requires complex power control, which restricts the widespread use of this paradigm. On the contrary, in an overlay paradigm [25], [26], also known as cooperative spectrum sharing, the secondary users assist the primary transmission through cooperative relaying techniques in exchange for spectrum access. Thereby, in contrast to the underlay paradigm, the overlay paradigm does not pose stringent transmit power restrictions to the secondary users. The integration of the overlay paradigm into the S-IoT network can provide significant benefits in terms of spectral efficiency and transmission reliability, which brings network coverage even when the direct communication (DC) link is disrupted due to shadowing and obstacles [27]. In addition, the infrastructures of T-IoT networks are widely deployed, and they can effectively cooperate with the existing S-IoT networks. Hence, to increase the potential payoff, the primary satellite network is willing to cooperate with the appropriate secondary networks, especially in the case of an unstable satellite link connection. The author in [28] firstly proposed that the secondary terrestrial users assist the primary satellite transmission through cooperative relaying techniques in exchange for spectrum access, where the outage performance improvement via relay selection was evaluated. However, existing works on hybrid satellite-terrestrial cooperative networks are mostly based on the orthogonal multiple access (OMA) scheme. Over the last few years, the CR-inspired non-orthogonal multiple access (NOMA) scheme has received considerable attention scenarios [29]–[31], as the NOMA scheme encourages spectrum sharing among transmission nodes, which not only improves the spectral efficiency but also ensures massive connectivity that can be effectively supported. [22], [23], [32] integrated the NOMA scheme into the cognitive hybrid satellite-terrestrial overlay network, where the NOMA scheme further improves the achievable performance. However, these works are restricted to a simplified single user and single-channel scenario. It is foreseeable that multi-channel cooperative spectrum sharing is expected to meet the increasing demand for user access and multimedia services.

The multiple relay selection and corresponding resource allocation are pivotal issues to be studied for the hybrid satellite-terrestrial IoT architecture. One of the potential solutions is the centralized approach, where the primary satellite network gathers the channel state information (CSI) of potential secondary networks and applies the exhausted search algorithm to obtain the globally optimized solution for the primary network [33]. The centralized approach would cause huge overheads in the CSI acquisition and computational complexity. Comparing to the centralized approach, the secondary network would offer the actual transmission rate by proper incentive mechanism within the distributed implementation, which could reduce the complexity of the cooperative. Meanwhile, both primary and secondary networks are rational and willing to obtain the maximum payoffs by the cooperation [23]. Without considering the fairness in overlay networks, the secondary relay has no willingness to cooperate with the primary networks. Therefore, fairness should be taken into account as an important indicator.

Recently, as a subfield of economics and business management, auction theory has been introduced to provide an interdisciplinary technology for radio resource allocation in the wireless systems, which can be implemented in asymmetric and incomplete information scenarios [34], [35]. To handle the problem of resource competition among selfish users via an incentive-compatible mechanism, auction theory has been widely used in wireless communications for solving the problem of maximizing utilization in the case of resource scarcity [36], [37]. One of the most applied mechanism is the sealed-bid second-price auction, also named Vickrey auction. In Vickrey auction, the bidder who submitted the highest bid is awarded the object being sold and pays a price equal to the second-highest amount bid. The dominant strategy is bidding one's true value, which gives the unique Nash equilibrium (NE). However, the Vickrey auction mechanism is only suitable for a single commodity. In [32], the authors proposed a relay selection based on the Vickrey auction mechanism to allow secondary networks to compete for one cooperative spectrum sharing channel, but they did not consider multi-channel systems. The Vickrey-Clarke-Groves (VCG) mechanism, a natural extension of the Vickrey multiunit auction, provides a ready means of achieving resource allocation efficiency [35]. The strategy-proof VCG mechanism provides bidders with incentives for submitting their true valuations as the bid prices and guarantees that bidders get benefits from their participation [38]. Among all mechanisms for allocating multiple objects that are efficient, incentive compatibility, and individually rational, the VCG mechanism maximizes the expected payment of each agent [38]. The VCG mechanism not only achieves efficiency but from the perspective of the seller. Because it raises the highest revenue among all efficient mechanisms [34]. Furthermore, another way to extend Vickrey auction to multiple commodities is to apply the sequential-auction mechanism. This mechanism further reduces complexity. Besides, it can be easily used when the users enter and leave the system in a dynamic manner [33], which is easy to be applied in a rapidly changing network topology. Therefore, both the VCG auction and sequential Vickrey auction are considered in this paper.

C. Contributions and Organization

In this paper, we investigate the auction-based multi-channel cooperative spectrum sharing in hybrid satellite-terrestrial IoT networks. The main contributions of this paper are summarized as follows:

- We establish a multi-channel cooperative spectrum sharing framework in hybrid satellite-terrestrial IoT networks, where the S-IoT network is the primary network sharing the spectrum resource and the T-IoT networks are potential secondary networks sharing the infrastructure. We propose an auction-based optimization problem to maximize the sum transmission rate of all primary S-IoT receivers with the appropriate secondary network selection and the corresponding radio resource allocation profile by the distributed implementations while meeting the minimum transmission rate of secondary receivers of each T-IoT network.
- The one-shot VCG auction is introduced to obtain the maximum social welfare by the distributed implementation, where the winner determination problem is transferred into the assignment problem and solved by the Hungarian algorithm. Due to the incentive compatibility of VCG, the secondary T-IoT cluster yields the true bids of each channel, where both the NOMA and time division multiple access (TDMA) scheme are implemented in the cooperative transmission. Besides, the average allocation and proportional allocation methods are proposed to reallocate the extra payoff from the VCG auction to the secondary network.
- To further reduce the complexity of the winner determination problem for primary satellite network, the sequential Vickrey auction is implemented sequentially until all channels are auctioned, where both the NOMA and TDMA scheme are implemented in the cooperative transmission. The extra payoff is reallocated by average allocation and proportional allocation methods.
- The proposed auction-based approaches are compared to the centralized approach, the location-based approach, and the random selection approach, which validate the effectiveness of the auction mechanism on cooperative spectrum sharing in hybrid satellite-terrestrial IoT networks for multiple secondary relay selection. Moreover, the achievable performance of the NOMA scheme is proved to be superior to the OMA scheme. Finally, the effects of key factors on the performance of the auction mechanism are analyzed.

The rest of this paper is organized as follows. Section II presents the multiple spectrum sharing system model in hybrid satellite-terrestrial IoT networks and formulates the signal transmission in the NOMA scheme. In section III, the optimization problem is formulated for the considered cooperative spectrum sharing framework. Section IV and Section V implement the VCG auction and sequential Vickrey auction approach for the proposed system, respectively. In Section VI, the auction mechanism is introduced for the OMA scheme. Section VII shows the simulation results. Finally, conclusions are drawn in Section VIII.

II. Network model and Problem Statement

A. System Model

We consider the downlink scenario of multi-channel cooperative spectrum sharing in hybrid satellite-terrestrial IoT networks illustrated in Fig. 1. This architecture consists of M primary satellite receivers, denoted as $\mathbf{M} = \{PR_1, PR_2, \cdots, PR_m, \ldots, PR_M\}$, where the different primary receivers (PRs) employ the frequency division multiplexing access (FDMA) scheme. We suppose that reliable DC links between satellite (S) and $\mathbf{M}$ are challenging to maintain since the heavy shadowing and obstacles. Therefore, the primary network tries to seek cooperation from the nearby secondary IoT networks by recruiting the cluster heads as relays. The potential secondary T-IoT networks obtain the access grant of licensed spectrum by sharing the infrastructure with primary S-IoT network. There are N secondary cluster heads denoted as $\mathbf{N} = \{R_1, R_2, \cdots, R_n, \ldots, R_N\}$. Each cluster head, say R_n ($n \in \{1, 2, \cdots, N\}$), serves K_n secondary receivers (SRs), denoted as $\mathbf{K}_n = \left\{SR_1^n, SR_2^n, \cdots, SR_{k_n}^n, \cdots, SR_{K_n}^n\right\}$. Each node is equipped with a single antenna and operates in a half-duplex mode, which means that the node cannot transmit and receive signals simultaneously.

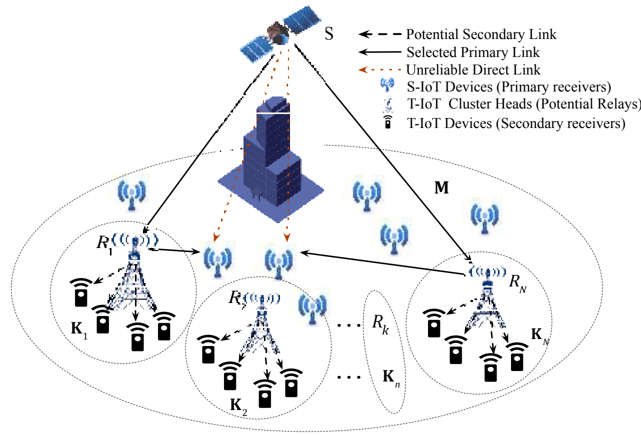

Fig. 1: System model.

We consider $N \gg M$ and each secondary network assists at most one PR owing to the power constraint. Hence, the proper relays selection for M primary channel increases the spectrum efficiency and the transmission capacity of PRs. Since the multi-relay cooperation for one channel at the same time is overhead in synchronization and coding, as well as the unnecessary co-channel interferences, we consider one primary channel only recruits one relay to forward the signal. The transmission is divided into two temporal phase, where the first temporal phase is satellite multicast the M primary signal $\{x_{p_1}, x_{p_2}, \cdots, x_{p_m}, \cdots, x_{p_M}\}$ to the all potential secondary relays. The R_n intends to transmit $\left\{x_{s_1}, x_{s_2}, \cdots, x_{s_{k_n}}, \cdots, x_{s_{K_n}}\right\}$ for K_n SRs. $E\left[x_{p_m}\right] = E\left[x_{s_{k_n}}\right] = 0$ and $E\left[x_{p_m}^2\right] = E\left[x_{s_{k_n}}^2\right] = 1$, where $p_m \in \mathbf{M}$, $k_n \in \mathbf{K}_n$, $n \in \mathbf{N}$ and $E\left[\cdot\right]$ means the expectation operation.

In this paper, $H_{X,Y}$ denotes the channel between nodes X and Y, where $X, Y \in \{S, \mathbf{N}, \mathbf{M}, \mathbf{K}_n\,(n \in \{1, 2, \cdots, N\})\}$, respectively. The propagation model in the first temporal phase is given as $H_{SR_t} = L_{SR_t} G_t G_s \left|h_{SR_t}\right|^2$, where L_{SR_t} is the free space loss and other related losses, G_t and G_s are antenna gains of terrestrial devices and satellite, respectively, $h_{SR_t}^m$ is the shadowing and channel fading [39], [40]. The shadowing and channel fading of satellite channel is assumed to follow a Shadowed-Rician fading model, which is mathematically tractable and has been widely applied in various fixed and mobile satellite services for a variety of frequency bands, such as the UHF-band, L-band, S-band, and Ka-band. The probability density function (PDF) of $h_{SR_t}^2$ is shown as [23]

$$f_{\left|h_{SR_t}\right|^2}(x) = \alpha \exp\left(-\beta x\right) {}_1F_1\left(m, 1, \delta x\right), \tag{1}$$

where ${}_1F_1\left(\cdot,\cdot,\cdot\right)$ denotes the confluent hypergeometric function and $\alpha = \frac{(2bp)^p}{2b(2bp+\Omega)^p}$, $\delta = \frac{\Omega}{2b(2bp+\Omega)}$, and $\beta = \frac{1}{2b}$, with $2b$ being the average power of the scatter component, Ω denotes the average power of the LOS component, p is the Nakagami fading parameter.

For the terrestrial link, the channel gain is $H_{R_k n} = d_{R_k n}^{-\eta}\left|h_{R_k,n}^2\right|$ in the second temporal phase, where $d_{R_k n}$ is the distance between R_k and n, η is propagation path loss exponent, $h_{R_k n}$ is the small scale of fading obeying the Nakagami-m distribution, which is given by [22]

$$f_{\left|h_{R_k,n}^2\right|}(x) = \left(\frac{m_{R_k n}}{\Omega_{R_k n}}\right)^{m_{R_k n}} \frac{x^{m_{R_k n}-1}}{\Gamma\left(m_{R_k n}\right)} e^{-\frac{m_{R_k n} x}{\Omega_{R_k n}}}, \tag{2}$$

where $m_{R_k n}$ is the fading severity, which is assumed as integer values in this paper, $\Omega_{R_k n}$ is the average power, $\Gamma\left(\cdot\right)$ denotes the complete gamma function.

We consider all channels are assumed to experience independent and identically distributed (i.i.d.) fading. Furthermore, we consider that all channels follow quasi-static fading, i.e. the channel gains remain constant within each transmission block but vary independently between different blocks [39], [40]. The secondary relay gathers instantaneous CSI between the PRs and SRs by the pilot in different channels, and the cooperative relays do not share CSIs among them. The auction process can be implemented in every block interval.

B. The Cooperative Matrix

An $M \times N$ matrix $\mathbf{E}$ is introduced to describe the multi-relays cooperation between the PRs, i.e. set $\mathbf{M}$, and the secondary cluster heads i.e. set $\mathbf{N}$. Specifically, $\mathbf{E}$ can be expressed as

$$\mathbf{E} = \begin{pmatrix} e_1^1 & \cdots & e_N^1 \\ \vdots & \ddots & \vdots \\ e_1^M & \cdots & e_N^M \end{pmatrix}, \tag{3}$$

where $e_n^m = 1$ indicates that the PR_m chooses $n-th$ secondary network to implement cooperative spectrum sharing, and $e_n^m = 0$ otherwise.

C. Signal Transmission in The First Temporal Phase

The transmitted power and the bandwidth for PR_m are denoted as P_m^S and W_m, respectively. The transmitted power for R_n is P_n, and the background noise is modeled by a zero-mean, complex Gaussian variable with variance σ^2. If $e_n^m = 1$, the satellite multicast the signal of PR_m to the R_n in the first temporal phase. The received signal of R_n secondary relay is given by

$$y_n^m = \sqrt{P_m^S H_{S,R_n}^m}\, x_{p_m} + \eta_n^m, \tag{4}$$

where η_n^m is the additive white Gaussian noise (AWGN) observed by R_n, H_{S,R_n}^m is the propagation gain of the satellite link. Therefore, the transmission rate of the first temporal phase is given as

$$R_{p_n^m} = \frac{1}{2} w_m \log_2\left(1 + \frac{P_m^S H_{S,R_n}^m}{\sigma^2}\right). \tag{5}$$

D. NOMA Signaling in The Second Temporal Phase

For the second temporal phase, the cooperative relays implement the Decode-and-Forward (DF) protocol to retransmit the signal of PR_m. Furthermore, we introduce the NOMA scheme, where the primary and secondary messages are superimposed by using the NOMA principle for cooperative communications.

The observations at the PR_m and the k_n-th SR are written as Eq. (6) and Eq. (7), where $\eta_{PR_m}^{m,n}$ and $\eta_{SR_{k_n}^n}^{m,n}$ are the AWGN, respectively, $\alpha_0^{m,n}$ and $\alpha_i^{m,n}$ are the power allocation coefficient for different receivers obeying $\alpha_0^{m,n} + \sum_{i=1}^{K_n} \alpha_i^{m,n} = 1$.

We consider that the SRs of $n-th$ secondary T-IoT nework and PR_m connect to the cluster head, where the $m-th$ channel gain are ordered as $H_{R_n,SR_1^n}^m < \cdots < H_{R_n,SR_k^n}^m < H_{R_n,PR_m}^m < H_{R_n,SR_{k+1}^n}^m \cdots < H_{R_n,SR_{K_n}^n}^m$. The SIC follows the order of the channel gains of receivers as $x_{s_1} \to \cdots \to x_{s_k} \to x_{p_m} \to x_{s_{k+1}} \to \cdots \to x_{s_{K_n}}$.

The SIC is carried out to separate the multiplexed signals and combat the negative impact of the inter-user interference. The PR_m decodes $x_{s_1} \to \cdots \to x_{s_k}$. Therefore, the achievable data rate for the PR_m is given by

$$R_{p_m}^{m,n} = \frac{1}{2} w_m \log_2\left(1 + \frac{\alpha_0^{m,n} H_{R_n,PR_m}^m}{\sum_{i=k+1}^{K_n} \alpha_i^{m,n} H_{R_n,PR_m}^m + 1/\rho_n}\right), \tag{8}$$

where $\rho_n = P_n/\sigma^2$.

If $k_n > k$, the receiver decodes the signal following the order of $x_{s_1} \to \cdots \to x_{s_k} \to x_{p_m} \to x_{s_{k+1}} \to \cdots \to x_{s_{k_n-1}}$. Hence the achievable data rate for k_n-th SR is given by Eq. (9) in the next page.

If $k_n \le k$, the receiver decodes the signal following the order of $x_{s_1} \to \cdots \to x_{s_{k_n-1}}$. Hence the achievable data rate for k_n-th SR is given by Eq. (10) in the next page.

If $e_n^m = 1$, the transmission rate of the PR_m is $\min\left\{R_{p_n^m}, R_{p_m}^{m,n}\right\}$. Besides, if the PR_m does not choose to cooperate, the transmission rate is given by

$$R_{p_m} = w_m \log_2\left(1 + \frac{P_m^S H_{S,PR_m}^m}{\sigma^2}\right), \tag{11}$$

which can be seen as the reserved price for the satellite in auction mechanisms.

III. The Optimization Problem Formulation

The proper multi-relays selection can make full use of M channels, which brings benefits for both PRs and SRs. Since the primary and secondary networks are rational, the PRs are eager to achieve as much sum capacity as possible. Owing to support the infrastructure, including energy consumption,

$$y_{PR_m}^{m,n} = \sqrt{\alpha_0^{m,n} P_n H_{R_n,PR_m}^m} x_{p_m} + \sum_{i=1}^{K_n} \sqrt{\alpha_i^{m,n} P_n H_{R_n,PR_m}^m} x_{s_{k_n}} + \eta_{PR_m}^{m,n}. \tag{6}$$

$$y_{SR_{k_n}^n}^{m,n} = \sqrt{\alpha_0^{m,n} P_n H_{R_n,SR_{k_n}^n}^m} x_{p_m} + \sum_{i=1}^{K_n} \sqrt{\alpha_i^{m,n} P_n H_{R_n,SR_{k_n}^n}^m} x_{s_{k_n}} + \eta_{SR_{k_n}^n}^{m,n}. \tag{7}$$

$$R_{SR_{k_n}^n}^{m,n} = \frac{1}{2} w_m \log_2 \left(1 + \frac{\alpha_{k_n}^{m,n} H_{R_n,SR_{k_n}^n}^m}{\sum_{i=k_n+1}^{K_n} \alpha_i^{m,n} H_{R_n,SR_{k_n}^n}^m + 1/\rho_n} \right). \tag{9}$$

$$R_{SR_{k_n}^n}^{m,n} = \frac{1}{2} w_m \log_2 \left(1 + \frac{\alpha_{k_n}^{m,n} H_{R_n,SR_{k_n}^n}^m}{\left(\alpha_0^{m,n} + \sum_{i=k_n+1}^{K_n} \alpha_i^{m,n} \right) H_{R_n,SR_{k_n}^n}^m + 1/\rho_n} \right). \tag{10}$$

hardware price, and time-window value, the cooperative payoffs of $k_n - th$ SR in $n - th$ secondary network have to be satisfied with the minimum rate requirement $R_{\min,k_n}^n$ when $e_n^m = 1$. Otherwise, the secondary network has no incentive to join the network for cooperation.

In this paper, we consider a cooperative spectrum sharing scheme for hybrid satellite-terrestrial IoT networks. The key objective is to maximize the sum transmission rate of all PRs with appropriate secondary network selection and corresponding power allocation profile while meeting the minimum transmission rate of SRs of each T-IoT network. Therefore, the maximization problem can be formulated as

$$\arg\max_{\mathbf{E},\alpha} \sum_{n=1}^{N} \sum_{m=1}^{M} e_n^m R_{p_m}^{m,n}, \tag{12}$$

$$s.t. \quad \alpha_0^{m,n} + \sum\nolimits_{i=1}^{K_n} \alpha_i^{m,n} \le 1, \tag{12a}$$

$$\sum\nolimits_{m=1}^{m=M} e_n^m \le 1, \forall n \in \mathbf{N}, \tag{12b}$$

$$\sum\nolimits_{n=1}^{n=N} e_n^m \le 1, \forall m \in \mathbf{M}, \tag{12c}$$

$$e_n^m \in \{0,1\}, \forall n \in \mathbf{N}, m \in \mathbf{M}, \tag{12d}$$

$$R_{SR_{k_n}^n}^{m,n} \ge R_{\min,k_n}^n, \forall e_n^m = 1, \tag{12e}$$

where α is the set of NOMA power allocation profile for all chosen secondary networks. The constraint Eq. (12a) means that the total power of the secondary cluster head is limited. The N constraints in Eq. (12b) ensure that each secondary network is allocated at most one channel. The M constraints in Eq. (12c) ensure that each channel is allocated to at most one secondary network. The $M \times N$ constraints in Eq. (12d) mean that PR_m chooses $n - th$ secondary network or not, which has been defined by Eq. (3). The constraints in Eq. (12e) are satisfied with the minimum rate requirement for each SR of the chosen secondary network, which makes the secondary network willing to participate in the cooperation.

Problem (12) can be solved by using a centralized approach with an exhausted search algorithm, which has the following two disadvantages. To begin with, the potential secondary networks are forced to reveal all local information, including all required channel gains for M channels in each secondary network and the minimum required rate for each SR, which may not be desirable due to high control overhead, delay, and privacy. In addition, the centralized scheduler, i.e. the primary satellite network, requires sophisticated computational capabilities to solve a complicated mixed integer nonlinear programming problem in a short time, which is almost impossible for the satellite systems with severely limited computing resources and large transmission delay.

The essential issue in multi-channel relay selection for hybrid satellite-terrestrial IoT networks is the possibility of a distributed implementation, which means the computation is offloaded to distributed secondary networks. In this paper, we apply the auction mechanism to devise distributed solutions for the resource allocation problems, which reduces the computational complexity for the primary satellite network. In the auction mechanism, the bids of secondary networks for channels are based on their value. The value of the channel is not the same for all users since the channel gains are different due to the location and the fading variations. Therefore, the proper incentive auction mechanism facilitates the cooperation between the primary network and secondary networks and maximizes channel resource utilization to achieve efficiency.

IV. VCG Auction Formulation for NOMA Scheme

In this section, we would discuss the way to implement the auction mechanism in multi-relay selection for multi-channel cooperative spectrum sharing in hybrid satellite-terrestrial IoT networks with the NOMA scheme. Practically, the number of potential secondary relays is far larger than the number of primary channels. The PRs can benefit from the relay with appropriate channel conditions to retransmit the signal and the potential competition among the secondary networks. We consider the channel is block fading, the channel gain is time-varying for each block. Hence, each auction process is independent and does not affect each other. The auction commodities are M non-homogeneous channels, we would apply the multiple nonidentical objects auction mechanism.

Suppose that all the secondary and primary networks are rational but with incomplete global CSI, and they expect long term maximum payoffs from the cooperative spectrum sharing mechanism. The auction process is divided into two steps: (1) Secondary cluster heads evaluate the value of the M primary channels, respectively, $\mathbf{V}^n = \{v^{1,n}, v^{2,n}, \cdots, v^{M,n}\}$, which is determined by the channel gains and the corresponding NOMA power allocation profile. Then, secondary cluster heads offer the vector bids, $\mathbf{B}^n = \{b^{1,n}, b^{2,n}, \cdots, b^{M,n}\}$, to the primary satellite system; (2) According to the bidding vector and the auction mechanism, the primary satellite system chooses the proper secondary networks for multi-channels cooperative spectrum sharing, accordingly.

Definition 1: *The commodities are the utilization of the multi-channels. The bids of all secondary networks are defined by the cooperation transmission rate of PRs within the help of secondary relays, which is straightforward to be obtained, calculated and compared.*

Definition 2: *The primary satellite network is the auctioneer, which means all bids from secondary networks are sent to the primary satellite network by sealed methods, which means the bids vectors are a secret for other bidders before announcing the bidding results. After the auction, the primary satellite network broadcasts all bids and M winners to all secondary networks.*

Our primary concern is about the possibility of achieving efficient allocations via an incentive-compatible auction mechanism.

Theorem 1: Without the auction mechanism design in the proposed system model, the auction is an untruthful bidding, i.e. $v^{m,n} \neq b^{m,n}, \forall m \in \mathbf{M}$.

Proof: The evaluation of $v^{m,n}$ is defined by $R^{m,n}_{p_m}$. The value of $v^{m,n}$ is the transmission rate under the minimum transmission requirement of other SRs. If $v^{m,n} < b^{m,n}$, which means that if a lower power is allocated to the PR, i.e. $\alpha_0^{m,n}$ decreases, the utility of the PR is reduced. Meanwhile, utilities of SRs may rise with more power assumption. Due to the selfishness of the secondary network, the bid must be lower than the truth value, i.e $v^{m,n} < b^{m,n}$. Therefore, without the auction mechanism design, the auction is an untruthful bidding.

In this regard, the trustful biding mechanism is expected to be established for the distributed framework to facilitate the cooperative spectrum sharing. VCG mechanism was first designed for the multiple commodities problem, which can be implemented in the M heterogeneous channels in this paper. The objective of this mechanism is to implement a feasible and efficient allocation. The social utility is guaranteed to be maximized by charging the opportunity cost of the channels for winners. In addition, bidding one's true value is a dominant strategy to obtain the maximum reward, which gives a unique NE. There is no incentive to bid higher or lower than his true valuation for a channel.

A. The Bids for Secondary Networks

In the second temporal phase, we would apply the NOMA scheme to transmit the mixed PR and SR superposition signals simultaneously at the same time and frequency block. Therefore, we discuss the way to obtain the true value of the channel by implementing the NOMA power allocation profile in this subsection. The true value of the channel is the maximum transmission rate of the PR under the conditions of the minimum required rate of each SR. Therefore, the maximization problem of the true bid for $m-th$ channel is given by

$$\begin{aligned} &\arg\max_{\alpha_n} \quad R^{m,n}_{p_m}, \\ &s.t. \quad 12\,(e)\,, 12\,(f)\,. \end{aligned} \tag{13}$$

Theorem 2: If $x_{s_{k-1}}$ can be decoded in user s_{k-1}, the user s_k could decode the $x_{s_{k-1}}$ and implement the perfect SIC for the first $k-1$ signals.

Proof: The transmission rate of $x_{s_{k-1}}$ at user s_k is denoted by $R^{m,n}_{SR^n_{k_n \to k_{n-1}}}$, which are given by Eq. (14) for $k_n > k$ and Eq. (15) for $k_n \leq k$. Due to $H^{m,n}_{R_n, SR^n_{k_{n-1}}} < H^{m,n}_{R_n, SR^n_{k_n}}$, we have $R^{m,n}_{SR^n_{k_n \to k_{n-1}}} > R^{m,n}_{SR^n_{k_{n-1}}}$, which completes the proof.

Theorem 3: If the decoding order is $x_{s_1} \to x_{s_2} \to \cdots \to x_{s_k}$ for the $k-th$ NOMA user in the secondary temporal phase, the transmission rate increases with increasing power allocation factor.

Proof: If perfect SIC is implemented, the transmission rate increases with increasing power allocation factor $\alpha^{m,n}_{k_n}$ according to Eq. (16) and Eq. (17), which completes the proof.

Lemma 1: The true value of the channel for the secondary network is that the rest power is allocated to the PR's signal when the minimum requirement of all SRs is satisfied within the predefined NOMA SIC order.

Proof: According to *Theorem 3*, we acknowledge that more power allocates to the NOMA user would increase the transmission capacity. Therefore, only if the transmission rate of the secondary user meets the requirement of the $R^n_{\min,k_n}$, the transmission rate of the PR reaches the maximum one, where the SIC implementation is predefined by the order of channel gains.

The true value vector $\mathbf{V}$ for N secondary networks of M channels is the same as the bidding vector $\mathbf{B}$ based on the VCG mechanism. According to *Lemma 3.1*, the optimization problem of (13) can be solved by applying **Algorithm 1**.

B. The Winner of The Secondary Network

The primary satellite network receives the N bids vectors from the N secondary networks. According to the VCG auction mechanism, the satellite would obtain the maximum social welfare overall allocations, i.e., the sum of bidders values. Since the VCG auction rule is efficient, the winner determination problem is given as

$$\begin{aligned} &\pi\,(\mathbf{B}) \in \arg\max_{\mathbf{E}} \sum_{m\in\mathbf{M}} \sum_{n\in\mathbf{N}} b^{m,n} e^m_n, \\ &s.t. \quad 12\,(b)\,, 12\,(c)\,, 12\,(d)\,. \end{aligned} \tag{18}$$

The problem in (18) belongs to the binary integer linear programming, which requires to solve the allocation matrix. The straightforward approach to find the exact or optimal winner determination problem solution is to enumerate all partitions, where each item is included in exactly one subset of

$$R_{SR_{k_n\to k_{n-1}}^n}^{m,n} = \frac{1}{2} w_m \log_2 \left(1 + \frac{\alpha_{k_{n-1}}^{m,n} H_{R_n,SR_{k_n}^n}^m}{\sum_{i=k_n}^{K_n} \alpha_i^{m,n} H_{R_n,SR_{k_n}^n}^m + 1/\rho_n} \right). \tag{14}$$

$$R_{SR_{k_n\to k_{n-1}}^n}^{m,n} = \frac{1}{2} w_m \log_2 \left(1 + \frac{\alpha_{k_{n-1}}^{m,n} H_{R_n,SR_{k_n}^n}^m}{\left(\alpha_0^{m,n} + \sum_{i=k_n}^{K_n} \alpha_i^{m,n}\right) H_{R_n,SR_{k_n}^n}^m + 1\big/\rho_n} \right). \tag{15}$$

$$\alpha_{k_n,bid}^{m,n} = \begin{cases} \dfrac{\left(2^{2R_{\min,k_n}^{m,n}/w_m} - 1\right)\left(H_{R_n,SR_{k_n}^n}^m + 1/\rho_n\right)}{2^{2R_{\min,k_n}^{m,n}/w_m} H_{R_n,SR_{k_n}^n}^m} & k_n = 1 \\ \dfrac{\left(2^{2R_{\min,k_n}^{m,n}/w_m} - 1\right)\left[\left(1 - \sum_{i=1}^{k_n-1} \alpha_{i,bid}^{m,n}\right) H_{R_n,SR_{k_n}^n}^m + 1/\rho_n\right]}{2^{2R_{\min,k_n}^{m,n}/w_m} H_{R_n,SR_{k_n}^n}^m} & 1 < k_n \le k \end{cases} \tag{16}$$

$$\alpha_{k_n,bid}^{m,n} = \begin{cases} \dfrac{2^{2R_{\min,k_n}^{m,n}/w_m} - 1}{\rho_n H_{R_n,SR_{k_n}^n}^m} & k_n = K_n \\ \dfrac{\left(2^{2R_{\min,k_n}^{m,n}/w_m} - 1\right)\left(\sum_{i=k_n+1}^{K_n} \alpha_{i,bid}^{m,n} H_{R_n,SR_{k_n}^n}^m + 1/\rho_n\right)}{H_{R_n,SR_{k_n}^n}^m} & k < k_n < K_n \end{cases} \tag{17}$$

the partition [38]. However, enumerating all partitions may not be a suitable approach unless the number of items is extremely small. The winner determination problem can be equivalent to the weighted set packing problem, which is still an NP-hard problem. A tractable solution of the winner determination problem can be obtained by using the classic technique of linear programming-relaxation in combinatorial optimization theory [38]. However, this solution is restricted to some special cases, such as linearly ordered bids, hierarchical bids, and single item bids, which could not be applied in this paper.

In this paper, we transform the winner determination problem into the assignment problem, where a bidding vector is a number of agents and the multi-channels are a number of tasks. Any agent can be assigned to perform any task, incurring some cost that may vary depending on the agent-task assignment. Therefore, the winner determination problem can be solved by a combinatorial optimization algorithm, named **Hungarian algorithm** in polynomial time of $O\left(n^3\right)$ [41].

C. The Payoffs of VCG Auctions

The M channels are allocated to selected M secondary networks with the maximum social welfare. The VCG payment for bidder n is calculated by taking the difference between the optimal welfare when the bidder n is not participating. Therefore, the payment rule can be expressed as

$$\mathbf{R}_{pay}^n = P_n(\mathbf{B}) = \pi\left(\mathbf{0}, \mathbf{B}^{-n}\right) - \pi_{-n}(\mathbf{B}), \tag{19}$$

where $\mathbf{B}^{-n}$ denotes the bidding vector without the bidder n, and $\pi_{-n}(\mathbf{B})$ is the social welfare of individuals other than bidder n from an efficient allocation, which can be defined as

$$\pi_{-n}(\mathbf{B}) = \sum_{j\neq n} \mathbf{E}^j \mathbf{B}^j. \tag{20}$$

Generally, the payment rule in the VCG mechanism is based on the second-highest bid which guarantees that the winning bidder pays less than his/her submitted bid.

The extra payoffs of the bidders are

$$\mathbf{R}_{payoff}{}^n(\mathbf{B}) = \pi(\mathbf{B}) - \pi\left(\mathbf{0}, \mathbf{B}^{-m}\right), \tag{21}$$

which means the distinction in social welfare when bidder n reports $\mathbf{B}^n$ versus when bidder n reports 0.

If the the winner of $m-th$ channel is the highest bid, the payment of the winner is the second-highest bid, i.e $R_{pay}^m = \left[\mathbf{R}_{pay}^n\right]_m$, where $[\mathbf{A}]_n$ is used to denote the $n-th$ element of set $\mathbf{A}$, and the winner would get extra payoffs. Besides, if the R_{pay}^m is lower than the reserved price R_{p_m}, the $m-th$ channel would not cooperate with the T-IoT networks.

For the NOMA system, the extra payoff needs to be reallocated to all SRs. Besides, the extra payoff will improve all SRs' utility as well as fairness. According to *Theorem 3*, the payoffs of SRs would increase with more power allocation. Hence, we introduce two methods to reallocate the extra power resources to obtain fairness as much as possible.

- The first is the average allocation method, which means extra power is distributed evenly to each user. We introduce the reallocation power factor β_1 into the average allocation method in the secondary temporal phase, which is ranging $(0,1]$. The power factor of PR is $(1-\beta 1)\,\alpha_0^{m,n}$, and the power of $k_n - th$ SR is $\left(\beta_1 \alpha_0^{m,n}/K_n + \alpha_{k_n}^{m,n}\right)$. Based on the new power allocation profile, the payment of PR is given as Eq. (22) in the next page. Furthermore, β_1 is formulated as (23) in the next page.
- Another is the proportional allocation method, i.e., SRs power increases proportionally by reallocating the extra power. The reallocation power factor β_2 are introduced

Algorithm 1 The algorithm for calculating the true value for secondary T-IoT networks

Initialization:
The $n-th$ secondary network acquires the channel gain of $\mathbf{M}_m$, i.e., $H^m_{R_n,SR^n_{k_p}}$ and $H^m_{R_n,PR^m}$, where $n \in \mathbf{N}, m \in \mathbf{M}$, and the transmission power of cluster head and the AWGN are P_n and σ_n^2, respectively.
Calculation Process:
for Multicast channels $m = 1$ to M **do**
  Toward $n - th$ secondary network:
  for $k_n = 1$ to k, n++ **do**
    The NOMA power allocation factors for users with better channel gains than PR is given by Eq. (16) on the next page.
    $k_n + +$
  end for
  for $k_n = K_n$ to $k + 1$ **do**
    The NOMA power allocation factors for users with better channel gains than PR is given by Eq. (17) on the next page.
    $k_n - -$
  end for
  The power allocation factor is given by $\alpha^{m,n}_{0,bid} = 1 - \sum_{i=1}^{K_n} \alpha^{m,n}_{i,bid}$.
  if $\forall i \in \{0, 1, \cdots K_n\}, 0 < \alpha^{m,n}_{i,bid} < 1$ **then**
    The bid of $n - th$ secondary network for $m - th$ channel is given by
$$b^{m,n} = R^{m,n}_{p_m}\left(\alpha^{m,n}_{0,bid}, \alpha^{m,n}_{k+1,bid}, \cdots, \alpha^{m,n}_{K_n,bid}\right).$$
  else
    The bid of $n - th$ secondary network for $m - th$ channel is equated to 0.
  end if
  Store the NOMA power profiles and the bid into $\Lambda^{m,n}$ and $b^{m,n}$, respectively.
  m++
end for
return The bidding vector $\mathbf{B} = \left\{\mathbf{B}^1, \cdots, \mathbf{B}^N\right\}$, where $\mathbf{B}^n$ is $n - th$ secondary network of M channels.

into the ratio method, which is ranging among $(0, 1]$. We have the following identity

$$\alpha_0^{m,n}(1 - \beta_2) + \tau \sum_{i=1}^{K_n} \alpha_i^{m,n} = 1, \tag{24}$$

where τ is the NOMA power reallocation factor for SRs corresponding to the β_2. There is $\tau = 1 + \alpha_0^{m,n}\beta_2/(1 - \alpha_0^{m,n})$. It can be derived that $\tau > 0$, which means all SRs obtain more transmission capacity by the extra payoff power allocation. Therefore, the payment equation can be given as Eq. (25) in the next page. Furthermore, β_2 is calculated as Eq. (26) in the next page.

The payoffs of selected T-IoT networks are obtained by substituting a new power allocation profile into Eq. (9) and Eq. (10).

D. The Implementation of VCG Auction

Based on the above observations, the VCG auction can be implemented as follows:

- *Information:* Each secondary network cluster head, acted as a bidder, acquires the channel gain $H^m_{R_n,PR_m}$ and $H^m_{R_n,SR_n}$ for M channels, which is not available for other bidders. Hence, the incomplete information prevents bidders from cheating. Since the dominant strategy for $k-th$ bidder is to report the truth capacity for forwarding the PR's signal, all potential relays would implement the transmitted power P_n to achieve as high capacity as possible.
- *Bids:* Due to the shared infrastructure, including the cost of energy consumption, hardware price, and time-window value, the $k - th$ bidder requires the minimum transmission rate $R^n_{\min,k_n}$ for each SR. Based on **Theorem 3**, the dominant strategy for each bidder is to transmit the remaining power to the primary user under the requirement of meeting the $R^n_{\min,k_n}$. Hence, the NOMA power allocation factor and truth bids vector $\mathbf{B}$ for the bidder are obtained by **Algorithm 1**, respectively. Moreover, all relays send their bids to the satellite simultaneously by the sealed method.
- *Allocation:* The primary satellite network adopts the Hungarian algorithm to solve the winner determination problem. Furthermore, after the auction progress, the primary satellite network broadcasts all bids with the number of bidders to the potential cluster heads and announces the winner of the bidding. If the T-IoT network finds that the broadcasted bids are not the previous bids, it regards that the primary satellite network is deceptive, and chooses to quit the cooperation as a penalty. Besides, if R^m_{pay} is lower than the reserved price R_{p_m}, the PR_m would apply the DC link to transmit.
- *Payoffs:* According to the broadcast information of the satellite, the chosen secondary T-IoT network would reallocate the NOMA power allocation profile by the average allocation method or the proportional allocation method.

After the auction progress, all parameters are determined and the transmission is ready to start.

V. Sequential Vickrey Auction Formulation for NOMA Scheme

In the last section, we introduce the VCG auction, where the auction decision is determined by one shot through the Hungarian algorithm. The computation complexity of Hungarian algorithm is $O(n^3)$. Although the optimization problem (18) can be solved in the polynomial time, it is still complicated for the primary satellite network with limited computing resources. Moreover, the sequential-auction algorithm can be used when the users enter and dynamically leave the system. Based on these observations, we propose a sequential Vickrey auction mechanism to further reduce the complexity of the auctioneer.

Definition 3: *A sequential bidding fashion allows each co-operative spectrum sharing channel to be auctioned one after*

$$\frac{1}{2}w_m\log_2\left(1+\frac{(1-\beta_1)\,\alpha_0^{m,n}H_{R_n,PR_m}^m}{\left[(K_n-k)\,\beta_1\alpha_0^{m,n}/K_n+\sum_{i=k+1}^{K_n}\alpha_i^{m,n}\right]H_{R_n,PR_m}^m+1/\rho_n}\right)=R_{pay}^m. \tag{22}$$

$$\beta_1=\frac{\alpha_0^{m,n}H_{R_n,PR_m}^m-\left(2^{2R_{pay}^m}-1\right)\left(\sum_{i=k+1}^{K_n}\alpha_i^{m,n}H_{R_n,PR_m}^m+1/\rho_n\right)}{\left[1+\frac{K_n-k}{K_n}\left(2^{2R_{pay}^m}-1\right)\right]\alpha_0^{m,n}H_{R_n,PR_m}^m}. \tag{23}$$

$$\frac{1}{2}w_m\log_2\left(1+\frac{(1-\beta)\,\alpha_0^{m,n}H_{R_n,PR_m}^m}{\tau\sum_{i=k+1}^{K_n}\alpha_i^{m,n}H_{R_n,PR_m}^m+1/\rho_n}\right)=R_{pay}^m. \tag{25}$$

$$\beta_2=\frac{\alpha_0^{m,n}H_{R_n,PR_m}^m-\left(2^{2R_{pay}^m}-1\right)\left(\sum_{i=k+1}^{K_n}\alpha_i^{m,n}H_{R_n,PR_m}^m+1/\rho_n\right)}{\alpha_0^{m,n}H_{R_n,PR_m}^m+\frac{\alpha_0^{m,n}}{1-\alpha_0^{m,n}}\left(2^{2R_{pay}^m}-1\right)\sum_{i=k+1}^{K_n}\alpha_i^{m,n}H_{R_n,PR_m}^m}. \tag{26}$$

another. Moreover, when a channel is auctioned, the winner for the channel and the channel itself does not participate in the rest of the auction. This continues until all bands are sold-off one by one.

The Vickrey auction achieves efficient and effective decision making in a single commodity scenario. The dominant strategy for the bidder is bidding one's true value.

Remark 1: The proposed sequential Vickrey auction mechanism is truthful. The Vickrey auction is the truthful bids for a single commodity [32]. Since M channels are independent, already auctioned channels do not affect the bid of each newly auctioned channel. Therefore, bidding one's true value is a dominant strategy for each step of the sequential auction.

The calculation of truthful value for each secondary network is the same as the VCG auction progress. **Algorithm 2** illustrates the sequential Vickrey auction fashion.

A. The Payoffs of the Sequential Vickrey Auction

If PR_m chooses to cooperate with a T-IoT network, the payoff R_{pay}^m is the highest no-winner bid or the reserved price R_{p_m}, whichever is higher. The calculations of the extra payoffs of the winner in T-IoT networks are the same as VCG auctions by the average allocation or the proportional allocation method.

VI. Auction Formulation for OMA Scheme

In this section, we introduce the OMA scheme for comparison, where the TDMA scheme is adopted in the second temporal phase as illustrating in Fig. 2. The PR takes t_0 sub-timeslot , and $i-th$ SR takes t_i sub-timeslot to transmit the signal. Therefore, the transmission rate of PR_m in $n-th$ secondary network is given as

$$R_{PR_m-OMA}^{m,n}=\frac{1}{2}t_0w_m\log_2\left(1+\rho_nH_{R_n,PR_m}^m\right). \tag{27}$$

Similarly, the transmission rate of k_n SR in $n-th$ secondary network is given as

$$R_{SR_{k_n}^n-OMA}^{m,n}=\frac{1}{2}t_{k_n}w_m\log_2\left(1+\rho_nH_{R_n,PR_m}^m\right). \tag{28}$$

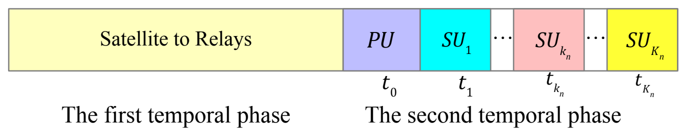

Fig. 2: The TDMA sub-timeslot allocation.

A. The VCG Auction in TDMA Scheme

Similar to the NOMA case, the VCG auction in the TDMA scheme is divided into two steps. For the first step, the bidders evaluate the true value of each channel. The true value for PR_m in $n-th$ secondary network is the maximum transmission rate under the requirement of the minimum rate of SRs. The maximization problem is formulated as

$$\arg\max_{t_0}\quad R_{p_m-OMA}^{m,n} \tag{29}$$

$$s.t.\quad \sum_{i=0}^{K_n}t_i^{m,n}\le 1, \tag{29a}$$

$$R_{SR_{k_n-OMA}^n}^{m,n}\ge R_{\min,k_n}^n,\forall e_{n,OMA}^m=1, \tag{29b}$$

where $e_{n,OMA}^m=1$ indicates that the PR_m chooses $n-th$ secondary network to implement cooperative spectrum sharing, and $e_{n,OMA}^m=0$ otherwise. The constraint in Eq. (29a) is the total sub-timeslot limitation. The constraint in Eq. (29b) means that SRs should meet at least the minimum transmission rate. Due to the users' access to the cluster head by OMA scheme, the optimization problem can be solved by calculating the minimum requirement time-slot for each SR, and then the rest time-slot is allocated to the PR, where the bidding vector is $\mathbf{B}_{OMA}$.

Another step is the winner determination problem for the primary network, the optimization problem is formulated as

Algorithm 2 The sequential Vickrey auction algorithm

Initialization:
The $n-th$ secondary network acquires the channel gain of $H_{R_n,SR_{k_n}^n}^m$ and H_{R_n,PR^m}^m, where $n \in \mathbf{N}, \mathbf{m} \in \mathbf{M}$, and the transmission power and the AWGN are P_n and σ_n^2, respectively. The winner set $\mathbf{W}$ is set to null.
Sequential auction:
for Multicast channels $m = 1$ to M **do**
  The truthful bid calculation:
  for $n = 1$ to $|\mathbf{N}|$ **do**
    Toward $n-th$ secondary network:
    for $k_n = 1$ to k **do**
      The NOMA power allocation factors for users with better channel gains than PR is given by Eq. (16).
      n++
    end for
    for $k_n = K_n$ to $k+1$ **do**
      The NOMA power allocation factors for users with better channel gains than PR is given by Eq. (17).
      n−−
    end for
    The power allocation factor is given by $\alpha_{0,bid}^{m,n} = 1 - \sum_{i=1}^{K_n} \alpha_{i,bid}^{m,n}$.
    if $\forall i \in \{0, 1, \cdots K_n\}, 0 < \alpha_{i,bid}^{m,n} < 1$ **then**
      The bid of $n-th$ secondary network for $m-th$ channel is given by
      $$b^{m,n} = R_{p_m}^{m,n}\left(\alpha_{0,bid}^{m,n}, \alpha_{k+1,bid}^{m,n}, \cdots, \alpha_{K_n,bid}^{m,n}\right).$$
    else
      The bid of $n-th$ secondary network for $m-th$ channel is equated to 0.
    end if
  end for
  The truthful bids for $m-th$ channel are sent to the primary satellite network by the sealed method. If the reserved price R_{p_m} higher than all bids, the PR_m applies the DC link. Otherwise, the satellite choose the highest bids as the winner.
  $\mathbf{W} = [w_m] \cup \mathbf{W}$
  $\mathbf{N} = \mathbf{N} \backslash [w_m]$
  m++
end for
return All winners of the sequential auction $\mathbf{W}$.

$$\pi(\mathbf{B}_{OMA}) \in \arg\max_{\mathbf{E}} \sum_{m\in\mathbf{M}} \sum_{n\in\mathbf{N}} b_{OMA}^{m,n} e_{n,OMA}^{m}, \tag{30}$$

$$s.t. \sum\nolimits_{m=1}^{m=M} e_{n,OMA}^{m} \le 1, \forall n \in \mathbf{N}, \tag{30a}$$

$$\sum\nolimits_{n=1}^{n=N} e_{n,OMA}^{m} \le 1, \forall m \in \mathbf{M}, \tag{30b}$$

$$e_{n,OMA}^{m} \in \{0, 1\}, \forall n \in \mathbf{N}, m \in \mathbf{M}. \tag{30c}$$

The constraint Eq. (30a) means that the total time slot of the secondary cluster head is limited. The M constraints in Eq. (30b) ensure that each secondary network is allocated at most one channel. The $M \times N$ constraints in Eq. (30c) ensure that each channel is allocated to at most one secondary network. The objective function Eq. (30) is a binary integer programming, which can be solved with **Hungarian algorithm**.

According to the payment of VCG mechanism, if the bid of $m-th$ channel winner is the highest bids in all bids for $m-th$ channel, the payment of the winner is the second highest bid $R_{pay-OMA}^{m}$. Hence, the time resource is requited to reallocate and the SRs obtain the extra payoff. The subtimeslot is reconfigured as

$$t_{0,win}^{m,n} = {R_{p_m-OMA}^{m,n}}^{-1}\left(R_{pay-OMA}^{m}\right), \tag{31}$$

where the superscript $^{-1}$ is the reverse function. Since $t_{0,win}^{m,n} < t_{0,bid}^{m,n}$, the remain time resources $t_{left} = t_{0,bid}^{m,n} - t_{0,win}^{m,n}$ are distributed to K_n SRs by the two proposed methods to obtain more utilities and fairness, i.e., the average allocation method and the proportional allocation method. For the average allocation method, each SR is allocated additional $\mathrm{t_{left}}/K_n$ of time resources. For the proportional allocation method, k_n SR is allocated additional $\mathrm{t_{left}} t_{k_n} \Big/ \sum_{k=1}^{K_n} t_k$ of time resources.

If the bid of $m-th$ channel winner is not the highest bids in all bids for $m-th$ channel, the payment of the winner is the bidder. The payoffs of SRs are equivalent to the minimum required transmission rate.

B. The Sequential Vickrey Auction in TDMA Scheme

The sequential Vickrey auction in the TDMA scheme is introduced to reduce the complexity of the auctioneer. The auction progress is the same as **Algorithm 2**. The difference depends mainly on the allocation of time resources, which is the same as the Eq. (31). The channels are sold one after another. Besides, when a channel is auctioned, the winner for the channel and the channel itself do not participate in the rest of the auction. This continues until all bands are sold-off one by one. The payment of the winner is the second-highest bids $R_{pay-OMA}^{m}$ for $m-th$ channel. Hence, the time resource is required to reallocate and the SRs obtain the extra payoff, where the proposed average allocation and proportional allocation can be applied in the same way as the VCG auction.

VII. Simulation Results and Discussion

In this section, simulation results are provided to evaluate the effectiveness of the proposed two auction-based mechanisms and the priority of the NOMA scheme.

We consider that LEO satellite PRs suffer from frequent heavy shadowing severity, which is blocked by bushes or buildings. The shadowing and fading parameter in (1) of the h_{S,PR_m} is given as $\left[b = 0.063, p = 0.739, \Omega = 8.97 \times 10^{-4}\right]$. The PRs are randomly distributed in a square range area with a side length of 1000 meters. The IoT cluster heads are randomly distributed in this area, and the links between the satellite to cluster heads undergo light frequency shadowing, where the shadowing and fading parameter of the h_{S,R_n} in (1) is given as $[b = 0.158, p = 19.4, \Omega = 1.29]$. The secondary IoT receivers are subject to uniform distribution around its transmitter in a circle with a radius of 300 meters. The small scale of fading parameters for second temporal phase is given

TABLE I
SIMULATION PARAMETERS

Parameters	Values
Satellite transmission power	100 W
Terrestrial noise temperature	300 K
Satellite noise temperature	350 K
Noise band	10 MHz
Satellite antenna gain G_s	20 dBi
Cluster heads antenna gain G_t	25 dBi
PRs antenna gain G_s	5 dBi
Center frequency	4 GHz
Satellite hight	800 Kilometers
Terrestrial path loss exponent	2
The number of cooperative sharing channels	5

as $[m_{R_k n} = 1, \Omega_{R_k n} = 1]$. The bandwidth is normalized to one. Without loss of generality, the simulation results are obtained through 10^6 independent channel realizations, and the system parameters are provided in Table I, which are chosen according to real-world use cases. Besides, we consider the Doppler Frequency Shift, caused by the mobility of the satellite, can be estimated perfectly and mitigated by the mature pre-compensation method [42].

A. The Payoffs of PRs in Cooperative Spectrum Sharing

In order to prove the effectiveness of the proposed auction-based approach, the centralized approach, location-based approach, and random selection approach are also provided for performance comparison[1]. The centralized approach requires that the primary satellite network is aware of the global CSI, even including each secondary network in each channel, which is unrealistic for hybrid architecture. The location-based approach means each PR chooses the closest cluster head to cooperate, which only requires the location information of the cluster heads and is feasible to implement in practice. Besides, the random selection approach represents that the satellite can randomly select a cluster head for cooperative transmission as the benchmark.

Fig. 3 and Fig 4 reveal the sum transmission capacity of PRs under the different approaches versus the transmission power of cluster head P_k for both NOMA and TDMA schemes based secondary phase transmissions. The number of potential relays is 50, and the location of the PRs and secondary T-IoT network are the same for both schemes. Besides, the minimum transmission rate of two users are considered as $R_{\text{min}}^{k_1} = 0.4$ bps/Hz and $R_{\text{min}}^{k_2} = 0.8$ bps/Hz. The optimal capacity is achieved for the centralized approach, which acquires the globe CSIs and achieves the upper bound for the transmission rate of the PRs. The primary satellite would only satisfy the minimum transmission in the centralized approach as the global CSIs are obtained. Furthermore, overheads remain a major concern, especially for onboard processing satellite systems, which would cause an intolerable delay owning to the CSI acquisition and computation complexity. For the location-based approach, the primary satellite network requires

[1]Once the payment of the bidders is higher than that of the direct transmission, the satellite would choose to cooperate with the terrestrial IoT cluster since the satellite is rational. Therefore, the proper relay selection for multi-channels would greatly improve the utility of the primary satellite users.

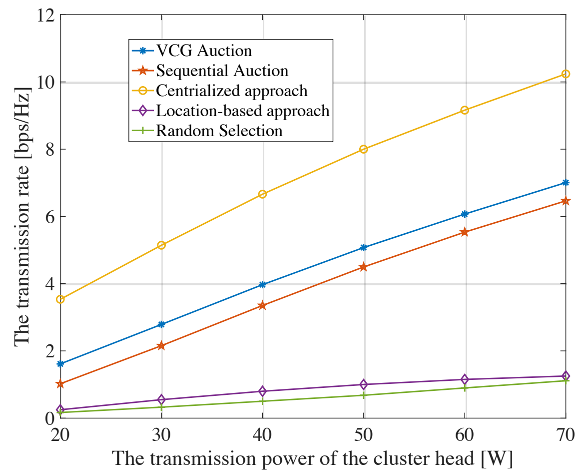

Fig. 3: The sum PRs' transmission rate of the different approaches versus the power of the cluster heads for the NOMA scheme in the secondary phase.

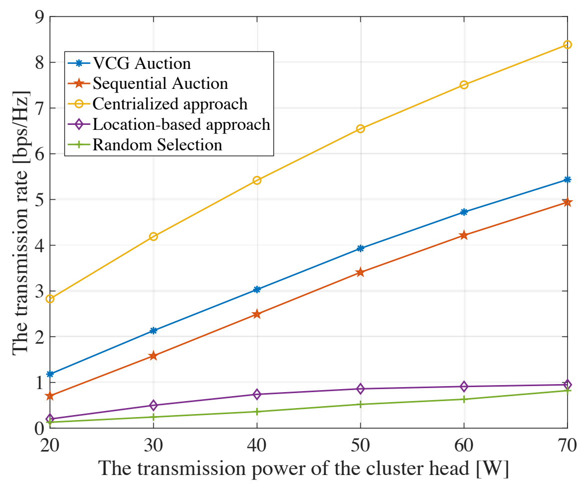

Fig. 4: The sum PRs' transmission rate of the different approaches versus the power of the cluster heads for the TDMA scheme in the secondary phase.

the location information of the PRs and cluster heads, then chooses the shortest distance cluster head for each PR to cooperate. The complexity of the location-based approach and sequential Vickrey auction is almost the same for the primary satellite network. Moreover, it is can be seen in Fig. 3 and Fig. 4 that the PRs' sum transmission capacity of sequential Vickrey auction is almost five times that of a location-based approach. Furthermore, the VCG auction is also obviously superior to the sequence Vickrey auction. This is since the VCG auction applies the Hungarian algorithm to obtain the globe optimization of all bids, but the sequential auction only auctions the channel one by one, which can be seen as one sub-optimal solution of the winner determination problem of Eq. (18). We notice that the order of the sequential auction slightly affects the sum transmission capacity, where each sequential auction order can be seen as one sub-optimal solution of the winner determination problem of Eq. (18). Additionally, the random selection approach presents a benchmark or the lower bound for the transmission rate of the PRs in the considered network. Furthermore, comparing Fig. 3 and Fig. 4, the transmission rate of the NOMA scheme is superior to the TDMA scheme under the arbitrary transmission power of cluster head in the second temporal phase, which proves the superiority of the NOMA scheme.

Fig. 5 and Fig 6 depict the sum transmission capacity of PRs by different approaches versus the number of potential secondary T-IoT networks for both NOMA and TDMA schemes based on the second phase transmissions. The power of cluster heads is 50 W, and the location of the PRs and secondary T-IoT network are the same for the NOMA scheme and TDMA scheme at the same varying parameters. The minimum transmission rate of two users in $k_n - th$ secondary network are considered as $R_{\min}^{k_1} = 0.4$ bps/Hz and $R_{\min}^{k_2} = 0.8$ bps/Hz. It is obvious that the transmission rate of all approaches increases with the increasing number of relays, which is resulted from the competition among the secondary networks increases as the increasing numbers. According to the auction rules, if the relay finds that the broadcasted bids are not the previous bids, it can be deduced that the primary satellite network is deceptive and chooses to quit the cooperation as a penalty. Decreasing the number of bidders would result in less satellite payoff. Since the satellite is rational, it will not cheat during the auction for obtaining long term profits. If the primary satellite network would like to obtain as many payoffs as possible, it must recruit as many secondary relays as possible for the competition. Besides, the proposed auction approaches are superior to the location-based approach, which proves the effectiveness of the proposed approaches. The sequential auction is one sub-optimal solution of the winner determination problem of Eq. (18) and the VCG auction is the optimal result of Eq. (18). Besides, the random selection approach presents a benchmark for the transmission rate of the PRs in the considered network. The centralized approach achieves the upper bound for the transmission rate of the PRs, which would cause an intolerable delay owning to the CSI acquisition and computation complexity. Moreover, comparing Fig. 5 and Fig. 6, the transmission rate of the NOMA scheme is superior to the TDMA scheme under the arbitrary number of potential secondary T-IoT networks in the second temporal phase, which proves the superiority of the NOMA scheme.

B. The Fairness for Cooperative Spectrum Sharing

The fairness is a key indicator to facilitate the cooperation between the primary S-IoT network and the secondary T-IoT networks. Therefore, we analyze the fairness by using Jain's fair index (JFI) [23], which is defined by

$$JFI = \frac{\left(\sum_{i=1}^{N} R_i\right)^2}{N \sum_{i=1}^{N} (R_i)^2}, \tag{32}$$

where R_i denotes the rate of user i. It is noted that JFI translates a resource allocation vector $\{R_1, R_2, \cdots, R_N\}$ into a score in the interval of $[1/N, 1]$. A higher JFI indicates a fairer resource allocation method. We generate two SRs in each secondary cluster. The minimum transmission rate of two users in $k - th$ secondary network are at least satisfied with $R_{\min}^{k_1} = 0.4$ bps/Hz and $R_{\min}^{k_2} = 0.8$ bps/Hz. All simulation results are obtained with the average JFI applying the transmission of the PRs and each SR in the winner secondary network.

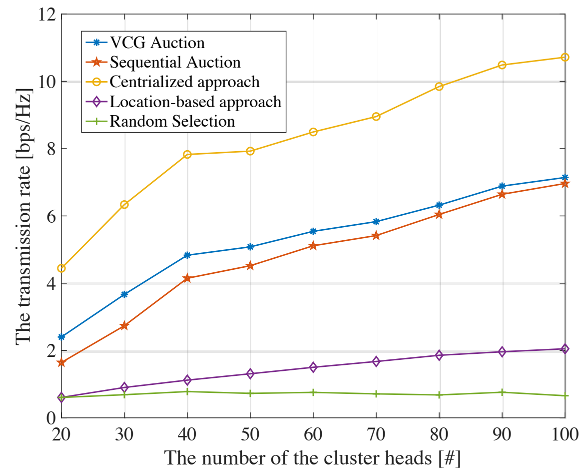

Fig. 5: The sum PRs' transmission rate of the different approaches versus the number of potential secondary T-IoT networks for the NOMA scheme in the secondary phase.

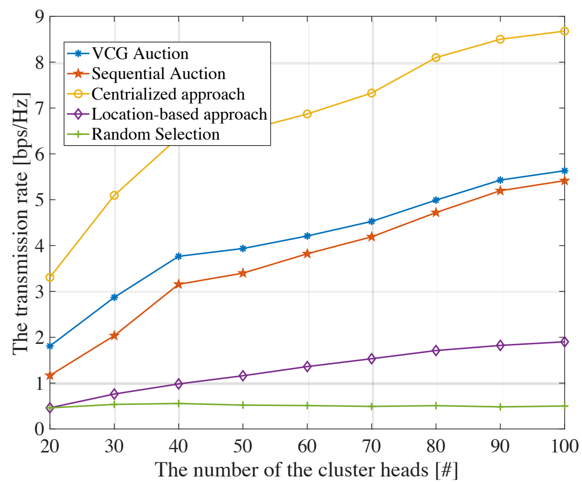

Fig. 6: The sum PRs' transmission rate of the different approaches versus the number of potential secondary T-IoT networks for the TDMA scheme in the secondary phase.

Fig. 7 and Fig. 8 reveal the JFI of the VCG auction, the sequential auction, and the centralized approach versus transmit power of cluster heads P_k for both NOMA and TDMA schemes based secondary phase transmissions. The number of potential relays is 50. The primary satellite would only satisfy the minimum transmission in the centralized approach as the global CSIs are obtained. The transmission rate of PRs is increasing with the power increase. Therefore, the JFI of the centralized approach decreases as is shown in Fig. 7 and Fig. 8. In the auction mechanism, the payments of winning cluster heads would be no more than the bids and obtain the extra payoff. For the scenarios with the NOMA scheme, the extra power is reallocated to the SRs. For the

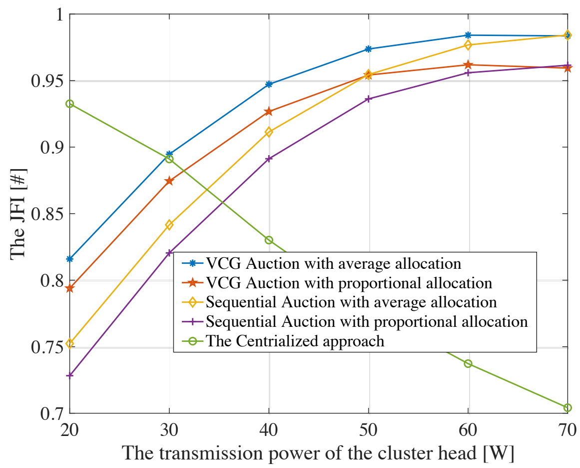

Fig. 7: The JFI of the VCG auction, the sequential auction, and the centralized approach versus the power of the cluster heads for the NOMA scheme in the secondary phase, where the power reallocation adopts the average allocation and proportional allocation methods, respectively.

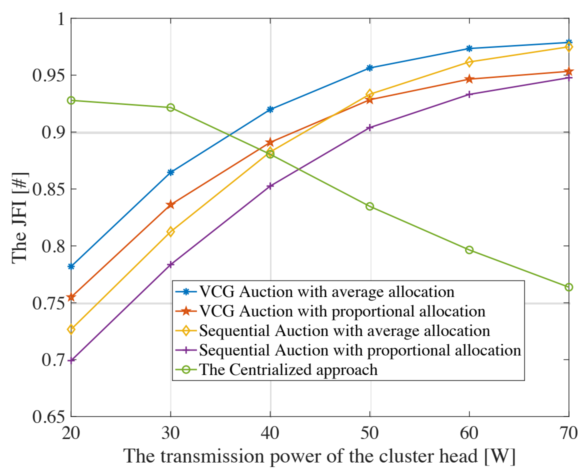

Fig. 8: The JFI of the VCG auction, the sequential auction, and the centralized approach versus the power of the cluster heads for the TDMA scheme in the secondary phase, where the power reallocation adopts the average allocation and ratio allocation methods, respectively.

scenarios with the TDMA scheme, the extra time slot is reallocated to the SRs. The proportional allocation method and the average allocation method are adopted for both the NOMA scheme and the TDMA scheme. As shown in Fig. 7 and Fig. 8, the proportional allocation method achieves better fairness than the average allocation method for both the VCG auction and the sequential auction. The fairness continues to increase with the increasing power until it stabilizes in auction-based approaches.

Fig. 9 and Fig. 10 show the JFI of the VCG auction, the sequential auction, and the centralized approach versus the number of potential secondary T-IoT networks for both NOMA and TDMA schemes based secondary phase transmissions. The transmission power of relays is 50 W. Since

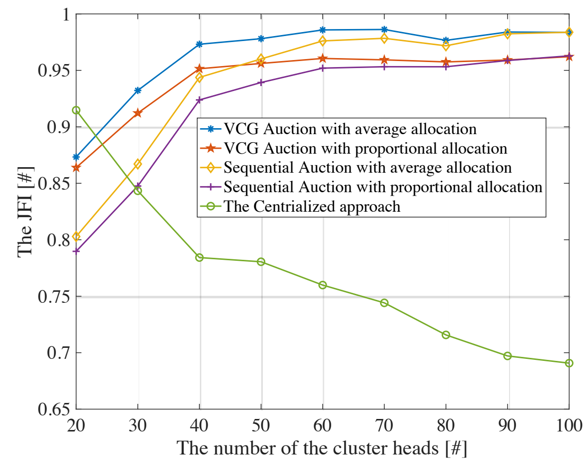

Fig. 9: The JFI of the VCG auction, the sequential auction, and the centralized approach versus the number of the cluster heads for the NOMA scheme in the secondary phase, where the power reallocation adopts the average allocation and proportional allocation methods, respectively.

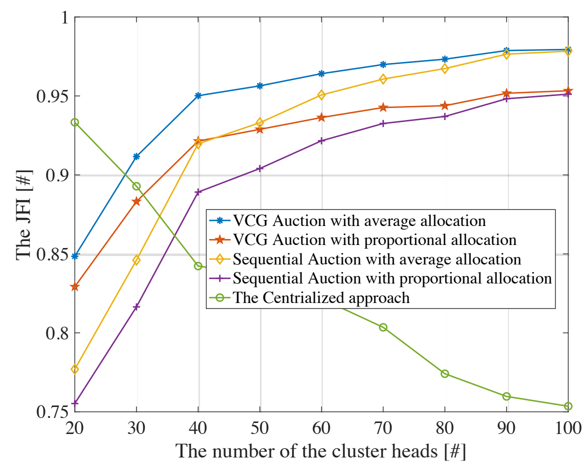

Fig. 10: The JFI of the VCG auction, the sequential auction, and the centralized approach versus the number of the potential secondary T-IoT networks for the TDMA scheme in the secondary phase, where the power reallocation adopts the average allocation and proportional allocation methods, respectively.

the transmission rate of PR will increase with the increase of the number of cluster heads, and the SR can only obtain the minimum transmission rate, the fairness of the centralized method decreases as the number of relays increases. The fairness of the auction-based approach increases with the number of the secondary network, which results from the fact that transmission rates of both PRs and SRs are increasing. Besides, the proportional allocation method achieves better fairness than the average allocation method for both the VCG auction and the sequential auction. Based on the observations in Fig. 7 - Fig. 10, the proposed auction-based approaches achieve better fairness, which improves the cooperation between the S-IoT network and T-IoT networks.

VIII. Conclusion

In this paper, we investigated the multi-channel cooperative spectrum sharing in hybrid satellite-terrestrial IoT networks by auction mechanism, where the selected secondary T-IoT cluster heads assisted the primary satellite users transmission through cooperative relaying techniques in exchange for spectrum access. We proposed an auction-based optimization problem to maximize the sum transmission rate of all primary S-IoT receivers with the appropriate secondary network selection and corresponding power allocation profile while meeting the minimum transmission rate of secondary receivers of each T-IoT network. The VCG auction has been introduced to obtain the maximum social welfare, where the winner determination problem is solved by the Hungarian algorithm. The sequential Vickrey auction has been implemented by sequential fashion until all channels are assigned. Due to the incentive compatibility of those two auction mechanisms, the secondary T-IoT cluster yielded the true bids of each channel, where both the NOMA and TDMA scheme are implemented in the second temporal phase. Finally, simulation results validated the effectiveness and fairness of the proposed auction-based approach as well as the superiority of the NOMA scheme in secondary relays selection. Moreover, the influence of key factors on the performance of the auction mechanism was analyzed in detail. This paper mainly focuses on the downlink of the multi-channel cooperative spectrum sharing scenario. With the development of the symbol synchronization of the NOMA scheme, we will explore the efficient mechanism for uplink cooperative spectrum sharing in hybrid satellite-terrestrial IoT networks within the NOMA scheme in our future work.

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