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Ubiquitous Transmission Service: Hierarchical Wireless Data Rate Provisioning in Space-Air-Ocean Integrated Networks

Qichao Xu, Zhou Su, Rongxing Lu, and Shui Yu

***Abstract*—Space-air-ocean integrated networks (SAOINs), composed of low earth orbit (LEO) satellites, unmanned aerial vehicles (UAVs), and unmanned surface vehicles (USVs), have been advocated to provide seamless, high-rate, and reliable wireless transmission services for USVs. However, due to the restrictions of limited resources (e.g., spectrum bandwidth, transmission power, etc.), diverse demands of USVs, and selfishness of both UAVs and LEOs, there comes a significant challenge to provision high-quality wireless data rate for USVs to achieve their satisfied quality of experience (QoE). To this end, in this paper, we propose a hierarchical on-demand wireless data rate provisioning scheme to provide ubiquitous transmission services for USVs. Specifically, we first devise a hierarchical wireless data rate provisioning framework. The LEO satellite with an extensive wireless coverage is utilized to provide LEO satellite-to-UAV (L2U) data rate for UAVs with a certain L2U data rate price. Each UAV is employed to provide UAV-to-USV (U2U) data rate for covered multiple USVs with a certain U2U data rate price. We then propose a modified three-stage Stackelberg game to model the wireless data rate assignments among LEO satellites, UAVs, and USVs, where the time-varying data rate demands of USVs are considered to formulate the utility maximization problem. Afterwards, the backward induction approach is leveraged to attain the Stackelberg equilibrium as the solution of the formulated problem, where the closed-form expressions on the optimal strategies of both USVs and UAVs under different data rate budgets are obtained by the nonlinear programming method. Besides, an accelerated conjugate gradient descent (ACGD) based iteration algorithm is also designed to obtain the optimal strategies of the LEO satellites on the L2U data rate prices. At last, extensive simulations are carried out to demonstrate that the proposed scheme can significantly increase the utilities of USVs, as compared to other benchmark schemes.**

***Index Terms*—Space-air-ocean integrated networks (SAIONs), unmanned surface vehicles (USVs), hierarchical wireless data rate provisioning, and Stackelberg game.**

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Q. Xu is with the School of Mechatronic Engineering and Automation, Shanghai University, Shanghai, China

Z. Su is with the School of Cyber Science and Engineering, Xi'an Jiaotong University, Xi'an, China (E-mail: zhousu@ieee.org).

R. Lu is with the Faculty of Computer Science, University of New Brunswick, Canada.

S. Yu is with the School of Software, University of Technology Sydney, Australia.

I. Introduction

The 21st century is the era of the ocean that contains rich biological resources, oil and gas resources, and mineral resources [1]. It is a strategic space and resource for human survival and sustainable development. For better understanding, developing, and protecting the oceans, unmanned surface vehicles (USVs) as cost-effective, high-speed, and flexible characteristics have been widely applied to perform dangerous and complex tasks in maritime activities, such as marine resource exploration, environment monitoring, maritime search and rescue, etc [2]. In the applications of USVs, the efficient communication between USVs and other entities (e.g., ground control station, remote cloud server, and mother vessel, etc.) is of great importance to achieve timeliness-sensitive data transmission [3]. For example, dynamic and variable maritime weather data, such as wind speed and atmospheric visibility, should be delivered to the USV in time for intelligent decisions on stable and reliable navigation paths [4]. However, due to lack of land communication infrastructures such as base stations in maritime environment, it is intractable to provide low-delay and high-reliable transmission services for USVs. At present, USVs in general work offline or take satellites as communication carriers to deliver data. When working offline, UAVs have to send/receive data when they return to the network-connected shores, which induces a large access delay. When connecting to a satellite, each USV must install an expensive satellite communication module and the satellite has to deal with a large number of simultaneous USV accesses, which inevitably causes considerable economic and resource costs, including computing, energy and storage, etc. Therefore, if a communication network exists that can be accessed anywhere and anytime by USVs to deliver data at low cost, it can significantly improve the efficiency of task execution and enhance the safety of USV sailing.

Space-air-ocean integrated networks (SAIONs), as the most promising one of next-generation wireless communication network paradigms, can efficiently provide

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ubiquitous transmission services for USVs [5], [6]. A typical SAOIN is composed of LEO satellites, UAVs, and USVs. An LEO satellite can provide a much extensive and seamless communication coverage to ground entities [7]. LEO satellites are capable of supporting broad services when operating over Ka-band [8]. It can achieve on the downlink over 50 Mbps data rates and even up to several hundred megabits per second , enabling to provide multimedia services for USVs, such as the deliveries of sea floor map and weather video streaming, etc., [9]. Meanwhile, due to low costs, easy deployments and agile mobilities, UAVs can be fast deployed by offshore equipments (e.g., oil platform, vessels, and airborne USVs, etc.), to provide temporary network accesses for USVs, so as to enlarge the capacity of the network [10]. As only a small number of UAVs need to be equipped with satellite communication modules, the larger amount of access requests from USVs to LEO satellites could be dramatically reduced. Therefore, by incorporation the merits of the LEO satellites and UAVs, the SAIONs can support seamless, reliable and low-cost wireless transmission for USVs.

However, the wireless transmission service provisioning for USVs in SAIONs face the following challenges, due to limited transmission resources, diverse demands of USVs, and selfishness of both UAVs and LEO satellites. First, as the number of new wireless transmission applications keeps increasing, the resources (e.g., spectrum bandwidth and transmission power, etc.) in current deployed networks become limited to provide each USV with a satisfied data rate. As a result, USVs need to compete with each other to request wireless data rates. Second, due to the different types of tasks, USVs have diverse demands on wireless data rate. When different USVs are assigned with the same amount of data rate, some may want more, but others may not need so much, resulting in the inefficiency of data rate assignment. Third, since it needs a certain cost on resources (e.g., energy, computing, etc.) to transmit data, both UAVs and LEO satellites are selfish. As such, transmission service is not provided for free, such that both satellites and UAVs need to determine data rate prices to make profits. If the data rate price determined by the LEO satellite is too high, UAVs will reduce the amount of purchased data rate. Similarly, if the data rate prices determined by the UAVs are high, the USVs also request a few data rates from their connected UAVs, resulting in sacrificing their QoE. Consequently, it is pressing to design a wireless data rate provisioning scheme for USVs to achieve satisfied transmission services in SAOINs.

Some existing wireless data rate provisioning schemes have recently been proposed to improve the transmission services, such as bandwidth allocation, power allocation, and time schedule. In [11], [12], bandwidth allocation based data rate provisioning scheme is used to support the wireless transmission between UAVs and ground nodes. The game model is employed to obtain the optimal bandwidth allocation strategy. Besides, in [13], [14], the power allocation problem of the terrestrial-satellite network is studied to search for the optimal data rate provisioning solution for satisfying mobile users' QoE. Meanwhile, mobile users can be provided with the optimal wireless transmission services by allocating the number of time slots to access the communication network [15]. However, most current works on wireless data rate provisioning focus on the terrestrial networks or terrestrial-satellite networks, while the complicated interactions among entities under the three-layer architecture of SAIONs are not sufficiently considered. In addition, different from the assumption in the current works, the demands of ground requesters are usually time-varying in different time slots. Therefore, it is still a vital issue to devise a proper wireless data rate provisioning scheme in SAIONs.

In this paper, we propose a hierarchical on-demand wireless data rate provisioning scheme in SAIONs, to efficiently provide ubiquitous transmission services for USVs. Specifically, we first employ a modified three-stage Stackelberg game to formulate the wireless data rate provisioning problem among LEO satellite, UAVs and USVs. Especially, the utility of each USV is designed based on the individual demand degree on the wireless data rate and unsatisfactory degree on the quality of wireless transmission service. Different from the original Stackelberg game with two parties, the modified game is really appropriate for modeling the complicated interactions of three parties (i.e., LEO satellite, UAVs and USVs), so as to search for the optimal strategy profile. Wherein, the LEO satellite acts as a leader to determine the optimal selling prices to assign LEO satellite-to-UAV (L2U) data rate. Afterwards, each UAV first makes decisions on the L2U data rate request from the LEO satellite and then determines the optimal selling price to assign UAV-to-USV (U2U) data rate. USVs, as followers of the game, decide the optimal U2U data rate request responding to the selling price of their connected UAVs. Furthermore, to optimally solve the wireless data rate provisioning problem, we exploit the backward induction approach to analyze the proposed three-stage game to obtain the optimal strategy profile as the Stackelberg equilibrium solution. In specific, the closed-form expressions on the optimal strategies of both USVs and UAVs under different data rate budgets are obtained by the nonlinear programming method, and the optimal strategy of the LEO satellite is achieved by an accelerated conjugate gradient descent (ACGD) based iteration algorithm, which can significantly improve the convergence rate by combining the conjugate factors

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and optimal step rate binary searching policy. The main contributions of this paper are three-fold.

- *Framework.* We propose a hierarchical wireless data rate provisioning framework in SAOINs. The LEO satellite with its extensive wireless coverage is utilized to provide L2U data rate for UAVs with a certain L2U data rate price. Each UAV with flexibility and easy deployment is employed to provide U2U data rate for multiple ground USVs with a certain U2U data rate price, based on the requested L2U data rate. As such, the seamless, high-rate, and cost-efficient wireless transmission service is provisioned to USVs for improving their QoE.
- *Modelling.* We propose a modified three-stage Stackelberg game to model the hierarchical wireless data rate provisioning among LEO satellites, UAVs, and USVs. Three optimization problems are formally formulated to maximize the utilities of LEO satellites, UAVs, and USVs, where the decision variables are selected as the L2U data rate price, L2U data rate request, U2U data rate price, and U2U data rate request, respectively.
- *Strategy.* We employ the backward induction approach to obtain the Stackelberg equilibrium as the optimal strategies to maximize the utilities of all game players. Specifically, the closed-form expressions on the optimal strategies of both UAVs and USVs under different budget conditions are obtained based on the nonlinear programming method. An ACGD based iteration algorithm is then devised to achieve the optimal strategies on L2U data rate price of the LEO satellite.

The remainder of this paper is organized as follows. Related work is reviewed in Section II. Section III describes the system model. Section IV shows the analysis of the Stackelberg game. Performance evaluation is given in Section V and we conclude the paper in Section VI.

II. Related Work

In this section, we review the related works including performance optimization of SAOINs, wireless data rate provisioning, and Stackelberg game.

A. Performance Optimization of SAOINs

SAION is an emerging communication networking paradigm, where a few researches have conducted on its performance optimization. Liu *et al.* [16] proposed multiple satellites based passive location parameter estimator for moving aerial target. It can provide the estimation not only the time difference of arrival and the frequency difference of arrival, but also the distance between the target and the receiver and the velocity of the moving target. Chen *et al.* [17] presented a civil aircraft augmented space-air-ground integrated networks architecture and optimization, including resource allocation and auction. Liu *et al.* [18] introduced a spectrum sensing with a deep neural network-based detection framework to extract features in a data-driven way according to the covariance matrix of the received signal. Lyu *et al.* [19] devised an online control framework to slice the spectrum resource for remote vehicular services provisioning dynamically. Online decisions on the request admission and scheduling, UAV dispatching, and resource slicing for different services are real-time made. However, the existing works on the performance optimization of SAIONs should further consider the hierarchical wireless data rate provisioning for USVs.

B. Data Rate Provisioning in Wireless Networks

In wireless networks, the data rate provisioning issues have been studied extensively to improve the QoE of mobile users. Fei *et al*. [20] investigated the effect of social centrality on the dynamic data rate provisioning in vehicular social networks and proposed a dynamic bandwidth allocation algorithm. Esmailpour *et al*. [21] proposed a new dynamic QoS based data rate provisioning framework to support heterogeneous traffic with different QoS requirement in WiMAX networks. Wang *et al*. [22] presented a hierarchical bandwidth allocation approach in heterogeneous networks. This work consists of network-level and connection-level bandwidth allocation, different from the two-tier HetMSNs neither. Nan *et al*. [23] presented a cloud-based living-streaming distribution method by formulating the bandwidth allocation problem as a non-cooperative game. Although many schemes have been proposed to realize the optimal wireless data rate provisioning, the restriction of available resources for data rate provisioning and USVs' diverse demands should be further taken into account.

C. Stackelberg Game in Wireless Networks

The Stackelberg game has been extensively employed to optimize the resource assignments in wireless networks. Xiao *et al.* [24] formulated the power control strategy of a secondary user against a smart jammer as a Stackelberg game based on power constraints, where the Stackelberg equilibrium of the anti-jamming game is obtained and compared with the Nash equilibrium of the game. Zheng *et al.* [25] designed a scalable and convergent Stackelberg game for edge caching, where the game is decomposed into different types of subgames. Xin *et al.* [26] proposed a credit-based incentive mechanism to encourage users to cooperate to help with each other in a heterogeneous network. Wang *et*

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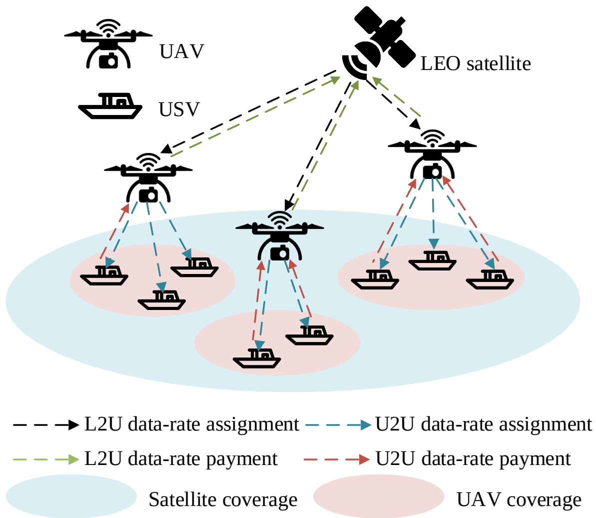

Fig. 1. An illustration of the system model.

al. [27] studied the transmission adaptation in an RF-powered cognitive radio network, with a single-leader-multi-follower Stackelberg game to model the sensing-pricing-transmitting process of the secondary gateway and the transmitters. Although many existing works have employed the Stackelberg game to enhance the performances of the wireless networks, few of them consider the effects of time-varying and diverse USVs' demands.

III. System Model

In this section, we elaborate the system model, involving the network model, the motion model, and the communication model. The notations utilized in this paper are summarized in Table I.

A. Network Model

We consider the communication problem of downlink transmission in three-layer SAOINs, as shown in Fig. 1. The space layer comprises one LEO satellite, which can provide seamless coverage for an extensive area. The air layer is supported by multiple UAVs to guarantee effective and efficient communication requirements for USVs. The ocean lay is supported by a large number of USVs, who have diverse data rate demands. Let $\mathcal{I} = \{1, 2, \cdots, I\}$ and $\mathcal{J} = \{1, 2, ..., J\}$ denote the set of USVs and UAVs, respectively. Here, we utilize a time slot model, where there exist T time slots and each one has an equal length δ. In each time slot, there exist a certain amount of USVs within the coverage of a UAV. Let binary variable $\eta_{i,j,t}$ denote whether USV i, $i \in \mathcal{I}$, within the coverage of UAV j, $j \in \mathcal{J}$, in the t-th time slot. In specific, if USV i sails within the coverage of UAV j in the t-th time slot, $\eta_{i,j,t} = 1$, and otherwise, $\eta_{i,j,t} = 0$. Without loss of generality, each USV can connect to at most one UAV in a time slot, i.e., $\sum_{j=1}^{J} \eta_{i,j,t} \leq 1, \forall i \in \mathcal{I}$.

TABLE I
VARIABLES

Notations	Description
$\mathcal{I}$	The set of USVs.
$\mathcal{J}$	The set of UAVs.
T	The number of time slots in a time horizon.
δ	The length of a time slot.
$\eta_{i,j,t} \in \{0, 1\}$	Whether USV i locates within the coverage of UAV j in the t-th time slot.
$\mathbf{L}_{j,t}$	The 3D location of UAV j in the t-th time slot.
V_{max}	The maximum flying velocity of each UAV.
$\mathbf{L}_{i,t}$	The 3D location of USV i in the t-th time slot.
$\boldsymbol{\xi}_{i,t}$	The motion state of USV i in the t-th time slot.
$\mu_{i,t}/\nu_{i,t}/\varphi_{i,t}$	Forwarding velocity/sway velocity/heading angle of USV i in the t-th time slot.
H_o	The altitude of the LEO satellite
Ψ_0	Channel gain at the unit distance from the satellite to UAVs.
ϑ	Path loss parameter of the communication link.
$P_{o,j,t}$	Transmission power of the LEO satellite to UAV j in the t-th time slot
$b_{j,t}$	Spectrum bandwidth assigned to UAV j from the LEO satellite in the t-th time slot.
σ_0^2	Noise power spectral density.
Λ	Rain attenuation ratio on the LEO satellite-to-UAV communication link.
$\rho_{i,j,t}$	The channel gain from UAV j to USV i in the t-th time slot.
β_0	The channel gain of UAV-to-USV link with the unit distance.
$b_{i,j,t}$	Spectrum bandwidth from UAV j to USV i in the t-th time slot.
$P_{i,j,t}$	Transmission power from UAV j to USV i in the t-th time slot.
$p_{o,t}$	L2U data rate price determined by the LEO satellite in the t-th time slot.
c_o	Cost of the LEO satellite on the unit L2U data rate.
$r_{j,t}$	L2U data rate request of UAV j in the t-th time slot.
$p_{j,t}$	U2U data rate price of UAV j in the t-th time slot.
$q_{i,j,t}$	U2U data rate request of USV i from UAV j in the t-th time slot.
$c_{j,t}$	Cost of UAV j on the unit U2U data rate in the t-th time slot.
$\widetilde{q}_{i,t}$	Dissatisfaction degree of USV i on the U2U data rate in the t-th time slot.
$\varrho_{i,t}$	Cumulative Data rate demand degree of USV i on U2U data rate from the t-th time slot to the T-th time slot.
$\widetilde{\varrho}_{i,t}$	Data rate demand degree of USV i on U2U data rate in the t-th time slot.
ϑ_i	Discount factor of USV i on future data rate demand degree.

B. Motion Model

In the t-th time slot, the 3D location of UAV j is denoted as $\mathbf{L}_{j,t} = (x_{j,t}, y_{j,t}, h_{j,t})$, where $h_{min} \leq h_{j,t} \leq h_{max}$. Here, h_{min} and h_{max} are the allowable minimal

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and maximal flying heights of UAVs, respectively. The flying velocity of UAV j in the t-th time slot is denoted as $V_{j,t}$, which cannot exceed the maximum flying velocity V_{max} (i.e., $V_{j,t} \leq V_{max}$). As such, the flying distance of the UAV is restricted by

$$||\mathbf{L}_{j,t+1} - \mathbf{L}_{j,t}|| \leq V_{max}\delta. \tag{1}$$

Similarly, in the t-th time slot, the 3D location of USV i is expressed as $\mathbf{L}_{i,t} = (x_{i,t}, y_{i,t}, 0)$, where the altitude of each USV is 0. Here, owing to the large size of the USV, its moving cannot be roughly modeled as a rectilinear motion. Considering the environment factors on the sea (e.g., wave, wind, etc.), a standard three degrees of freedom model [28] is applied to describe the motion of the USV. In specific, the motion state of the USV is formulated by the forwarding velocity, sway velocity, and heading angle. The motion state of USV i in the t-th time slot is denoted as $\boldsymbol{\xi}_{i,t} = (\mu_{i,t}, \nu_{i,t}, \varphi_{i,t})$, where $\mu_{i,t}$ and $\nu_{i,t}$ are respectively the forwarding velocity and sway velocity, and $\varphi_{i,t}$ is the heading angle. The yaw rate of USV i in the t-th time slot is denoted as $\gamma_{i,t}$. As such, the motion model of UAV i is given by

$$\begin{cases} \dot{x}_{i,t} = \mu_{i,t} \cos\varphi_{i,t} - \nu_{i,t} \sin\varphi_{i,t}, \\ \dot{y}_{i,t} = \mu_{i,t} \sin\varphi_{i,t} + \nu_{i,t} \cos\varphi_{i,t}, \\ \dot{\varphi}_{i,t} = \gamma_{i,t}. \end{cases} \tag{2}$$

Based on above motion model, the heading angle of USV i in the $(t+1)$-th time slot is

$$\varphi_{i,t+1} = \gamma_{i,t}\delta + \varphi_i. \tag{3}$$

The sailing distance of USV i from the t-th time slot to the $(t+1)$-th time slot is

$$\begin{cases} x_{i,t+1} - x_{i,t} \\ = \begin{bmatrix} \mu_{i,t} \left(\sin\varphi_{i,t+1} - \sin\varphi_{i,t}\right) \\ +\nu_{i,t} \left(\cos\varphi_{i,t+1} - \cos\varphi_{i,t}\right) \end{bmatrix} \left(\gamma_{i,t}\right)^{-1}, \\ y_{i,t+1} - y_{i,t} \\ = \begin{bmatrix} \nu_{i,t} \left(\sin\varphi_{i,t+1} - \sin\varphi_{i,t}\right) \\ -\mu_{i,t} \left(\cos\varphi_{i,t+1} - \cos\varphi_{i,t}\right) \end{bmatrix} \left(\gamma_{i,t}\right)^{-1}. \end{cases} \tag{4}$$

C. Communication Model

In SAOINs, we consider two communication interfaces, i.e., LEO satellite-to-UAV and UAV-to-USV. Each of them utilizes different spectrum bands, thereby leading to no interference between the LEO satellite and USVs. In the following, the data rate of LEO satellite-to-UAV link (i.e., L2U data rate) and that of UAV-to-USV link (i.e., U2U data rate) are respectively described.

1) LEO Satellite-to-UAV Link: Currently, the LEO satellite-to-UAV link is mainly realized with Ka spectrum band [29], where channel condition is easily affected by the communication distance and the rain attenuation. Since the flying distance of the UAV is much shorter than the altitude of the LEO satellite, the variation of distance between the LEO satellite and each UAV can be negligible. As such, the channel gain of the LEO satellite-to-UAV link remains constant with the flying of UAVs, which is expressed by

$$\rho_{o,j,t} = \frac{\Psi_0}{\left(H_o - h_{j,t}\right)^{\vartheta}} \approx \frac{\Psi_0}{{H_o}^{\vartheta}}, \tag{5}$$

where H_o denotes the altitude of the LEO satellite. Ψ_0 is the channel gain at the unit distance from the satellite to the UAV and ϑ is the path loss parameter of the communication link. The transmission power of the LEO satellite to UAV j in the t-th time slot is denoted as $P_{o,j,t}$. Let $b_{j,t}$ indicate the spectrum bandwidth allocated to UAV j from the LEO satellite in the t-th time slot. As such, the L2U data rate between the LEO satellite and UAV j in the t-th time slot is obtained by

$$r_{j,t} = \Lambda b_{j,t} \log_2\left(1 + \frac{P_{o,j,t}\Psi_0}{b_{j,t}\sigma_0^2 {H_o}^{\vartheta}}\right) \tag{6}$$

where σ_0^2 is the noise power spectral density. Λ indicates the rain attenuation ratio.

2) UAV-to-USV Link: Initial measurements of the channel indicate that the UAV-to-ground channel is typically composed of a strong line-of-sight (LoS) chain [30]. For simplicity, we suppose that the LoS link can dominate the channel between the UAV and each USV. The channel gain from UAV j to USV i can be calculated by

$$\rho_{i,j,t} = \beta_0(||\mathbf{L}_{i,t} - \mathbf{L}_{j,t}||)^{-\vartheta} \tag{7}$$

where β_0 is the channel gain of UAV-to-USV link with the unit distance. Let $b_{i,j,t}$ denote the bandwidth of USV i from UAV j in the t-th time slot. As such, the U2U data rate from UAV j to USV i is expressed by

$$q_{i,j,t} = b_{i,j,t} \log_2\left(1 + \frac{P_{i,j,t}\rho_{i,j,t}}{\sum_{j'=1,j'\neq j}^{J} P_{i,j',t}\rho_{i,j',t} + b_{i,j',t}\sigma_0^2}\right) \tag{8}$$

where $P_{i,j,t}$ is the transmission power of UAV j to USV i in the t-th time slot. $\sum_{j'=1,j'\neq i}^{J} P_{i,j',t}\rho_{i,j',t}$ is the interference from all UAVs except UAV j. Here, the OFDMA communication mode is utilized for USVs to access connected UAVs, whereby there only exist co-channel interferences from other UAVs.

IV. Problem Formulation

In this paper, we study the data rate provisioning in SAIONs, including L2U data rate assignment and U2U data rate assignment. The LEO satellite provides L2U data rate to each UAV by allocating wireless resources (i.e., spectrum bandwidth and transmission power) and each UAV allocates its spectrum bandwidth/transmission power to provide U2U data rate for its connected USV. Here, specific bandwidth or power allocation scheme is

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not the focus of this paper, which have been extensively studied by existing works, such as [13], [15].

In each time slot, the LEO satellite first determines the L2U data rate price to maximize its profit, according to the demands of UAVs. Then, each UAV purchases the proper amount of L2U data rate from the LEO satellite and then determines the U2U data rate price to assign its owned U2U data rate to USVs, where the total assigned U2U data rate cannot exceed the requested L2U data rate from the LEO satellite. Finally, each USV decides the appropriate U2U data rate request responding to the connected UAV.

According to the above process, the wireless data rate provisioning problem in SAOINs can be formulated as a three-stage Stackelberg game, where the up-stage acts as the leaders to make the decisions first and the down-stage acts as the followers to move subsequently based on the leaders' strategies. Thus, in stage I, the LEO satellite serves as the leader and determines the L2U data rate price, according to the demands of UAVs. Then, in stage II, the UAVs, as followers of stage I, make decisions on the L2U data rate requests from the LEO satellite, and then act as the leaders of stage III to assign their U2U data rates to USVs by the optimal U2U data rate prices for maximizing their utilities. In stage III, each USV, as the follower of stage II, determines the optimal U2U data rate request based on the U2U data rate price of its connected UAV to gain its utility. The similar three-stage Stackelberg game has been utilized in literatures [31], [32]. However, most of them assume that the game strategies of the first and the second stages lack direct correlations with those of the second and the third stages. The proposed modified three-stage Stackelberg game in this paper sufficiently takes the interplays among strategies of three game players. In particular, the determination of the U2U data rate price is partly based on the L2U data rate request from the LEO satellite, where the amount of available U2U data rate cannot exceed the amount of requested L2U data rate. The utilities of LEO satellite, UAVs, and USVs are expressed as follows.

1) Utility of LEO Satellite

The responsibility of the LEO satellite is to assign L2U data rate to UAVs with a ceratin L2U data rate price for gaining its utility. The utility of the LEO satellite is the difference between the benefit and cost to assign L2U data rates for UAVs. As such, its utility is expressed by

$$U_{o,t}(p_{o,t}) = p_{o,t}\sum_{j=1}^{J} r_{j,t} - c_o \sum_{j=1}^{J} r_{j,t} \tag{9}$$

where $p_{o,t}$ denotes the L2U data rate price determined by the LEO satellite in the t-th time slot. c_o is the cost of the LEO satellite on the unit L2U data rate. $r_{j,t}$ indicates the L2U data rate request of UAV j in the t-th time slot.

2) Utility of UAV

Each UAV is employed to act as an agent, who purchases L2U data rate from the LEO satellite and assign U2U data rate to USVs within its coverage. The utility of each UAV is the difference between the benefit to assign U2U data rates for USVs and the cost on delivering data for USVs. Specifically, the cost includes the payment for the L2U data rate purchased from the LEO satellite and the transmission consumption for USVs. Hence, the utility of UAV j in the t-th time slot is given by

$$U_{j,t}(p_{j,t}, r_{j,t}) = (p_{j,t} - c_j)\sum_{i=1}^{I} \eta_{i,j,t} q_{i,j,t} - p_{o,t} r_{j,t}, \tag{10}$$

where $p_{j,t}$ and $c_{j,t}$ are the U2U data rate price and unit cost of UAV j in the t-th time slot, respectively. $q_{i,j,t}$ is the U2U data rate request of USV i to UAV j in the t-th time slot.

3) Utility of USV

For a USV, it requests U2U data rate from its connected UAV to receive message. As each USV is a risk-averse entity, the satisfaction function should be concave, non-decreasing with respect to the acquired data rate. As such, the satisfaction function of USV j in the t-th time slot is

$$Sat_{i,t} = \log\left(1 + \varrho_{i,t}\frac{\sum_{j=1}^{J}\eta_{i,j,t} q_{i,j,t}}{\tilde{q}_{i,t}}\right), \tag{11}$$

where $\tilde{q}_{i,t}$ is the dissatisfaction degree of USV i on the U2U data rate in the t-th time slot. $\varrho_{i,t}$ represents the cumulative demand degree of USV i on U2U data rate from the t-th time slot to the T-th time slot, which is based on the data rate demand degree in the current time slot and those in the future time slots. As such, it can be expressed as

$$\varrho_{i,t} = \sum_{t'=t}^{T} \vartheta_i^{-(t'-t)} \tilde{\varrho}_{i,t'}, \tag{12}$$

where $\tilde{\varrho}_{i,t'}$ is the data rate demand degree of USV i in the t'-th time slot. $\vartheta_i \in [0,1]$ is the discount factor of USV i on future data rate demand degree. Here, if ϑ_i is small, the cumulative demand degree of USV i will much focus on the demand degree in the current time slot. With requesting U2U data rate for its wireless transmission demand, each USV has a certain cost linearly dependent on the acquired data rate. The cost function of USV i in the t-th time slot is

$$Cost_{i,t} = \sum_{j=1}^{J} \eta_{i,j,t} p_{j,t} q_{i,j,t}. \tag{13}$$

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Synthesizing the benefit function and the cost function, the utility of USV i in the t-th time slot is

$$\begin{aligned} U_{i,t}(\mathbf{q}_{i,t}) =& \lambda \log \left(1 + \frac{\varrho_{i,t}}{\tilde{q}_{i,t}} \sum_{j=1}^{J} \eta_{i,j,t} q_{i,j,t} \right) \\ & - \sum_{j=1}^{J} \eta_{i,j,t} p_{j,t} q_{i,j,t}, \end{aligned} \tag{14}$$

where $\mathbf{q}_{i,t} = (q_{i,1,t}, q_{i,2,t}, \cdots, q_{i,J,t})$. λ is the weighted parameter, which is used to avoid the negative utility.

Let $\mathbb{G}$ denote the proposed three-stage Stackelberg game strategic form. In game $\mathbb{G}$, the objectives of all parties including LEO satellite, UAVs and USVs are to maximize their utilities. Therefore, we define the following three problems:

$$\begin{aligned} \text{P1}: \ & \max_{p_{o,t}} \ U_{o,t}(p_{o,t}) \\ & \text{s.t.} \sum_{j=1}^{J} r_{j,t} \le R_o, \end{aligned} \tag{15}$$

$$\begin{aligned} \text{P2}: \ & \max_{p_{j,t}, r_{j,t}} \ U_{j,t}(p_{j,t}, r_{j,t}), \forall j \in \mathcal{J} \\ & \text{s.t.} \left\{ \begin{array}{l} p_{j,t} \ge 0 \\ \sum\limits_{i=1}^{I} \eta_{i,j,t} b_{i,j,t} \le r_{j,t}. \end{array} \right. \end{aligned} \tag{16}$$

$$\begin{aligned} \text{P3}: \ & \max_{\mathbf{q}_{i,t}} \ U_{i,t}(\mathbf{q}_{i,t}), \forall i \in \mathcal{I} \\ & \text{s.t.} \ \mathbf{q}_{i,t} \ \ge \mathbf{0}. \end{aligned} \tag{17}$$

where R_o denotes L2U data rate budget that can be assigned to UAVs.

The Stackelberg equilibrium is utilized as the solution of game $\mathbb{G}$, which is defined as follows.

Definition 1: In the t-th time slot, let $p^*_{o,t}$ be a solution of problem P1. Let $\pi^*_{j,t} = (p^*_{j,t}, r^*_{j,t})$ be a solution of problem P2 and $\mathbf{q}^*_{i,t}$ be a solution of problem P3. Then, let $\mathbf{q}_t = \{\mathbf{q}_{1,t}, \mathbf{q}_{2,t}, \cdots, \mathbf{q}_{I,t}\}$ and $\boldsymbol{\pi}_t = \{\pi_{1,t}, \pi_{2,t}, \cdots, \pi_{J,t}\}$. The point $(p^*_{o,t}, \boldsymbol{\pi}^*_t, \mathbf{q}^*_t)$ is a Stackelberg equilibrium of $\mathbb{G}$ for any $(p_{o,t}, \boldsymbol{\pi}_t, \mathbf{q}_t)$, if

$$U_{o,t}\left(p^*_{o,t}, \boldsymbol{\pi}^*_t\right) \ge U_{o,t}\left(p_{o,t}, \boldsymbol{\pi}^*_t\right), \tag{18}$$

$$U_{j,t}\left(\pi^*_{j,t}, p^*_{o,t}, \mathbf{q}^*_t\right) \ge U_{j,t}\left(\pi_{j,t}, p^*_{o,t}, \mathbf{q}^*_t\right), \tag{19}$$

$$U_{i,t}\left(\mathbf{q}^*_{i,t}, \boldsymbol{\pi}^*_t\right) \ge U_{i,t}\left(\mathbf{q}_{i,t}, \boldsymbol{\pi}^*_t\right). \tag{20}$$

V. Stackelberg Game Analysis

In this section, we analyze the game $\mathbb{G}$ to find the Stackelberg equilibrium. The backward induction approach is introduced to search the Stackelberg equilibrium. Specifically, we first analyze the optimal U2U data rate request of each USV. The optimal U2U data rate price of each UAV is then investigated. Afterwards, the optimal L2U data rate request of each UAV is discussed, which is followed by the analysis on the L2U data rate price of the LEO satellite by the ACGD based iteration algorithm. At last, we prove the existence of the Stackelberg equilibrium.

A. Optimal U2U Data Rate Requests of USVs in Stage III

Given the U2U data rate price of each UAV, USVs determine the optimal U2U data rate requests to maximize their utilities. By solving P3, we can obtain the optimal strategies for USVs with the following theorem.

Theorem 1: Given U2U data rate price of UAV j, $\forall j \in \mathcal{J}$, the optimal U2U data rate request of USV i in the t-th time slot is

$$q^*_{i,j,t} = \left\{ \begin{array}{l} 0, \ \text{if} \ \eta_{i,j,t} = 0 \\ \left[\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{i,t}} \right]^+, \text{if} \ \eta_{i,j,t} = 1 \end{array} \right. \tag{21}$$

where $[\cdot]^+ = \max(\cdot, 0)$ and $\alpha_{i,t} = \varrho_{i,t}/\tilde{q}_{i,t}$.

Proof: First of all, we consider that USV i is not within the coverage of UAV j in the t-th time slot, i.e., $\eta_{i,j,t} = 0$. As USV i cannot connect to UAV j, the U2U data rate requested by USV i is zero, i.e., $q^*_{i,j,t} = 0$.

We then consider that USV i sails within the coverage of USV j in the t-th time slot, i.e., $\eta_{i,j,t} = 1$. The utility of USV i is rewritten as

$$U_{i,t}(\mathbf{q}_{i,t}) = \lambda \log\left(1 + \alpha_{i,t} q_{i,j,t}\right) - p_{j,t} q_{i,j,t}, \text{if} \ \eta_{i,j,t} = 1. \tag{22}$$

The first derivative of $U_{i,t}(\mathbf{q}_{i,t})$ with respect to $r_{i,j,t}$ is

$$\frac{\partial U_{i,t}(\mathbf{q}_{i,t})}{\partial q_{i,j,t}} = \frac{\lambda \alpha_{i,t}}{1 + \alpha_{i,t} q_{i,j,t}} - p_{j,t}. \tag{23}$$

The second derivative of $U_{i,t}(\mathbf{q}_{i,t})$ with respect to $r_{i,j,t}$ is

$$\frac{\partial^2 U_{i,t}(\mathbf{q}_{i,t})}{\partial {q_{i,j,t}}^2} = -\frac{\lambda \alpha^2_{i,t}}{\left(1 + \alpha_{i,t} q_{i,j,t}\right)^2}. \tag{24}$$

Because of the negativity of the second derivative, the utility function of the USV is concave, i.e., there exists the maximum utility for USV i. We then conduct the following limitation operations:

$$\lim_{q_{i,j,t} \to +\infty} \frac{\partial U_{i,t}(\mathbf{q}_{i,t})}{\partial q_{i,j,t}} = -p_{j,t} < 0, \tag{25}$$

$$\lim_{q_{i,j,t} \to 0} \frac{\partial U_{i,t}(\mathbf{q}_{i,t})}{\partial q_{i,j,t}} = \lambda \alpha_{i,t} - p_{j,t}. \tag{26}$$

From (26), we cannot determine whether the first derivative of the utility is positive or negative, when $q_{i,j,t} = 0$. We then consider two cases:

Case 1: Low price regime.

The low price case is that the U2U data rate price of UAV j is not larger than $\lambda \alpha_{i,t}$, i.e., $p_{j,t} \le \lambda \alpha_{i,t}$. As such, $\lim\limits_{q_{i,j,t} \to 0} \frac{\partial U_{i,t}(\mathbf{q}_{i,t})}{\partial q_{i,j,t}}$ is larger than zero. $U_{i,t}(\mathbf{q}_{i,t})$

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first increases and then decreases with $q_{i,j,t}$. The optimal request strategy of USV i in t-th time slot is obtained by solving the equation: $\partial U_{i,t}(\mathbf{q}_{i,t})/\partial q_{i,j,t} = 0$. Therefore, the optimal U2U data rate request of USV i from UAV j in the t-th time slot is

$$q_{i,j,t}^* = \frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{i,t}} \tag{27}$$

Case 2: High price regime.

The high price means that the U2U data rate price of UAV j is larger than $\lambda\alpha_{i,t}$, i.e., $p_{j,t} > \lambda\alpha_{i,t}$. As such, $\lim\limits_{q_{i,j,t}\to 0} \frac{\partial U_{i,t}(\mathbf{q}_{i,t})}{\partial q_{i,j,t}}$ is smaller than zero, and the first derivative of the utility keeps negative. Therefore, the optimal U2U data rate request of USV i from UAV j in the t-th time slot is $q_{i,j,t}^* = 0$. ■

B. Optimal U2U Data Rate Price of UAV in Stage II

For the sake of ease exposition, in the t-th time slot, the set of USVs within the coverage of UAV j is denoted as $\mathcal{M} = \{1, 2, \cdots, M\}$, i.e., $\forall m \in \mathcal{M}, \exists \eta_{m,j,t} = 1$, where these USVs are also sorted with decrease of $\lambda\alpha_{i,t}$, i.e., $\lambda\alpha_{1,t} \geq \lambda\alpha_{2,t} \geq \cdots \geq \lambda\alpha_{M,t}$. According to Theorem 1, the utility of UAV j can be rewritten as

$$U_{j,t} = (p_{j,t} - c_j) \sum_{m=1}^{M} \left[\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{m,t}}\right]^+ - p_{o,t} r_{j,t}. \tag{28}$$

We then define an indicator variable for each USV:

$$f_{m,j,t} = \begin{cases} 1, \text{ if } p_{j,t} \leq \lambda\alpha_{m,t}, \\ 0, \text{ otherwise.} \end{cases} \tag{29}$$

P2 for U2U date rate price is reformulated as

$$\text{P2-1:} \max_{p_{j,t}, f_{m,j,t}} (p_{j,t} - c_j) \sum_{m=1}^{M} \left\{ \begin{array}{l} f_{m,j,t} \left(\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{m,t}}\right) \\ -p_{o,t} r_{j,t} \end{array} \right\},$$
$$s.t. \begin{cases} p_{j,t} \geq c_j + p_{o,t}, \\ \sum\limits_{m=1}^{M} f_{m,j,t} \left(\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{m,t}}\right) \leq r_{j,t}, \\ f_{m,j} \in \{0, 1\}. \end{cases} \tag{30}$$

It can be observed that P2-1 is non-convex due to $f_{m,j,t}$, whose elements are 0-1 variables. However, this problem has a nice property that can be explored as follows. Given indicator vector $f_{m,j,t}$, P2-1 is convex.

At first, we consider a special case that the available U2U data rate of each UAV is large enough. Besides, the U2U data rate price is low, so as to provide data rate for all USVs within the coverage. As a result, the indictors of all USVs are equal to 1, i.e., $p_{j,t} \leq \lambda\alpha_{M,t}$. In this case, P2-1 can be transformed to the following form.

$$\text{P2-1(I):} \max_{p_{j,t}} (p_{j,t} - c_j) \sum_{m=1}^{M} \left(\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{m,t}}\right) - p_{o,t} r_{j,t},$$
$$\text{s.t.} \begin{cases} \text{C1}: \sum_{m=1}^{M} \left(\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{m,t}}\right) \leq r_{j,t}, \\ \text{C2}: p_{j,t} \geq c_j + p_{o,t}, \\ \text{C3}: p_{j,t} \leq \lambda\alpha_{M,t}. \end{cases} \tag{31}$$

The optimal solution of Problem 2-1(I) is given by the Theorem 2.

Theorem 2: In the t-th time slot, the optimal U2U data rate price of UAV j for Problem 2-1(I) is given by

$$p_{j,t}^{M*} = \begin{cases} Q_1^M, \text{ if } r_{j,t} \geq L_1^M \text{ and } Q_3^M \leq Q_1^M \leq Q_2^M, \\ Q_2^M, \text{ if } r_{j,t} \geq L_2^M \text{ and } Q_3^M \leq Q_2^M < Q_1^M, \\ Q_3^M, \text{ if } r_{j,t} \geq L_3^M \text{ and } Q_1^M < Q_3^M \leq Q_2^M, \\ Q_4^M, \text{ if } L_2^M \leq r_{j,t} \leq \min\left\{L_1^M, L_3^M\right\}. \end{cases} \tag{32}$$

where $Q_z^M,\ L_z^M, z \in \{1, 2, 3, 4\}$ are abbreviations for

$$\begin{cases} Q_1^M = \sqrt{\frac{\lambda M c_j}{\phi_{j,M,t}}}, \\ Q_2^M = \lambda\alpha_{M,t}, \\ Q_3^M = c_j + p_{o,t}, \\ Q_4^M = \frac{\lambda M}{r_{j,t} + \phi_{j,M,t}}, \\ L_z^M = \frac{\lambda M}{Q_z^M} - \phi_{j,M,t}. \end{cases} \tag{33}$$

Here, $\phi_{j,M,t} = \sum_{m=1}^{M} \frac{1}{\alpha_{m,t}}$.

Proof: See the Appendix A. ■

Then, we continue to make the analysis of the optimal solution of P2-1.

Proposition 1: The U2U data rate price given by Theorem 2 is the optimal solution of P2-1 if and only if $r_{j,t} \geq L_2^M$.

Proof: See the Appendix B. ■

With above results, we continue to solve P2-1. The optimal solution of P2-1 is given as follows.

Theorem 3: The optimal solution of P2-1 is

$$p_{j,t}^* = \begin{cases} p_{j,t}^{M*}, & \text{if } r_{j,t} \geq L_2^M, \\ p_{j,t}^{M-1*}, & \text{if } L_2^M > r_{j,t} \geq L_2^{M-1}, \\ \vdots & \\ p_{j,t}^{1\ *}, & \text{if } L_2^2 > r_{j,t} \geq L_2^1. \end{cases} \tag{34}$$

Here, when $L_2^{\widetilde{M}+1} > r_{j,t} \geq L_2^{\widetilde{M}}, \widetilde{M} \in \{1, 2, \cdots, M\}$ and $L_2^{M+1} = \infty$, the optimal U2U data rate price of UAV j is expressed as

$$p_{j,t}^{\widetilde{M}^*} = \begin{cases} Q_1^{\widetilde{M}}, \text{ if } r_{j,t} \geq L_1^{\widetilde{M}} \text{ and } Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}, \\ Q_2^{\widetilde{M}}, \text{ if } r_{j,t} \geq L_2^{\widetilde{M}} \text{ and } Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}} < Q_1^{\widetilde{M}}, \\ Q_3^{\widetilde{M}}, \text{ if } r_{j,t} \geq L_3^{\widetilde{M}} \text{ and } Q_1^{\widetilde{M}} < Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}, \\ Q_4^{\widetilde{M}}, \text{ if } L_2^{\widetilde{M}} \leq r_{j,t} \leq \min\left\{L_1^{\widetilde{M}}, L_3^{\widetilde{M}}\right\}. \end{cases} \tag{35}$$

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where $Q_z^{\widetilde{M}},\ L_z^{\widetilde{M}}, z \in \{1,2,3,4\}$ are abbreviations for

$$\begin{cases} Q_1^{\widetilde{M}} = \sqrt{\frac{\lambda \widetilde{M} c_j}{\phi_{j,\widetilde{M},t}}}, \\ Q_2^{\widetilde{M}} = \lambda \alpha_{\widetilde{M},t}, \\ Q_3^{\widetilde{M}} = c_j + p_{o,t}, \\ Q_4^{\widetilde{M}} = \frac{\lambda \widetilde{M}}{r_{j,t}+\phi_{j,\widetilde{M},t}}, \\ L_z^{\widetilde{M}} = \frac{\lambda \widetilde{M}}{Q_z^{\widetilde{M}}} - \phi_{j,\widetilde{M},t}. \end{cases} \tag{36}$$

Proof: If $r_{j,t} \geq L_2^M$, the optimal $p_{j,t}^*$ can be easily obtained by Proposition 1. For other intervals of $r_{j,t}$, e.g., $L_2^M > r_{j,t} \geq L_2^{M-1}$, the proof of the optimal solution with corresponding $p_{j,t}^*$ can be obtained similarly as Theorem 2. This completes our proof. ∎

C. Optimal L2U Data Rate Request of UAV in Stage II

In stage II, the target of each UAV is to maximize its utility by determining the optimal L2U data rate request from the LEO satellite. According to Theorem 3, the utility of UAV j that covers M mobile users in the t-th time slot is expressed as

$$\begin{aligned} & U_{j,t}\left(p_{j,t}^*, r_{j,t}\right) \\ & = \left(p_{j,t}^* - c_j\right) \sum_{m=1}^{M} \left[\frac{\lambda}{p_{j,t}^*} - \frac{1}{\alpha_{m,t}}\right]^+ - p_{o,t} r_{j,t}. \end{aligned} \tag{37}$$

As such, P2 for L2U date-rate request is reformulated as

$$\begin{aligned} \text{P2-2:} \quad & \max_{r_{j,t}} U_{j,t}\left(p_{j,t}^*, r_{j,t}\right), \\ & \text{s.t.} \sum_{m=1}^{M} \left[\frac{\lambda}{p_{j,t}^*} - \frac{1}{\alpha_{m,t}}\right]^+ \leq r_{j,t}. \end{aligned} \tag{38}$$

In specific, when $L_2^{\widetilde{M}+1} > r_{j,t} \geq L_2^{\widetilde{M}},\ \widetilde{M} \in \{1, 2, \cdots, M\}$ and $L_2^{\widetilde{M}+1} = \infty$, the optimal L2U data rate request of UAV j is obtained in the following theorem.

***Theorem** 4:* In the t-th time slot, when $L_2^{\widetilde{M}+1} > r_{j,t} \geq L_2^{\widetilde{M}}$, given the L2U data rate price of LEO satellite, i.e., $p_{o,t}$, optimal L2U data rate request of UAV j is given by

$$r_{j,t}^{\widetilde{M}*} = \begin{cases} \sqrt{\frac{\lambda \widetilde{M} \phi_{j,t}}{c_j + p_{o,t}}} - \phi_{j,\widetilde{M},t}, & \text{if } W_1 \text{ or } W_2, \\ \frac{\widetilde{M}}{\alpha_{\widetilde{M},t}} - \phi_{j,\widetilde{M},t}, & \text{if } W_3 \text{ or } W_4 \text{ or } W_5, \end{cases} \tag{39}$$

where, we have

$$\begin{cases} W_1 = p_{o,t} \leq \min\left\{H_1^{\widetilde{M}}, K_1^{\widetilde{M}}\right\} \text{ and } K_1^{\widetilde{M}} \leq K_2^{\widetilde{M}}, \\ W_2 = K_1^{\widetilde{M}} < p_{o,t} \leq \min\left\{H_1^{\widetilde{M}}, H_2^{\widetilde{M}}\right\}, \\ W_3 = H_1^{\widetilde{M}} < p_{o,t} < K_1^{\widetilde{M}} \text{ and } K_1^{\widetilde{M}} \leq K_2^{\widetilde{M}}, \\ W_4 = p_{o,t} \leq K_2^{\widetilde{M}} \text{ and } K_2^{\widetilde{M}} \leq K_1^{\widetilde{M}}, \\ W_5 = \min\left\{H_1^{\widetilde{M}}, K_1^{\widetilde{M}}\right\} < p_{o,t} \leq K_2^{\widetilde{M}}. \end{cases} \tag{40}$$

Here, $K_1^{\widetilde{M}}, K_2^{\widetilde{M}}, H_1^{\widetilde{M}}, H_2^{\widetilde{M}}$ are respectively abbreviations for

$$\begin{cases} K_1^{\widetilde{M}} = \sqrt{\frac{\lambda \widetilde{M} c_j}{\phi_{j,\widetilde{M},t}}} - c_j, \\ K_2^{\widetilde{M}} = \lambda \alpha_{\widetilde{M},t} - c_j, \\ H_1^{\widetilde{M}} = \frac{\lambda \alpha_{\widetilde{M},t}^2 \phi_{j,t}}{\widetilde{M}} - c_j, \\ H_2^{\widetilde{M}} = \frac{\lambda \widetilde{M}}{\phi_{j,\widetilde{M},t}} - c_j. \end{cases} \tag{41}$$

Proof: See the Appendix C. ∎

Then, we continue to analyze the optimal solution of problem P2-2.

***Proposition** 2:* The L2U data rate request given by Theorem 4 is the optimal solution of P2-2 if and only if $p_{o,t} \leq \lambda \alpha_{\widetilde{M},t} - c_j$.

Proof: See the Appendix D. ∎

Based on Proposition 2, the optimal solution of P2-2 is expressed as the following theorem.

***Theorem** 5:* In the t-th time slot, the optimal solution of P2-2 for UAV j is given by

$$r_{j,t}^* = \begin{cases} r_{j,t}^{M*}, & \text{if } p_{o,t} \leq \lambda \alpha_M - c_j, \\ r_{j,t}^{M-1*}, & \text{if } \lambda \alpha_M - c_j < p_{o,t} \leq \lambda \alpha_{M-1} - c_j, \\ \vdots & \\ r_{j,t}^{1\ *}, & \text{if } \lambda \alpha_2 - c_j < p_{o,t} \leq \lambda \alpha_1 - c_j. \end{cases} \tag{42}$$

Proof: If $\lambda \alpha_{\widetilde{M}+1} - c_j < p_{o,t} \leq \lambda \alpha_{\widetilde{M}} - c_j$, the optimal $r_{j,t}^*$ can be directly obtained by Proposition 2. For other intervals, e.g., $\lambda \alpha_{\widetilde{M}} - c_j < p_{o,t} \leq \lambda \alpha_{\widetilde{M}-1} - c_j$, the proof of the optimal solution on $r_{j,t}^*$ can be shown similarly as Theorem 4. This completes our proof. ∎

D. Optimal L2U Data Rate Price of LEO Satellite in Stage I

The target of the LEO satellite is to maximize its utility by assign L2U data rate to UAVs in problem P3. From Theorem 4 and Theorem 5, the utility of the LEO satellite can be rewritten as

$$\begin{aligned} U_{o,t} = (p_{o,t} - c_o) & \left[\sum_{j=1}^{F} \left(\sqrt{\frac{\lambda \widetilde{M}_j \phi_{j,t}}{c_j + p_{o,t}}} - \phi_{j,\widetilde{M}_j,t}\right)\right. \\ & \left. + \sum_{j=F+1}^{J} \left(\frac{\widetilde{M}_j}{\alpha_{\widetilde{M}_j,t}} - \phi_{j,\widetilde{M}_j,t}\right)\right], \end{aligned} \tag{43}$$

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where the optimal L2U data rate requests of F UAVs are similar to $\sqrt{\frac{\lambda \widetilde{M}\phi_{j,t}}{c_j+p_{o,t}}}-\phi_{j,\widetilde{M},t}$, while those of $J-F$ UAVs are alike to $\frac{\widetilde{M}}{\alpha_{\widetilde{M},t}}-\phi_{j,\widetilde{M},t}$. $\widetilde{M}_j$ denotes the number of USVs acquiring positive U2U data rates in the coverage of UAV j.

***Lemma** 1:* The utility of the LEO satellite denoted in (43) is a concave function.

Proof: See the Appendix E. ■

It is notable that if there is a local maximal solution for concave function, the solution is also globally optimal. Consequently, following theorem is obtained according to Lemma 1.

***Theorem** 6:* If $U_{o,t}(p_{o,t})$ is concave, there exists a unique globally optimal L2U data rate price $p_{o,t}^*$, where $p_{o,t}^*$ is calculated by

$$\begin{cases} \left.\frac{\partial U_{o,t}(p_{o,t})}{\partial p_{o,t}}\right|_{p_{o,t}=p_{o,t}^*} = 0, \text{if } \left.\sum_{j=1}^{J} r_{j,t}\right|_{p_{o,t}=p_{o,t}^*} \leq R_o, \\ \left.\sum_{j=1}^{J} r_{j,t}\right|_{p_{o,t}=p_{o,t}^*} = R_o, \text{if } \left.\frac{\partial U_{o,t}(p_{o,t})}{\partial p_{o,t}}\right|_{p_{o,t}=p_{o,t}^*} < 0. \end{cases} \tag{44}$$

Therefore, based on Theorem 6, the optimal L2U data rate price of the LEO satellite can be obtained by solving the nonlinear equation (44). However, as the L2U data rate price (i.e., $p_{o,t}$) is initially not determined, the detailed form of the optimal L2U data rate request of each UAV cannot be obtained. Besides, in reality, the number of UAVs and USVs are usually large, inducing a fairly sophisticated utility for the LEO satellite. As such, the LEO satellite's utility gradient is hard to obtain, whereby it is intractable to solve the nonlinear equation in Theorem 6. Alternatively, we devise an ACGD based iteration algorithm to obtain the optimal L2U data rate selling price for the LEO satellite, shown in Algorithm 1. The initialization of the algorithm is to set the total amount of L2U data rate and its L2U data rate price. In step 3, the gradient of $U_{o,t}(p_{o,t})$ at $p_{o,t}^{(k)}$ is calculated by the variation of utility with a small variate τ as follows:

$$\nabla U_{o,t}\left(p_{o,t}^{(k)}\right) \approx \frac{U_{o,t}\left(p_{o,t}^{(k)}+\tau\right)-U_{o,t}\left(p_{o,t}^{(k)}-\tau\right)}{2\tau} \tag{47}$$

In steps 4-12, the L2U data rate selling price of the LEO satellite is updated toward a direction to increase its utility and until converges to the optimal price $p_{o,t}^*$. In steps 14-22, when the total amount of L2U data rate requests with the optimal price from steps 4-12 exceeds the constriction R_0, the optimal price is re-searched to satisfy $\sum_{j=1}^{J} r_{j,t} = R_0$.

Now, the game $\mathbb{G}$ of wireless data rate provisioning among LEO satellite, UAVs and USVs is completely solved. The Stackelberg equilibrium of game $\mathbb{G}_t$ is then given as follows.

Algorithm 1 ACGD Based Iteration Algorithm

1: **Initialization:** The LEO satellite sets the total amount of L2U date rate R_o and determines the initial L2U data rate price $p_{o,t}^{(1)}$, $k := 1$.
2: **repeat**
3: Calculate the gradient of $U_{o,t}(p_{o,t})$ at $p_{o,t}^{(k)}$ by (47).
4: **if** $k = 1$ **then**
5: Let $d^{(k)} := \nabla U_{o,t}\left(p_{o,t}^{(k)}\right)$.
6: **else**
7: Searching direction is updated by $d^{(k)} := \nabla U_{o,t}\left(p_{o,t}^{(k)}\right) + \beta_{k-1} d^{(k-1)}$, where β_{k-1} is given by
$$\beta_{k-1} := ||\nabla U_{o,t}\left(p_{o,t}^{(k)}\right)||^2 / ||\nabla U_{o,t}\left(p_{o,t}^{(k-1)}\right)|| \tag{45}$$
8: **end if**
9: Search for the optimal step size ε_k^* by using gradient assisted binary searching method in [33], which solves the following maximization problem:
$$\max_{\varepsilon_k} U_{o,t}\left(p_{o,t}^{(k)} + \varepsilon_k d^{(k)}\right). \tag{46}$$
10: Update the L2U data rate price of the LEO satellite by $p_{o,t}^{(k+1)} := p_{o,t}^{(k)} + \varepsilon_k^* d^{(k)}$.
11: Let $k := k + 1$.
12: **until** $||p_{o,t}^{(k)} - p_{o,t}^{(k-1)}|| \leq \epsilon$, and then $p_{o,t}^* := p_{o,t}^{(k)}$.
13: Calculate the L2U data rate request of each UAV (i.e., $r_{j,t}$) according to $p_{o,t}^*$.
14: **if** $\sum_{j=1}^{J} r_{j,t} > R_o$ **then**
15: Let $k = 1$ and $p_{o,t}^{(k)} := p_{o,t}^* + \varpi(\sum_{j=1}^{J} r_{j,t} - R_o)$.
16: **for** $|| \sum_{j=1}^{J} r_{j,t} - R_o|| > \epsilon$ **do**
17: Search for optimal step size ϖ^* by gradient assisted binary searching method.
18: Calculate $r_{j,t}$ for each UAV based on $p_{o,t}^{(k)}$.
19: $p_{o,t}^{(k+1)} := p_{o,t}^{(k)} + \varpi^*(\sum_{j=1}^{J} r_{j,t} - R_o)$.
20: **end for**
21: The optimal L2U data rate price of the LEO satellite in the t-th time slot is $p_{o,t}^* := p_{o,t}^{(k)}$.
22: **end if**

***Proposition** 3:* The Stackelberg equilibrium of game $\mathbb{G}$ for wireless data rate provisioning among LEO satellite, UAVs and USVs, formulated in P1, P2 and P3 is $\left(p_{o,t}^*, \boldsymbol{\pi}_t^*, \mathbf{q}_t^*\right)$, where $p_{o,t}^*$ is obtained by Algorithm 1, elements of $\boldsymbol{\pi}_t^*$ (i.e., $r_{j,t}^*$ and $p_{j,t}^*$) are respectively given by (34) and (42), and each element of $\mathbf{q}_t^*$ (i.e., $q_{i,j,t}^*$) is given by (21).

Proof: When the LEO satellite broadcasts L2U data rate price $p_{o,t}$, each UAV responds with L2U data rate request $r_{j,t}^*$ which is given by (42). According to Theorem

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5, we know that $r^*_{j,t}$ is the optimal strategy on L2U data rate request of each UAV. As a result, for $\forall r_{j,t} \geq 0$, we have $U_{j,t}(r^*_{j,t}) \geq U_{j,t}(r_{j,t})$. Furthermore, with a ceratin $r_{j,t}$, the indicator function of each USV can be determined and each UAV's utility is concave with respect to $p_{j,t}$. As such, each UAV can always find the optimal $p^*_{j,t}$, i.e., for $\forall p_{j,t} \geq 0$, $U_{j,t}(p^*_{j,t}) \geq U_{j,t}(p_{j,t})$. Besides, given the optimal U2U data rate price of each UAV (i.e., $p^*_{j,t}$), according to Theorem 1, each USV responds the optimal U2U data rate request $\mathbf{q}^*_{i,t}$, so that $\forall q_{i,j,t} \geq 0, U_{i,t}(\mathbf{q}^*_{i,t}) \geq U_{i,t}(\mathbf{q}_{i,t})$. In addition, when R_o is determined, the LEO satellite can find optimal L2U data rate selling price $p^*_{o,t}$ by Algorithm 1, whereby $\forall p_{o,t} \geq 0$, $U_{o,t}(p^*_{o,t}) \geq U_{o,t}(p_{o,t})$. Therefore, according to Definition 1, $\left(p^*_{o,t}, \boldsymbol{\pi}^*_t, \mathbf{q}^*_t\right)$ is the Stackelberg equilibrium of game $\mathbb{G}$. ■

E. Convergence and Complexity Analysis

According to Lemma 1, the utility of the LEO satellite is concave, which guarantees the global convergence of Algorithm 1 [33]. Specifically, we first assume that the initial price is smaller than the optimal L2U data rate price, i.e., $p^{(0)}_{o,t} \leq p^*_{o,t}$. As such, searching direction $d^{(k)}$ is larger than zero at first. Besides, the optimal step size ε^*_k is obtained by maximizing the utility of the LEO satellite at this searching direction. Since the L2U data rate price $p_{o,t}$ is updated by $p^{(k+1)}_{o,t} = p^{(k)}_{o,t} + \varepsilon^*_k d^{(k)}$, the L2U data rate price $p_{o,t}$ increases and is close to $p^*_{o,t}$. Then, based on $d^{(k)} = \nabla U_{o,t}\left(p^{(k)}_{o,t}\right) + \beta_{k-1} d^{(k-1)}$, the searching direction $d^{(k)}$ gradually decreases with each iteration. When $d^{(k)}$ reaches to zero, the L2U data rate price $p_{o,t}$ no longer changes and converse to $p^*_{o,t}$. Then, if $p^{(0)}_{o,t} \geq p^*_{o,t}$, searching direction $d^{(k)}$ is smaller than zero at first. According to $p^{(k+1)}_{o,t} = p^{(k)}_{o,t} + \varepsilon^*_k d^{(k)}$, the L2U data rate price $p_{o,t}$ decreases and is close to $p^*_{o,t}$. Then, based on $d^{(k)} = \nabla U_{o,t}\left(p^{(k)}_{o,t}\right) + \beta_{k-1} d^{(k-1)}$, the searching direction $d^{(k)}$ gradually increase with each iteration. When $d^{(k)}$ reaches to zero, the L2U data rate price $p_{o,t}$ converse to $p^*_{o,t}$.

The complexity analysis of Algorithm 1 comes from three aspects. The first aspect is from the searching for the optimal L2U data rate price (step 2-12). The second aspect is from the obtaining the optimal step seize ε^*_k (step 9). The third aspect is from re-reaching the optimal L2U data rate price when $\sum_{j=1}^{J} r_{j,t} > R_o$ (step 14-22). Let L_1, L_2, and L_3 denote the number of iterations required above three aspects. Thus, according to [15], the total complexity of Algorithm 1 is $\mathcal{O}(L_1 \times L_2 + L_3)$, where $\mathcal{O}$ is the big-O notation.

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
ϑ	2	$P_{i,j',t}$	0
c_o	0.01	c_j	0.001
T	50	δ	0.05
ϵ	0.0001	Λ	0.8
$\rho_{i,j',t}$	0	Ψ_0	1.42×10^{-4}
λ	20	ϑ_i	0.01

VI. PERFORMANCE EVALUATION

In this section, we conduct the simulations of the proposed scheme. We first introduce the simulation setup and then the experiment results are discussed in detail.

A. Simulation Setup

We consider an SAOIN scenario in a 1000 m $\times$ 1000 m area. The number of the LEO satellite is one. The flying height of each UAV is fixed at 100m, whose communication radius is 300 m. The maximal flying velocity of each UAV is 10m/s . The forwarding speed of each USV is randomly in $[0, 10]$m/s, whereas the sway speed is 0. The yaw rate of the USV is uniformly distributed in $[-20, 20]$ deg/s [28]. The altitude of LEO satellite is 200km. The spectrum bandwidth of each UAV is randomly in [1,10] MHz, and that of the LEO satellite is randomly in [10,20] MHz. The noise power density is -174 dbm/Hz. The finite time horizon is 2 s, which is divided into $T = 50$ time slots, each with the equal length $\delta = 0.04$ s [15]. The channel gain of the UAV is 1.42×10^{-4} at the unit reference distance [15]. The maximum transmission power of the LEO satellite is 20 W and that of each UAV is 1W. The demand degree of each USV is randomly in [0.6, 1]. The dissatisfactory degree of each USV follows the uniform distribution in [0.1, 0.5]. The data rate demand of each USV in a time slot is randomly in [0.3,1.5] Mbps. The data rate demand degree (i.e., $\widetilde{\varrho}_{i,t}$) of each USV in a time slot is randomly in [0.6, 1]. To avoid collision, the shortest distance between adjacent UAVs is 100 and that between two USVs is 10. Each USV can be covered by multiple UAV, while only connecting to the nearest UAV. According to [15], [29], [34], other parameters in simulations are summarized in Table II. Here, the LEO satellite (or UAVs) adopts bandwidth uniform division and power on-demand allocation mode to provide data rates for UAVs (or USVs).

Based on above conditions, we also compare the proposed scheme with following benchmark schemes to show its superiority.

- *Uniform scheme [35]*: The LEO satellite provides its L2U data rate evenly to connected UAVs in

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a time slot. Each UAV then uniformly distributes owned U2U data rate to USVs within its coverage, where the U2U data rate cannot exceed the acquired L2U data rate from the LEO satellite.

- *Max-min scheme [36]*: The LEO satellite assigns its L2U data rate with the fair max-min algorithm, based on L2U data rate request of each UAV. Meanwhile, the assignment of U2U data rate from each UAV to connected USVs also adopts fair max-min algorithm.
- *Greedy scheme [37]*: The L2U data rate is assigned to the UAV with the highest demand, and the U2U data rate of each UAV is also assigned to the USV with the highest demand within its coverage. Besides, both the L2U data rate price and U2U data rate price are randomly determined.

B. *Simulation Results*

In this subsection, we first evaluate the convergence of ACGD based iteration algorithm, shown in Fig. 2, where the L2U data rate price of the LEO satellite varies with the iteration steps. From Fig. 2(a), it can be observed that the L2U data rate price converges to a unique stable value regardless of the initial L2U data rate price. The reason is that the utility of the LEO satellite is a concave function with respect to the L2U data rate price, whereby the L2U data rate price no longer changes when the gradient becomes zero. Fig. 2(b) shows the convergence with different dissatisfaction degrees. From Fig. 2(b), it can be seen that all L2U data rate prices converge to stable values. Besides, the L2U data rate price converges fast while the stable value is low when the dissatisfaction degree is large. This is because the USV with a large dissatisfaction degree requires a small U2U data rate from connected UAV, inducing that the amount of L2U data rate requested by the UAV is also small. As such, the LEO satellite selects the low L2U data rate price to motivate UAVs to request L2U data rate. From Fig. 2(c), we can observe that the L2U data rate price slowly converges to a high stable value when the demand degree of each USV is large. The reason is the USVs with high data rate demand degrees request large U2U data rates from connected UAVs which also require corresponding L2U data rates from the LEO satellite. Hereby, the LEO satellite increases its L2U data rate price to obtain a high utility. To sum up, Fig. 2 demonstrates that the L2U data rate price converges to the optimal by ACGD based iteration algorithm.

We then evaluate the proposed scheme on the interplays of USVs, UAVs, and LEO satellite, as shown in Fig. 3. Here, the number of UAVs is set to be 1 and the number of USVs is set to be 50. Wherein, Fig. 3(a) shows the total U2U data rate request of UAVs with U2U data rate price of UAV. Fig. 3(b) shows the evolution on U2U data rate price of UAV with L2U data rate request of UAV and Fig. 3(c) is the L2U data rate request of UAV with the L2U data rate price of the LEO satellite. From 3(a), it can be observed that the total U2U data rate request of USVs decreases with the increase of the U2U data rate price. Besides, if the U2U data rate price is fixed, the total U2U data rate request is large when the demand degree of each USV is high. Especially, when the demand degree is higher, more USVs request for the U2U data rates with the same U2U data rate price. From Fig. 3(b), it can be seen that the U2U data rate price decreases with the increase of L2U data rate request. In addition, the large demand degrees of UAVs make a large U2U data rate price. Especially, when the demand degree of each USV is large, more USVs can obtain the positive U2U data rates. From Fig. 3(c), we can observe that the L2U data rate request of UAV decreases with the increase of the L2U data rate price. Moreover, the decrease speed of L2U data rate request is slow when the demand degree of each USV is large. To sum up, Fig. 3 demonstrates that the strategies of USVs, UAVs, and LEO satellite have significant influences with each other.

Fig. 4. shows the impact of time-varying data rate demand degree on the network performance. Here, the time horizon contains 50 time slots, and the length of each time slot is 0.04 s. The number of USVs is set to be 50 and the number of UAVs is set to be 7. The data rate demand degree changes by $\widetilde{\varrho}_{i,t} = \widetilde{\varrho}_{i,t} + \varsigma$ every 4 time slots. The initial data rate demand degree of each USV is 0.7. Fig. 4(a) shows the changes on average U2U data rate request of USVs over time, Fig. 4(b) shows the changes on average U2U data rate price of UAVs with the change of time slots over time, Fig. 4(c) shows the changes on the total utility of USVs over time. From Fig. 4(a), when the data rate demand degree increases over time, i.e., $\varsigma > 0$, the U2U data rate request decreases with the evolution of time. Oppositely, the U2U data rate request increases over time, when the data rate demand degree decreases, i.e., $\varsigma < 0$. This is because each USV can obtain large satisfaction with a high data rate demand degree, whereby the mobile user requests a small U2U data rate to reduce the payment to the connected UAV. From Fig. 4(b), the U2U data rate price increases over time, when the data rate demand degree becomes larger and larger. Since the U2U data rate request of each USV becomes small when the demand degree is large, the connected UAV increases the U2U data rate price to gain profit. From Fig. 4(c), the total utility of USVs over time, when the data rate demand degree increases, i.e., $\varsigma > 0$. As the higher data rate demand degree poses to the larger satisfaction of the USV, though the U2U data rate price increases, the utility of each USV, i.e., the difference between satisfaction and payment, also becomes larger.

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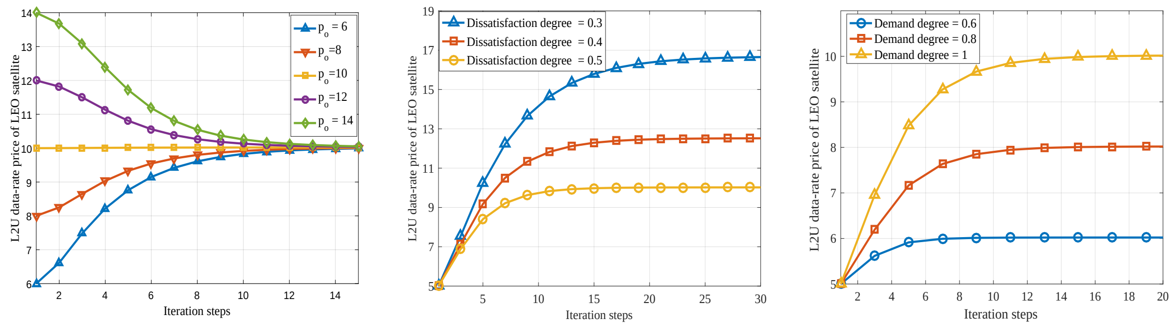
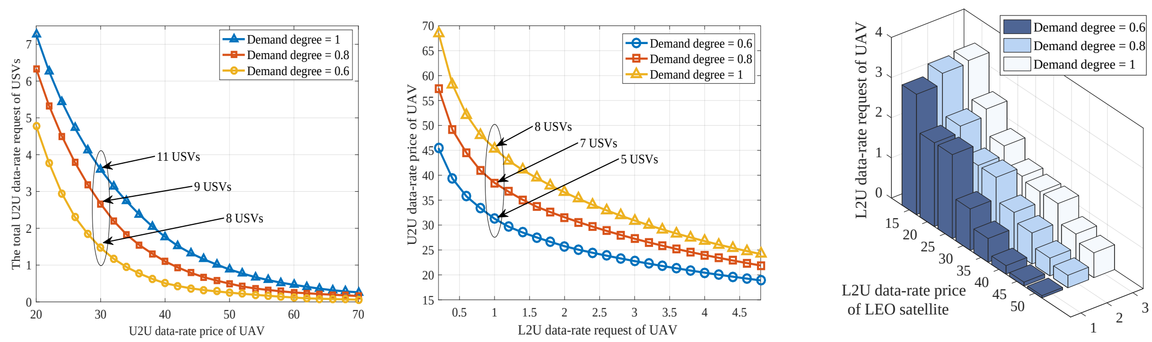


(a) (b) (c)

Fig. 2. The convergence of ACGD based iteration algorithm. (a) The convergence with different initial L2U data rate prices. (b) The convergence with different dissatisfaction degrees. (c) The convergence with difference demand degrees.



(a) (b) (c)

Fig. 3. Interplays among strategies of USVs, UAVs and LEO satellite. (a) The total utility U2U data rate request of USVs vs. U2U data rate price of UAV. (b) U2U data rate price of UAV vs. L2U data rate request of UAV. (c) L2U data rate request of UAV vs. L2U data rate price of the LEO satellite.

We last carry out the comparison of the proposed scheme with three benchmark schemes, which is shown in Fig. 5. Wherein, Fig. 5(a) shows the comparison on the total utility of USVs with the number of USVs. Fig. 4(b) shows the comparison on the total utility of USVs with the number of UAVs. Fig. 5(c) shows the comparison on the total utility of USVs with the L2U data rate budget of the LEO satellite. From Fig 5(a)-(c), we can observe that the total utility of USVs in the proposed scheme is larger than those in other three benchmark schemes. Especially, from Fig. 5(c), the total utility of USVs increases to be stable with the L2U data rate budget in the proposed scheme, while the total utilities gradually decrease after reaching the maximum values in uniform scheme, max-min based scheme, and greedy scheme. This can be explained as follows. In uniform scheme, the U2U data rate is evenly assigned to USVs from the connected UAVs, whereby USVs cannot obtain the optimal U2U data rate to maximize their utility. In max-min based scheme, the U2U data rate is only assigned based on demands of USVs, where the U2U data price is not taken into account. In greedy scheme, since L2U data rate and U2U data rate are respectively assigned to UAVs and USVs with large data rate demands, the UAVs or USVs with small data rate demands may not obtain the data rate. In the proposed scheme, the maximum utilities of USVs are obtained by the three-stage Stackelberg game, where each party makes the optimal strategy.

VII. Conclusion

In this paper, we have proposed hierarchical wireless data rate provisioning in SAOINs to support ubiquitous transmission services for USVs. Specifically, the data rate provisioning problem among the LEO satellite, UAVs and USVs has been formulated as a modified three-stage Stackelberg game. Wherein, the utility of each USV has been designed based on the individual time-varying demand degree on the wireless data rate and unsatisfactory degree on the quality of wireless transmission service. We have then employed the backward induction approach to attain the Stackelberg equilibrium as the solution of the formulated problem, where the closed-form expressions on the optimal strategies of both USVs and UAVs under different data

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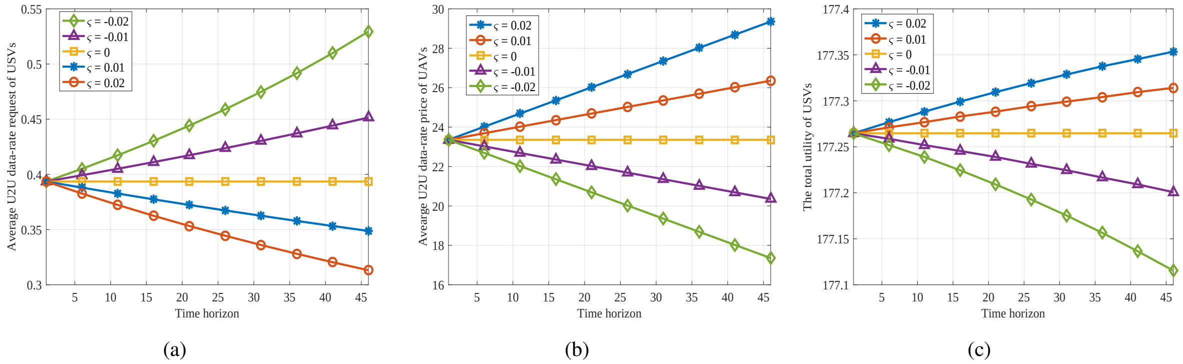

Fig. 4. The impact of time-varying data rate demand degree. (a) Average U2U data rate request of USVs vs. time horizon. (b) Average U2U data rate price of UAVs vs. time horizon. (c) The total utility of USVs vs. time horizon.

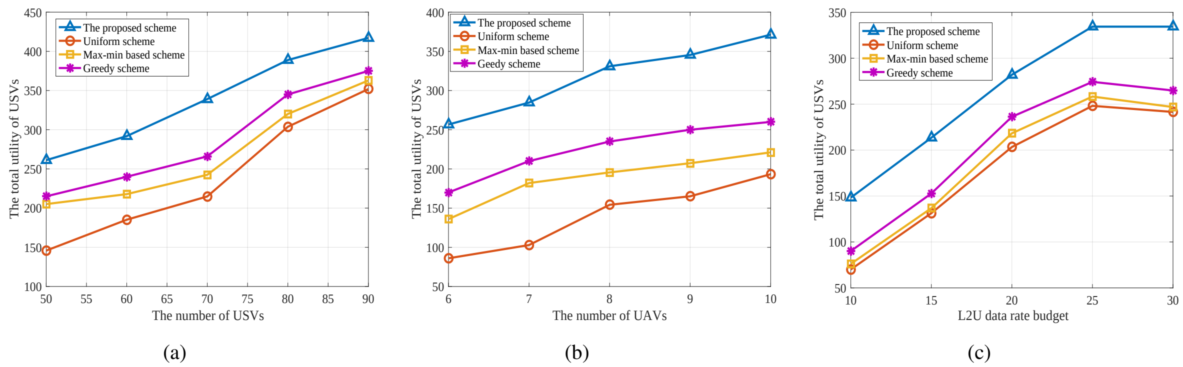

Fig. 5. Comparison of the proposed scheme with uniform scheme, max-min based scheme and greedy scheme. (a) Comparison on the total utility of USVs with changes in number of USVs. (b) Comparison on the total utility of USVs with changes in number of UAVs. (c) Comparison on the total utility of USVs with changes in L2U data rate budget.

rate budgets are obtained by the nonlinear programming method. Besides, an ACGD based iteration algorithm has been designed to obtain the optimal strategies of LEO satellites on the L2U data rate prices. Finally, extensive simulations have been conducted to demonstrate that the proposed scheme outperforms other benchmark schemes. For the future work, we will study the security preservation during wireless data rate provisioning in SAOINs.

Appendix A
Proof of Theorem 2

As P2-1(I) is a convex optimization problem, the solution that follows the Karush-Kuhn-Tucher (KKT) conditions is the optimal result. The Lagrangian function is written by

$$\begin{aligned}\mathfrak{L}\left(p_{j,t}\right) = &\left(p_{j,t}-c_j\right)\sum_{m=1}^{M}\left(\frac{\lambda}{p_{j,t}}-\frac{1}{\alpha_{m,t}}\right)-p_{o,t}r_{j,t}\\ &+\tau\left(r_{j,t}-\sum_{m=1}^{M}\left(\frac{\lambda}{p_{j,t}}-\frac{1}{\alpha_{m,t}}\right)\right)\\ &+\omega(p_{j,t}-p_{o,t}-c_j)+\upsilon\left(\lambda\alpha_{1,t}-p_{M,t}\right),\end{aligned} \tag{48}$$

where τ, ω and υ are non-negative Lagrangian coefficients associated with the constraints C1, C2, C3, respectively. The KKT conditions are given by

$$\begin{cases}\mathrm{K1}: \frac{\partial\mathfrak{L}(p_{j,t})}{\partial p_{j,t}}=0\\ \mathrm{K2}: \tau\left(r_{j,t}-\sum_{m=1}^{M}\left(\frac{\lambda}{p_{j,t}}-\frac{1}{\alpha_{m,t}}\right)\right)=0\\ \mathrm{K3}: \omega(p_{j,t}-p_{o,t}-c_j)=0\\ \mathrm{K4}: \zeta\left(\lambda\alpha_{M,j,t}-p_{j,t}\right)=0\\ \mathrm{K5}: \omega\geq 0; \zeta\geq 0; \tau\geq 0\\ \mathrm{K6}: \mathrm{C1, C2, C3}\end{cases} \tag{49}$$

Based on the features of ω, $\zeta$and τ, we consider four cases.

Case 1: Suppose $\omega=0$, $\zeta=0$ and $\tau=0$. According to (48), the U2U data rate price of UAV j in the t-th time slot is obtained by

$$p_{j,t}^{*}=\sqrt{M\lambda c_j/\sum_{m=1}^{M}\left(\alpha_{m,t}\right)^{-1}} \tag{50}$$

Substituting (50) into condition C1, the total U2U data

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rate of UAV j should satisfy

$$r_{j,t} \geq \sqrt{\frac{M\lambda}{c_j}\sum_{m=1}^{M}\frac{1}{\alpha_{m,t}}} - \sum_{m=1}^{M}\frac{1}{\alpha_{m,t}} \tag{51}$$

According to C2 and C3, the optimal U2U data rate price should respectively meet $p_{j,t}^* \geq c_j + p_{o,t}$, and $p_{j,t}^* \leq \lambda\alpha_{M,j,t}$.

Case 2: Suppose $\omega = 0$, $\zeta = 0$ and $\tau \neq 0$. According to K2, it follows that $r_{j,t} - \sum_{m=1}^{M}\left(\frac{\lambda}{p_{j,t}} - \frac{1}{\alpha_{m,t}}\right) = 0$. The optimal U2U data rate price is then given by $p_{j,t}^* = \frac{M\lambda}{r_{j,t}+\sum_{m=1}^{M}(\alpha_{m,t})^{-1}}$. From K1, we have $-\phi_{j,M,t} + \frac{\lambda M c_j}{(p_{j,t}^*)^2} + \tau\frac{\lambda M}{(p_{j,t}^*)^2} = 0$. As $\tau > 0$, $p_{j,t}^*$ should satisfy $r_{j,t} < \frac{\lambda M}{\sqrt{\frac{\lambda M c_j}{\phi_{j,M,t}}}} - \phi_{j,M,t}$. To make $p_{j,t}^*$ satisfy C2 and C3, $r_{j,t}$ should meet $r_{j,t} \leq \frac{\lambda M}{p_{o,t}+c_j} - \phi_{j,M,t}$, and $r_{j,t} \geq \frac{\lambda M}{\lambda\alpha_{M,t}} - \phi_{j,M,t}$.

Case 3: Suppose $\omega \neq 0$, $\zeta = 0$ and $\tau = 0$. According to K3, it follows that $p_{j,t}^* = p_{o,t} + c_j$. From K1, we have $p_{j,t}^* > \sqrt{\frac{M\lambda c_j}{\phi_{j,M,t}}}$. According C1 and C3, $p_{j,t}^*$ should satisfy $r_{j,t} \geq \frac{\lambda M}{p_{o,t}+c_j} - \phi_{j,M,t}$, and $p_{j,t}^* \leq \lambda\alpha_{M,t}$.

Case 4: Suppose $\omega = 0$, $\zeta \neq 0$ and $\tau = 0$. Based on K4, the optimal U2U data rate price is $p_{j,t}^* = \lambda\alpha_{M,j,t}$. From K1, as the first derivative of Lagrangian function with respect to $p_{j,t}$ equals to zero, $p_{j,t}^*$ should satisfy $p_{j,t}^* < \sqrt{\frac{M\lambda c_j}{\phi_{j,M,t}}}$. According C1 and C3, we have $r_{j,t} \geq \frac{\lambda M}{\lambda\alpha_{M,t}} - \phi_{j,M,t}$, and $c_j + p_{o,t} \leq p_{j,t}^*$.

Besides, when two or three of ω, ζ, and τ simultaneously equal to zero, it's just that the equal signs hold in above inequalities. This completes our proof.

Appendix B
Proof of Proposition 1

Firstly, we consider the "if" part. If $r_{j,t} \geq L_2^M$, all the indicator functions can be equal to 1. As such, from the proof of Theorem 2, it is observed that the U2U data rate price given by Theorem 2 is the optimal solution of P2-1 when all the indicator functions are equal to 1. Thus the "if" part is proved.

Next, we consider the "only if" part. Here, we use contradiction to show the proof. We assume that $L_2^{M-1} \leq r_{j,t} < L_2^M$. In this case, all USVs within the coverage of UAV j can obtain U2U data rate. As such, it is undoubted that the total amount of U2U data rate request is larger than $r_{j,t}$, which is contradict to the preassumption. This completes our proof.

Appendix C
Proof of Theorem 3

When $L_2^{\widetilde{M}+1} > r_{j,t} \geq L_2^{\widetilde{M}}$, the utility of UAV j in the t-th time slot is expanded as

$$U_{j,t}\left(Q_z^{\widetilde{M}}, r_{j,t}\right) = \left(Q_z^{\widetilde{M}} - c_j\right)\sum_{m=1}^{\widetilde{M}}\left(\frac{\lambda}{Q_z^{\widetilde{M}}} - \frac{1}{\alpha_{m,t}}\right) - p_{o,t}r_{j,t},$$
$$z = \begin{cases} 1, \text{ if } r_{j,t} \geq L_1^{\widetilde{M}} \text{ and } Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}, \\ 2, \text{ if } r_{j,t} \geq L_2^{\widetilde{M}} \text{ and } Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}} \leq Q_1^{\widetilde{M}}, \\ 3, \text{ if } r_{j,t} \geq L_3^{\widetilde{M}} \text{ and } Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}, \\ 4, \text{ if } L_2^{\widetilde{M}} \leq r_{j,t} \leq \min\left\{L_1^{\widetilde{M}}, L_3^{\widetilde{M}}\right\}. \end{cases} \tag{52}$$

According to expanded utility of UAV j, we consider following three cases.

Case 1: $Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}$. First, if $r_{j,t} \geq L_1^{\widetilde{M}}$, according to (52), $z = 1$ and the utility of UAV j in the t-time slot is expressed as

$$U_{j,t}\left(Q_1^{\widetilde{M}}, r_{j,t}\right) = \left(\sqrt{\frac{\lambda\widetilde{M}c_j}{\phi_{j,\widetilde{M},t}}} - c_j\right)\sum_{m=1}^{\widetilde{M}}\left(\sqrt{\frac{\lambda\phi_{j,\widetilde{M},t}}{Mc_j}} - \frac{1}{\alpha_m, t}\right) - p_{o,t}r_{j,t}. \tag{53}$$

Apparently, $U_{j,t}\left(Q_1^{\widetilde{M}}, r_{j,t}\right)$ has the negative relationship with the L2U data rate request of UAV j, i.e., $U_{j,t}\left(Q_1^{\widetilde{M}}, r_{j,t}\right) \propto \frac{1}{r_{j,t}}$. As such, if $r_{j,t} \geq L_1^{\widetilde{M}}$, the optimal L2U data rate request of UAV j is $r_{j,t}^*\Big|_{r_{j,t}\geq L_1^{\widetilde{M}}}^{Q_3^{\widetilde{M}}\leq Q_1^{\widetilde{M}}\leq Q_2^{\widetilde{M}}} = L_1^{\widetilde{M}}$. Then, if $L_2^{\widetilde{M}} \leq r_{j,t} < L_1^{\widetilde{M}}$, according to (1), $z = 4$ and the utility of UAV j in the t-th time slot is

$$\begin{aligned} &U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right) \\ &= \left(\frac{\lambda\widetilde{M}}{r_{j,t} + \phi_{j,\widetilde{M},t}} - c_j\right) \\ &\quad \times \sum_{m=1}^{\widetilde{M}}\left(\frac{r_{j,t} + \phi_{j,\widetilde{M},t}}{\widetilde{M}} - \frac{1}{\alpha_{m,t}}\right) - p_{o,t}r_{j,t}. \end{aligned} \tag{54}$$

The first derivative of $U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right)$ with respect to $r_{j,t}$ is

$$\frac{\partial U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right)}{\partial r_{j,t}} = \frac{\lambda\widetilde{M}\phi_{j,\widetilde{M},t}}{\left(r_{j,t} + \phi_{j,\widetilde{M},t}\right)^2} - c_j - p_{o,t}. \tag{55}$$

Besides, the second derivative of $U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right)$ with

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respect to $r_{j,t}$ is

$$\frac{\partial^2 U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right)}{\partial {r_{j,t}}^2} = -\frac{2\lambda \widetilde{M} \phi_{j,M,t}}{\left(r_{j,t} + \phi_{j,\widetilde{M},t}\right)^3}. \tag{56}$$

As $\lambda \widetilde{M} \phi_{j,M,t} > 0$, the second derivative of $U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right)$ is smaller than zero, such that $U_{j,t}\left(Q_4^{\widetilde{M}}, r_{j,t}\right)$ is a strictly concave function. As such, through the analysis based on KKT approach [38], if $L_2^{\widetilde{M}} \leq r_{j,t} < L_1^{\widetilde{M}}$, the optimal L2U data rate request of UAV j is given by

$$r_{j,t}^{*}\Big|_{L_2^{\widetilde{M}} \leq r_{j,t} < L_1^{\widetilde{M}}}^{Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}} = \begin{cases} \sqrt{\frac{\lambda \widetilde{M} \phi_{j,\widetilde{M},t}}{c_j + p_{o,t}}} - \phi_{j,\widetilde{M},t}, \\ \text{if } p_{o,t} \leq \frac{\lambda \alpha_{\widetilde{M},t}^2}{M} \phi_{j,\widetilde{M},t}, \\ L_2^{\widetilde{M}}, \text{ otherwise.} \end{cases} \tag{57}$$

Since $U_{j,t}\left(Q_1^{M}, r_{j,t}^{*}\Big|_{r_{j,t} \geq L_1^{\widetilde{M}}}^{Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right)$ with $U_{j,t}\left(Q_4^{M}, r_{j,t}^{*}\Big|_{L_2^{\widetilde{M}} \leq r_{j,t} < L_1^{\widetilde{M}}}^{Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right)$, we have

$$\begin{aligned} & U_{j,t}\left(Q_4^{M}, r_{j,t}^{*}\Big|_{L_2^{\widetilde{M}} \leq r_{j,t} < L_1^{\widetilde{M}}}^{Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right) \\ & \geq U_{j,t}\left(Q_1^{M}, r_{j,t}^{*}\Big|_{r_{j,t} \geq L_1^{\widetilde{M}}}^{Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right). \end{aligned} \tag{58}$$

Thus, when $Q_3^{\widetilde{M}} \leq Q_1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}$, the optimal L2U data rate request of UAV is

$$r_{j,t}^{M^*} = \begin{cases} \sqrt{\frac{\lambda \widetilde{M} \phi_{j,\widetilde{M},t}}{c_j + p_{o,t}}} - \phi_{j,\widetilde{M},t}, \text{ if } W_1, \\ \frac{\widetilde{M}}{\alpha_{\widetilde{M},t}} - \phi_{j,\widetilde{M},t}, \text{ if } W_3. \end{cases} \tag{59}$$

Case 2: $Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}} \leq Q_1^{\widetilde{M}}$. As $L_2^{\widetilde{M}+1} \geq r_{j,t} \geq L_2^{\widetilde{M}}$, according to (52), $z = 2$ and the utility of UAV j in the t-th time slot is

$$\begin{aligned} U_{j,t}\left(Q_2^{\widetilde{M}}, r_{j,t}\right) = & \left(\lambda \alpha_{\widetilde{M},t} - c_j\right) \sum_{m=1}^{\widetilde{M}} \left(\frac{1}{\alpha_{\widetilde{M},t}} - \frac{1}{\alpha_{m,t}}\right) \\ & - p_{o,t} r_{j,t} \end{aligned} \tag{60}$$

The utility of UAV j is also negatively related to $r_{j,t}$. Thus, when $Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}} \leq Q_1^{\widetilde{M}}$, the optimal L2U data rate request is

$$r_{j,t}^{\widetilde{M}^*} = \frac{\widetilde{M}}{\alpha_{\widetilde{M},t}} - \phi_{j,\widetilde{M},t}, \text{ if } W_4. \tag{61}$$

Case 3: $Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}$. First, if $r_{j,t} \geq L_3^{\widetilde{M}}$, according to (52), $z = 3$ and the utility of UAV j in the t-th time slot is

$$\begin{aligned} U_{j,t}\left(Q_3^{\widetilde{M}}, r_{j,t}\right) = & p_{o,t} \sum_{m=1}^{\widetilde{M}} \left(\frac{\lambda}{c_j + p_{o,t}} - \frac{1}{\alpha_{m,t}}\right) \\ & - p_{o,t} r_{j,t}. \end{aligned} \tag{62}$$

Similarly, it is also negatively related to $r_{j,t}$. As such, if $r_{j,t} \geq L_3^{\widetilde{M}}$, the optimal L2U data rate request is $r_{j,t}^{*}\Big|_{r_{j,t} \geq L_3^{\widetilde{M}}}^{Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}} = L_3^{\widetilde{M}}$. Then, if $L_2^{\widetilde{M}} \leq r_{j,t} < L_3^{\widetilde{M}}$, according to (52), $z = 4$ and the utility of UAV j in the t-th time slot is same to (54). As such, through the analysis based on KKT approach [38], if $L_2^{\widetilde{M}} \leq r_{j,t} < L_3^{\widetilde{M}}$, the optimal L2U data rate request of UAV j is given by

$$\begin{aligned} & r_{j,t}^{*}\Big|_{L_2^{\widetilde{M}} \leq r_{j,t} < L_3^{\widetilde{M}}}^{Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}} \\ & = \begin{cases} \sqrt{\frac{\lambda \widetilde{M} \phi_{j,\widetilde{M},t}}{c_j + p_{o,t}}} - \phi_{j,\widetilde{M},t}, \\ \text{if } p_{o,t} < \frac{\lambda \alpha_{\widetilde{M},t}^2 \phi_{j,\widetilde{M},t}}{\widetilde{M}} - c_j, \\ L_2^{\widetilde{M}}, \\ \text{if } \frac{\lambda \alpha_{\widetilde{M},t}^2 \phi_{j,\widetilde{M},t}}{\widetilde{M}} - c_j \leq p_{o,t} < \frac{\lambda \widetilde{M}}{\phi_{j,\widetilde{M},t}} - c_j. \end{cases} \end{aligned} \tag{63}$$

By comparing $U_{j,t}\left(Q_3^{M}, r_{j,t}^{*}\Big|_{r_{j,t} \geq L_3^{\widetilde{M}}}^{Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right)$ with $U_{j,t}\left(Q_4^{M}, r_{j,t}^{*}\Big|_{L_2^{\widetilde{M}} \leq r_{j,t} \leq L_3^{\widetilde{M}}}^{Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right)$, we have

$$\begin{aligned} & U_{j,t}\left(Q_4^{M}, r_{j,t}^{*}\Big|_{L_2^{\widetilde{M}} \leq r_{j,t} < L_3^{\widetilde{M}}}^{Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right) \\ & \geq U_{j,t}\left(Q_3^{M}, r_{j,t}^{*}\Big|_{r_{j,t} \geq L_3^{\widetilde{M}}}^{Q_1^{\widetilde{M}} \leq Q_3^{\widetilde{M}} \leq Q_2^{\widetilde{M}}}\right). \end{aligned} \tag{64}$$

Thus, when $Q_3^{\widetilde{M}} \leq Q1^{\widetilde{M}} \leq Q_2^{\widetilde{M}}$, the optimal L2U data rate request of UAV is

$$r_{j,t}^{\widetilde{M}^*} = \begin{cases} \sqrt{\frac{\lambda \widetilde{M} \phi_{j,\widetilde{M},t}}{c_j + p_{o,t}}} - \phi_{j,\widetilde{M},t}, \text{ if } W_2, \\ \frac{\widetilde{M}}{\alpha_{\widetilde{M},t}} - \phi_{j,\widetilde{M},t}, \text{ if } W_5. \end{cases} \tag{65}$$

Therefore, based on Case 1, Case 2, and Case 3, Theorem 4 is proved.

APPENDIX D
PROOF OF PROPOSITION 2

We first prove the "if" part. If $p_{o,t} \leq \lambda \alpha_{\widetilde{M},t} - c_j$, the U2U data rate price determined by UAV j can follow $p_{o,t} + c_j \leq p_{j,t} \leq \lambda \alpha_{\widetilde{M},t}$. According to analysis in Sec. V-B, indicator function can be equal to 1. Since the amount of requested U2U data rate by covered USVs cannot exceed the requested L2U data rate from the LEO satellite (refer to the condition in P2), the requested L2U data rate of UAV j should meet $r_{j,t} \geq L_2^{\widetilde{M}}$. As such, from the proof of Theorem 4, it is observed that the

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L2U data rate price given by Theorem 4 is the optimal solution of P2-2 when $r_{j,t} \geq L_2^{\widetilde{M}}$. Thus, the "if" part is proved.

Then, we use the contradiction to prove "only if part. We assume that when $\lambda\alpha_{\widetilde{M},t} - c_j < p_{o,t} \leq \lambda\alpha_{\widetilde{M}-1,t} - c_j$, the optimal L2U data rate request given by Theorem 4 is the optimal solution of P2-2. In this case, since $r_{j,t} \geq L_2^{\widetilde{M}}$, according to Theorem 3, the optimal U2U data rate price of UAV j is $p_{j,t}^* = p_{j,t}^{\widetilde{M}^*}$, where $p_{o,t} + c_j \leq p_{j,t}^{\widetilde{M}^*} \leq \lambda\alpha_{\widetilde{M},t}$. As such, the L2U data rate price should meet $p_{o,t} + c_j \leq \lambda\alpha_{\widetilde{M},t}$, which is contradict to the preassumption. Thus, the "only if" part is proved.

Therefore, combining the proofs of "if" part and "only if" part, Proposition 2 is proved.

Appendix E
Proof of Lemma 1

The first derivate of $U_{o,t}$ with respect to $p_{o,t}$ is

$$\begin{aligned} &\frac{\partial U_{o,t}\left(p_{o,t}\right)}{\partial p_{o,t}} \\ &= \sum_{j=1}^{F}\left(\sqrt{\frac{\lambda\widetilde{M}_j\phi_{j,M,t}}{c_j+p_{o,t}}} - \phi_{j,\widetilde{M}_j,t}\right) \\ &\quad - \left(p_{o,t}+c_j\right)\frac{1}{2}\sum_{j=1}^{F}\left(\left(c_j+p_{o,t}\right)^{-\frac{3}{2}}\sqrt{\lambda\widetilde{M}_j\phi_{j,M,t}}\right). \end{aligned} \tag{66}$$

The second derivate of $U_{o,t}$ with respect to $p_{o,t}$ is

$$\frac{\partial^2 U_{o,t}\left(p_{o,t}\right)}{\partial p_{o,t}^2} = -\frac{3}{4}\sum_{j=1}^{F}\left(\sqrt{\lambda\widetilde{M}_j\phi_{j,M,t}}\right). \tag{67}$$

Since the second derivate of $U_{o,t}(p_{o,t})$ is smaller than zero, $U_{o,t}(p_{o,t})$ is a strictly concave function with respect to $p_{o,t}$. This competes our proof.

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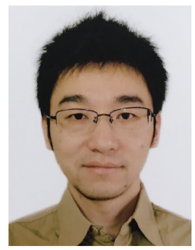
Qichao Xu received Ph.D degree from the school of Mechatronic Engineering and Automation of Shanghai University, Shanghai, P. R. China, in 2019. His research interests are in trust and security, the general area of wireless network architecture, internet of things, vehicular networks, and resource allocation.



Zhou Su has published technical papers, including top journals and top conferences, such as IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, IEEE TRANSACTIONS ON INFORMATION FORENSICS AND SECURITY, IEEE TRANSACTIONS ON DEPENDABLE AND SECURE COMPUTING, IEEE TRANSACTIONS ON MOBILE COMPUTING,IEEE/ACM TRANSACTIONS ON NETWORKING,and INFOCOM. His research interests include multimedia communication, wireless communication, and network traffic. Dr. Su received the Best Paper Award of International Conference IEEE ICC2020, IEEE BigdataSE2019, and IEEE CyberSciTech 2017. He is an Associate Editor of IEEE INTERNET OF THINGS JOURNAL, IEEE OPEN JOURNAL OF COMPUTER SOCIETY, and IET Communications.

Rongxing Lu (S'09-M'11-SM'15-F'21) is an associate professor at the Faculty of Computer Science (FCS), University of New Brunswick (UNB), Canada. Before that, he worked as an assistant professor at the School of Electrical and Electronic Engineering, Nanyang Technological University (NTU), Singapore from April 2013 to August 2016. Rongxing Lu worked as a Postdoctoral Fellow at the University of Waterloo from May 2012 to April 2013. He was awarded the most prestigious "Governor General's Gold Medal", when he received his PhD degree from the Department of Electrical & Computer Engineering, University of Waterloo, Canada, in 2012; and won the 8th IEEE Communications Society (ComSoc) Asia Pacific (AP) Outstanding Young Researcher Award, in 2013. Also, Dr. Lu received his first PhD degree at Shanghai Jiao Tong University, China, in 2006. Dr. Lu is an IEEE Fellow. His research interests include applied cryptography, privacy enhancing technologies, and IoT-Big Data security and privacy. He has published extensively in his areas of expertise (with H-index 76 from Google Scholar as of May 2021), and was the recipient of 9 best (student) paper awards from some reputable journals and conferences. Currently, Dr. Lu serves as the Vice-Chair (Conferences) of IEEE ComSoc CIS-TC (Communications and Information Security Technical Committee). Dr. Lu is the Winner of 2016-17 Excellence in Teaching Award, FCS, UNB.

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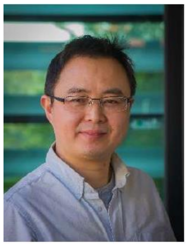

Shui Yu obtained his PhD from Deakin University, Australia, in 2004. He currently is a Professor of School of Computer Science, University of Technology Sydney, Australia. Dr Yus research interest includes Big Data, Security and Privacy, Networking, and Mathematical Modelling. He has published four monographs and edited two books, more than 400 technical papers, including top journals and top conferences, such as IEEE TPDS, TC, TIFS, TMC, TKDE, TETC, ToN, and INFOCOM. His h-index is 61. Dr Yu initiated the research field of networking for big data in 2013, and his research outputs have been widely adopted by industrial systems, such as Amazon cloud security. He is currently serving a number of prestigious editorial boards, including IEEE Communications Surveys and Tutorials (Area Editor), IEEE Communications Magazine, IEEE Internet of Things Journal, and so on. He served as a Distinguished Lecturer of IEEE Communications Society (2018-2021). He is a Distinguished Visitor of IEEE Computer Society, a voting member of IEEE ComSoc Educational Services board, and an elected member of Board of Governor of IEEE Vehicular Technology Society.

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