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Safety-Oriented Resource Allocation for Space-Ground Integrated Cloud Networks of High-Speed Railways

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***Abstract*—Enabling completely universal coverage, the space-ground communication system integration is one of the most important aspects in the fifth generation (5G) or even the next 6G wireless communications, which significantly benefits railways whose transportation lines always cross diverse environments. Based on this observation, to achieve seamless coverage for environment-diverse high-speed railways (HSRs), by leveraging the control/user-plane (C/U-plane) decoupling and cloud radio access network (C-RAN) technologies, we propose a space-ground integrated cloud railway network consisting of space and ground cloud layers, where in the space, baseband units (BBUs) of low earth orbit (LEO) satellites are collected and centrally-managed by geostationary earth orbit (GEO) satellites. To improve the mobility support and take advantage of the stable and ultra-wide terrestrial coverage of GEO satellites, we establish an additional backup space C-plane (BS-C-plane) connection between trains and GEO satellites. Under this architecture with diverse network resources, we develop a safety-oriented resource allocation scheme based on both the resource allocation priority of safety services and the network handover costs to deliver the safety-oriented services. Simulation results demonstrate that the proposed scheme can always meet the transmission requirements for safety services in HSRs.**

***Index Terms*—5G/6G space-ground integration; HSRs; safety services; resource allocation; Q-learning**

I. Introduction

The past decades have witnessed the rapid developments of terrestrial wireless communications. In densely-populated areas, owing to the high investment return, wireless systems, including the professional high-speed railway (HSR) wireless systems, have experienced an explosive growth in data transmission rate and network coverage performance in the fifth generation (5G) era [1], [2], [3]. Nevertheless, in remote areas, such as sparsely-populated areas, due to the cost considerations in building network infrastructure, there even exist no terrestrial wireless networks, which then pose a great challenge to the railway industry whose transportation lines usually cross diverse complicated geographic environments. Besides, terrestrial networks are vulnerable to disasters, implying that we cannot rely solely on terrestrial communications but need another supplementary technology to enhance the robustness of global wireless networks.

As wireless communications evolve to 6G, by combining advanced cloud computing and big data technologies, it is believed that the integration of space and ground communication systems provides a promising solution to the above problem, where space networks can supplement coverage holes of ground networks for any places on the earth [4]. In terms of the altitude, space satellites can be classified into three categories, i.e., low earth orbit (LEO) satellites with height of 160-2000km, medium earth orbit (MEO) satellites with height of 2000-35786km, and geostationary earth orbit (GEO) satellites with height of 35786km [4]. Due to the shortest distance among them to the earth, LEO satellites can provide relatively higher data rates and shorter propagation latency. Nevertheless, LEO satellites have high relative movement speeds with respect to the earth and consequently frequent inter-beam/satellite handovers are needed to guarantee the coverage continuity [5]. In contrast, although the farthest GEO satellites have lower data rate and longer propagation latency (about 270ms for one-way propagation), their geostationary motion promises stable and ultra-wide terrestrial coverage, enabling high mobility support for mobile users.

In the context of economic globalization and culture internationalization, more and more international communication services are emerging, in which the two end users usually locate in different countries and their data have to go through abundant routing hops in terrestrial communication systems, increasing the network forwarding burden and the end-to-end (E2E) latency. The statistical data from [6] shows that, even for the best-connected countries, the average country-level Internet routing latency of terrestrial communication systems is still longer than 200ms. According to [7], [8], owing to the significantly reduced routing hops, LEO satellite networks can provide cross-country communication services with much shorter E2E latency and in one of their case studies, the average E2E latency of services between Las Vegas in the USA and

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London in England is around 90ms. This comparison result shows that for end users with long geographic distances, satellite forwarding benefits significantly in terms of the E2E latency performance. In HSRs, especially for cross-country transportation lines, trains always cross diverse geographic areas, and therefore satellite communications are critical to keep trains always in contact with their domestic ground control centers.

To provide seamless network connections for HSRs to guarantee the transportation safety, we propose a space-ground integrated cloud railway communication network architecture as shown in Fig.1(a) by leveraging the control/user-plane (C/U-plane) decoupling and cloud radio access network (C-RAN) technologies. In our previous works [9], [10], [11], to guarantee the network mobility performance while extending spectrum to higher frequency bands to augment capacity, we apply the C/U-plane decoupling technology to HSRs, where the mobility management related C-plane signaling is carried by conventional high-quality sub-6GHz bands and the U-plane is separated and moved to higher frequency bands to gain wider spectrum. Even though the C/U-plane decoupled network architecture can to some extent balance the coverage and the capacity performance with operating frequency going higher, due to the limited coverage of terrestrial base stations, handovers still happen frequently under HSRs, resulting in low transmission reliability. While in space networks, with stable and ultra-wide terrestrial coverage, GEO satellites are good candidates to solve this problem. Therefore, by building the space-ground integrated network on the C/U-plane decoupling concept, to further improve the mobility-support ability of railway communication systems, we propose to establish an additional backup C-plane connection between trains and GEO satellites, namely, backup space C-plane (BS-C-plane), to achieve handover-free connections.

As wireless networks are constantly getting dense and heterogenous, through centralized resource management, the C-RAN architecture becomes an effective technology to improve the network resource utilization and reduce the network building costs for 5G [12]. In HSRs, to guarantee the transportation monitoring and tracking safety, the simultaneously dispatched trains on a rail line are usually sparse and trains need to keep a wireless blocking section distance in several kilometers between each other, resulting in the under-utilization of baseband units (BBUs) for track-side railway professional terrestrial communication systems. To alleviate this problem, we build the space-ground integrated railway communication network on the C-RAN architecture. From the physical space point of view, the whole network consists of two cloud layers, i.e., the space cloud and the ground cloud. In the space cloud, the BBUs of LEO satellites are gathered and centrally controlled in the BBU pool carried by GEO satellites, forming the space backbone network, while in the ground cloud, the BBUs of track-side base stations, including low-frequency remote radio units (LF-RRUs) and high-frequency RRUs (HF-RRUs), are gathered in the ground BBU pool, forming the ground backbone network.

In terms of the reliability requirement, railway services can be roughly classified into two categories, i.e., safety

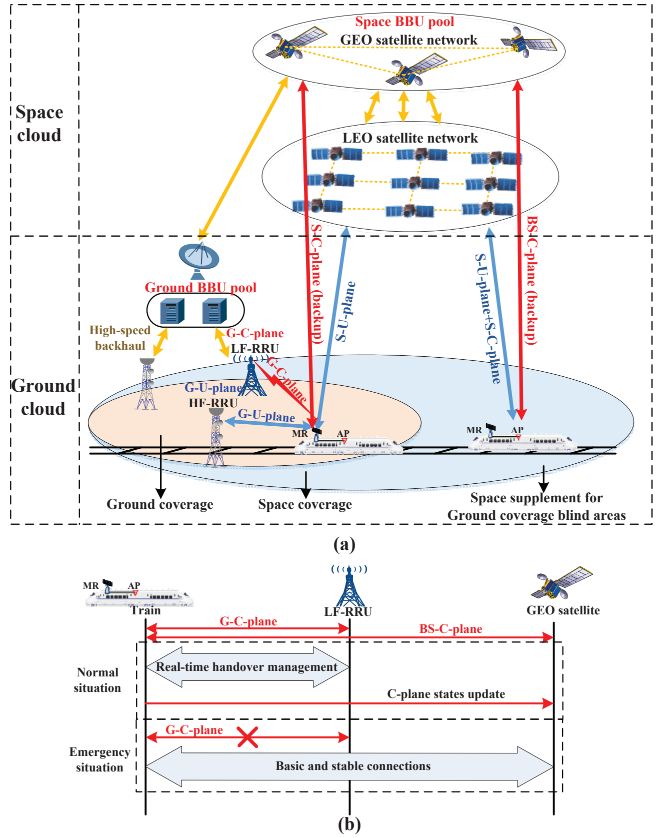

Fig. 1. (a) The space-ground integrated cloud network for HSRs, (b) the coordination between G-C-plane and BS-C-plane.

services and non-safety services. To guarantee the train operational safety, the train control and dispatching related mobile services are classed as the safety services, which demand high performance on bit error rate (BER) and E2E latency. While other railway services, such as video surveillance and passenger information system (PIS) services, are grouped into the non-safety services, which usually requires high data rate. By integrating space and ground communications, we can get diverse transmission resources gathered in a unified network and allocate them to firstly guarantee the transmission performance for safety services while improving the whole network performance. Moreover, in railway transportation, trains obey strict time schedule and run on determined routes, showing strong movement regularity and periodicity, while in the space network, satellites also have strong movement regularity in both space and time domains [13]. As a consequence, in the space-ground integrated railway professional wireless network, for a target transportation line, we can predict when and which space satellites and ground base stations could provide services for a train. Motivated by these salient characteristics in railway communications under the space-ground integrated network, to guarantee the performance for critical transportation safety services during a whole transportation trip, we propose a safety-oriented resource allocation scheme, in which a gain factor is introduced to give the resource allocation priority to safety services. Moreover, a handover discount factor is added

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to prevent unnecessary handovers to balance the handover gain and costs.

For clarity, we list in Table I the characteristics of HSR scenarios, the resulting benefits and drawbacks in terms of wireless communications, and the utilization of these benefits and the solutions to these drawbacks provided by our scheme. The remainder of this paper is organized as follows. In Section II, we give a brief overview of existing related works on the space-ground communication system integration. In Section III, we present the space-ground integrated cloud network for HSRs. In Section IV, we introduce the safety-oriented resource allocation scheme by leveraging Q-learning to solve the formulated problem. Section V provides simulation results and corresponding analysis to demonstrate the effectiveness of our proposed scheme. Finally, Section VI concludes this paper and prospects future worthwhile research directions.

TABLE I
SUMMARIZATION OF OUR MAIN CONTRIBUTIONS

HSR characteristics	Benefits(B) or drawbacks(D)	Utilization(U) or solutions(S) in our scheme
Diverse transportation environments	D: high demands on network coverage continuity	S: the space-ground integration
Sparsely dispatched trains	D: under-utilization of BBUs	S: the C-RAN technology
High mobility	D: frequent inter-site handovers	S: an additional BS-C-plane carried by GEO satellites
Bulky trains with sufficient physical space	B: deployments of antenna arrays	S: direct accesses to space satellites
Strict time scheduling	B: predictable movement patterns of trains	U: machine learning based safety oriented resource allocation algorithm
Operational safety services	D: high demands on transmission reliability	S: a gain factor introduced to guarantee the resource allocation priority for safety services

II. RELATED WORKS

Recently, to achieve completely seamless global coverage of mobile communications, the integration of space and ground communication networks generates tremendous research interests. In [4], Liu et al. developed a space-air-ground integrated network (SAGIN) consisting of satellite systems in the space, unmanned aerial vehicle (UAV) systems in the air, and terrestrial systems on the ground, and discussed the corresponding network designs, protocol optimizations and resource management of the integrated network. In [14], they further leveraged the software defined network (SDN) technology to facilitate the network management for complicated and multi-layered SAGIN. To enhance the network management flexibility, instead of configuring SDN controllers only on the ground segments as in most previous proposed network architecture, they also deployed SDN controllers in GEO satellites to timely send/receive information to/from high-speed moving satellites, even when satellites move out of the coverage of ground network control centers (NCCs). Then, in [15], [16], under the SDN-based SAGIN, they investigated the placement problems of controllers and satellite gateways to optimize the network reliability and latency performance. In [17], by considering the computation and power resource limitations in the space-air networks, in addition to the conventional mission offloading from ground to space-air networks, Zhou et al propose to reversely offload missions from space-air to ground networks to benefit from the rich spectrum, computation, storage and power resources in ground systems. In most existing works, the space-ground integrated network is designed in the background of common mobile users who need to mostly access ground networks while satellites act as relays. In HSRs, trains have plenty physical space and their own power supply, providing adequate conditions for trains to directly communicate with satellites. Based on this observation, in this paper, we focus on the access layer design for HSR space-ground integrated networks to improve the mobility support performance.

Resource allocation is another important research direction in space-ground integrated networks to improve the network transmission performance. In [18], taking energy efficiency and spectral efficiency as two major metrics, Peng et al studied the dynamic resource allocation strategies for space-ground integrated networks. In [19], Zhu et al proposed resource allocation schemes to harmonize the radio resource sharing between space and ground networks. Till now, there are few works on resource allocation for HSR, where the primary requirement is to guarantee the transmission performance for operational safety related services. Therefore, in this paper, with the diverse available resources in the space-ground integrated network, we investigate the resource allocation problem to best guarantee the stringent requirements for safety services.

III. NETWORK ARCHITECTURE

To achieve seamless wireless services for HSRs to guarantee the transportation safety, by building on the C/U-plane decoupling and C-RAN technologies, we propose a space-ground integrated railway communication network as shown in Fig. 1(a). From a global point of view, the whole network consists of two cloud layers, i.e., the space cloud and the ground cloud. In the space cloud, the BBUs at LEO satellites are managed in the BBU pool by relatively-stable GEO satellites, and LEO satellites communicate with the BBU pool through high-speed inter-beam/satellite links. To enhance the satellite network management flexibility and efficiency, compared with traditional satellite networks, an additional BBU controller is deployed in GEO satellites to enhance and offload the network management responsibility of NCCs on ground segments. Owing to the stable and ultra-wide coverage, the controllers in GEO satellites can timely communicate with LEO satellites to issue control commands, avoiding the problem that ground NCCs miss LEO satellites when they move out of the coverage [14].

In the ground cloud, there are two types of RRUs, i.e., LF-RRUs and HF-RRUs, where LF-RRUs operate at conventional sub-6GHz bands to guarantee the network coverage and HF-RRUs operate at higher frequency bands to enhance the data transmission capacity. The BBUs of RRUs are collected in the ground BBU pool. By deploying earth stations in the ground BBU pools to communicate with GEO

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satellites that manage the space BBU pool, we can further connect the two cloud layers to form a unified space-ground integrated cloud railway communication network. Even though the long propagation latency from/to GEO satellites may cause some concerns, due to the fact that the number of GEO satellites required to cover the whole earth surface is as small as three, we can carefully select the positions of ground earth stations to achieve one-hop reachable connections between ground and space clouds [20], [21]. Then, the forwarding latency between the two clouds can be managed for specific applications to meet the desired requirements.

In terms of the C/U-plane decoupling technology, to improve the mobility support and enhance the system capacity, trains maintain two pairs of C/U-plane connections with the space and ground network nodes, respectively. On the ground, even though the integrated sub-6GHz bands can to some extent guarantee the whole network coverage, due to the limited coverage of terrestrial base stations, the high mobility of trains in HSR still leads to frequent handovers and therefore degrades the transmission reliability. In the space, with almost zero relative movements with regards to the earth, GEO satellites can provide a stable and ultra-wide coverage for mobile users (trains in HSR), realizing handover-free communications. Based on these observations, to further enhance the mobility-support performance, in the proposed space-ground integrated network, we propose to establish an additional BS-C-plane between trains and GEO satellites. Unlike U-plane, C-plane usually supports low-data-rate signaling which can be satisfied by GEO satellites with limited capacity. Due to the long propagation latency from/to GEO satellites, the newly added BS-C-plane only acts as backup for emergency situations. In a normal situation, the ground C-plane (G-C-plane) takes charge of the real-time mobility management for trains, and then the updated connection states of trains, such as the link quality of G-C-plane and the tracking area information, will be periodically reported to GEO satellites through BS-C-plane links. The BBU controllers are responsible to real time monitor both of the G-C-plane and BS-C-plane. Once a train is confirmed losing the G-C-plane connection while the BS-C-plane is in normal working condition, the train will enter the emergency situation, and the BS-C-plane will take over the functionality of control plane to retain a basic connection. After the G-C-plane is recovered, the responsibility for the control plane will be handed back to the G-C-plane. For clarity, the coordination process between the G-C-plane and BS-C-plane is illustrated in Fig. 1(b).

Additionally, as Fig. 1(a) shows, the space U-plane (S-U-plane) between trains and LEO satellites is newly introduced to not only enhance the system transmission capacity, but also provide an alternative data routing option to reduce the E2E latency of long-distance services. In the area without terrestrial networks, trains get both C-plane and U-plane accesses from LEO satellites. With respect to trains, a two-hop onboard network architecture is applied, in which users' services are firstly collected by inside access points (APs) and then forwarded to track-side networks through outside mobile relays (MRs). With sufficient physical space and own power supply in trains, the on-board MR can be configured as a powerful entity with massive antenna arrays, computing resources, and caching components [22], [23], which supports general accesses to both space and ground networks.

IV. SAFETY-ORIENTATED RESOURCE ALLOCATION

A. Network settings

In HSRs, the train control and dispatching related mobile services, which directly affect the train operational safety, are defined as the safety services and have stringent requirements on the transmission performance of BER and E2E latency. Other railway services with relatively-low safety levels, such as track maintenance data and PIS services, are defined as non-safety services here, which usually demand high data rate. In the proposed space-ground integrated cloud railway network, there are diverse network resources. How to efficiently utilize them to meet different performance requirements for railway services is an important but challenging research task. Intuitively, to guarantee the railway transportation safety, safety services should be given high priority in resource allocation to best satisfy their performance requirements, especially in the areas there are no terrestrial networks and all services have to share limited transmission resources from space networks. Under the premise that the performance requirements for safety services have been guaranteed, the next design task comes the allocation of the remaining resources to maximize the transmission performance for non-safety services. From these observations, we propose a safety-oriented resource allocation scheme which has two steps, namely, network selections and channel allocation. According to the performance requirements for different services and the performance of different networks, we distribute services to suitable networks and then allocate corresponding channel resources to maximize the global network utility. In this problem, the objective utility function consists of three weighted components, i.e., data rate, BER and E2E latency, where the weighting factors reflect the diverse requirements for different services on these three metrics. To stimulate networks to offer the usage priority of high-performance resources to safety services, a gain factor is brought in to emphasize the acquired utility of resources serving safety services. Since in the C/U-plane decoupling based space-ground integrated network, the main data are carried by U-plane, we only consider the resource allocation in space LEO satellites and ground HF-RRUs that are responsible for U-plane transmissions. Besides, due to the fact that even under a unified architecture, space and ground systems may still have different physical frame structures and higher-layer protocols, at a given time, one service can only be transmitted by one network to avoid the combination complexities of data streams from different networks. When the performance of the current network degrades, the service can be switched to other networks. As network handovers always bring in overheads, a handover discount factor is introduced into our problem formulation to balance the network handover gains and costs.

On the ground, for an interested railway transportation line, the available terrestrial networks along the line and their coarse transmission performance are predictable. In the space, LEO satellites move in fixed orbits with regular and predictable velocity patterns, implying that at a given time of a day, we can predict which LEO satellites can provide services to which terrestrial areas. Moreover, in HSRs, to guarantee the transportation safety, trains must obey strict time scheduling. The above salient characteristics in the space-ground integrated railway communication system make it possible to predict when and which space and ground networks could serve the train on an interested transportation line and prepare the transmission resources along the line for the train. Assuming that a transportation line starts at S and ends at E with a total traveling duration of T_{total}, as a case study, Fig. 2(a) shows available networks and their service time along this transportation line, where the dash and solid lines stand for the space and ground network coverage, respectively. To simplify the analysis, according to the sequence of starting times, we reorder all available networks along the target transportation line in a serving time table. Suppose that within the SE duration, there are m space networks and n ground networks, then the serving time table of all the $m+n$ networks can be listed as

$$ServT = \begin{pmatrix} X_1 & t_{s,X,1} & t_{e,X,1} \\ X_2 & t_{s,X,2} & t_{e,X,2} \\ \vdots & \vdots & \vdots \\ X_{m+n} & t_{s,X,m+n} & t_{e,X,m+n} \end{pmatrix} \tag{1}$$

where $t_{s,X,1} \leq t_{s,X,2} \leq \cdots \leq t_{s,X,m+n}$.

Different from terrestrial systems whose general network coverage is in the same level of the movement scale of common terrestrial users, the coverage modes of space satellites are point-to-area, and an LEO satellite usually covers hundreds of terrestrial networks. Consequently, we assume that the channel conditions of LEO links are relatively stable within a large geographical region. In other words, as shown in Fig.2 (b), compared with terrestrial networks, a relatively large time scale can meet the real-time requirements for resource state information updates in space networks. Also because of this characteristic in space networks, the propagation latency between the space and ground clouds will not heavily impact the validity of the resource state information in the space networks, and therefore we do not consider the information exchange latency between the two clouds to simplify our analysis. To guarantee the real-time performance for resource allocation in the whole network, as well as to ensure the availability of our resource allocation algorithm in the area without terrestrial networks, as shown in Fig. 2(a), our proposed resource allocation scheme is implemented in both the ground and space BBU pools. In the area with terrestrial networks, the proposed scheme in ground BBU pools is activated to manage the resource allocation, while space BBU pools periodically send the resource state information in space networks to ground BBU pools. Then, as shown in Fig.2(b), the time granularity of resource allocation is the same as the resource state update period of terrestrial networks. While in the area without terrestrial networks, the proposed scheme in space BBU pools is activated to serve trains and the resource allocation period is the same as the space resource state update period. To ease the understanding, we take the resource structure of OFDM based long-term evolution (LTE) as the study case, in which the term "channel" is used to express the resource allocation unit in this problem.

In brief, the assumptions used in this paper are as follows. First, due to the strong time regularity in the movement patterns of trains and satellites, we assume that the network properties along an interested transportation line are predictable with strong time regularity. Second, considering the data combination complexity, at a given time, all data of a service can only be carried by a single network. Third, within a resource allocation period, we assume that the wireless channels stay constant. For high-mobility scenarios, how to track the fast-varying wireless channel is still a challenge and attracts a lot of research interests [24], [25]. Although in reality the accuracy of channel estimations impacts on the final system performance, it will not affect the feasibility and effectiveness evaluation of our proposed resource allocation scheme. Therefore, for simplicity, we ignore the effects of the fast channel variations on our resource allocation analysis. Besides, for clarity, the major notations and their definitions used in this paper are listed in Table II.

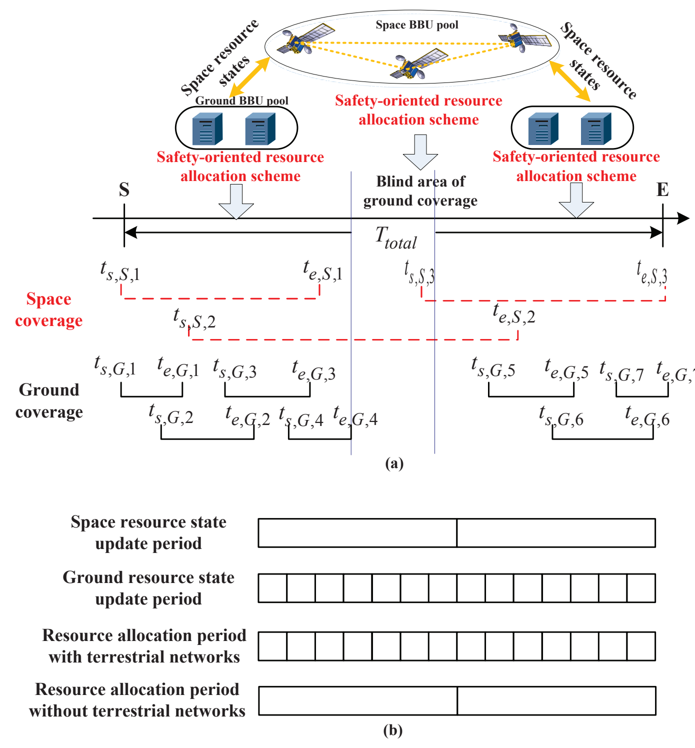

Fig. 2. (a) Available networks along the transportation line, (b) the relationship between resource information update period and the scheduling period.

B. Problem formulation

Without loss of generality, we assume that the arrivals of data services follow a Poisson distribution [26]. Then, during a scheduling period of T_s, the arriving traffic volume of service

TABLE II
THE MAIN NOTATIONS AND THEIR DEFINITIONS

Notations	Definitions
T_s	Scheduling period
$X = S$ or G	Subscript representing space/ground networks
$SNR_{X,j,k}$	SNR of channel k in network j
Bw	Bandwidth of a channel
Q	Number of services
$B_{X,j}$	Number of channels in network j
P_t	Transmit power
N_0	Noise power
PL	Path loss
$h_{G,j,k}$	Small-scale fading of channel k in network j
$d_{\min,G,j}$	Distance between ground RRUs and rails
$R_{G,j}$	Coverage radius of ground RRUs
f_c	System frequency
$d_{S,j}$	Distance between trains and LEO satellites
G_T	Transmit antenna gain of satellites
G_R	Receive antenna gain of trains
η_q	Gain factor of service q
$\gamma_{i\to j}^{q,C}$	Weighting factor on data rate for service q
$\gamma_{i\to j}^{q,BER}$	Weighting factor on BER for service q
$\gamma_{i\to j}^{q,D}$	Weighting factor on E2E latency for service q
$\delta_{i\to j}^{q}$	Handover discount factor
s_t	Network state at time t
a_t	Action taken at time t
I_q	Network selection indication
$U_t(s,a)$	Immediate return at time t

q is

$$\begin{aligned} &P_{n,q}(T_s) = \text{Prob}\{n \text{ bits arrive in } (0,T_s)\} \\ &= \frac{\lambda_q T_s}{n!} e^{-\lambda_q T_s} \end{aligned} \tag{2}$$

where λ_q is the arrival rate of service q.

Typically, the transmission performance of wireless networks can be characterized by the data rate, BER and E2E latency, and different types of services have different requirements on these three metrics. Usually, safety services have high requirements on BER and E2E latency while non-safety services need high data rate. Therefore, in this problem, our objective utility function is defined as the sum of the three weighted metrics, and for a metric, the higher its weighting factor is, the higher requirement on this metric this service will have [27]. As aforementioned, although the wireless access time to space networks is longer than that of ground networks, from the E2E latency point of view, space networks may outperform ground networks when forwarding long-distance data services, such as cross-country services, owing to the reduced routing hops. Next, we give the definitions of the three metrics and normalize them to the same scale.

Data rate. Considering that the space and ground networks have quite different transmission characteristics, we present the data rate models separately. In the time domain, when a train moves out of network i and switches to network j, the service duration the train can get from network j can be calculated as $T_{X,j} = t_{e,X,j} - t_{e,X,i}$, where $\mathrm{X} = \mathrm{S}\,\mathrm{or}\,\mathrm{G}$ represent the label of a space or ground network. Correspondingly, the number of scheduling periods within network j can be obtained as $N_{X,j,s} = \left\lfloor \frac{T_{X,j}}{T_s} \right\rfloor$. Then, when a train leaves network i and goes into ground network j, in the pth scheduling period, the data rate for the train is expressed as

$$C_{X,i\to G,j}^{q}(p) = \sum_{k=1}^{B_{G,j}^{q}(p)} Bw \cdot f_{MCS}\left(SNR_{G,j,k}(p)\right) \tag{3}$$

where $f_{MCS}(\bullet)$ is a mapping function from the signal to noise ratio (SNR) to the achieved modulation and coding schemes (MCSs), which can be found in [28]. $B_{G,j}^{q}(p)$ and Bw represent the number of allocated channels to service q and the bandwidth of a unit channel, respectively. The subscript X is equal to S or G. Let $B_{G,j}$ and Q denote the total number of channels in ground network j and the total number of services, respectively. The channel allocation for ground network j is constrained by

$$\sum_{q=1}^{Q} B_{G,j}^{q}(p) \le B_{G,j}. \tag{4}$$

In (3), the SNR of channel k in the pth scheduling period has an expression as

$$SNR_{G,j,k}(p) = \frac{P_t \cdot PL(p) \cdot h_{G,j,k}}{N_0}, \tag{5}$$

where P_t, N_0, $PL(t)$ and $h_{G,j,k}$ are the transmit power, noise power, path loss and small-scale fading, respectively. Using $d_{\min,G,j}$, $R_{G,j}$ and f_c to denote the distance between ground RRUs and rails, the coverage radius and the system frequency, respectively, the path loss of ground networks within the p scheduling period is assumed to be [29]

$$\begin{aligned} &PL(p)[dB] = -(32.4 + 20\lg f_c \\ &+ 20\lg\sqrt{d_{\min,G,i}^2 + \left(R_{G,i} - (t_{e,X,i} - t_{s,G,j} + p\cdot T_s)\cdot v\right)^2}\,). \end{aligned} \tag{6}$$

For space networks, let $B_{S,j}$ denote the total number of available channels. Then, in the pth scheduling period, the achievable data rate when a train leaves previous network i and goes into space network j is

$$C_{X,i\to S,j}^{q}(p) = \sum_{k=1}^{B_{S,j}^{q}(p)} Bw \cdot f_{MCS}\left(SNR_{S,j,k}\right), \tag{7}$$

where $B_{S,j}^{q}(p)$ is the number of channels allocated to service q, and ([30])

$$SNR_{S,j,k} = \frac{P_t \cdot G_T \cdot G_R \cdot PL(d_{S,j}) \cdot h_{S,j,k}}{N_0}. \tag{8}$$

where $d_{S,j}$, G_T, G_R and $h_{S,j,k}$ denote the distance between the train and LEO satellites, the transmit antenna gain, the receive antenna gain, and the small-scale fading, respectively.

In high-mobility scenarios, Doppler effect, which heavily degrades the system performance, is an inevitable concern. Fortunately, for terrestrial systems, the regularity and periodicity of train movement patterns make it possible to use frequency offset correction techniques to precisely pre-compensate Doppler shifts, such as in [31]. For space networks, as investigated in [8], owing to the fixed orbit motion of satellites, the Doppler shifts under all user and satellite movement cases appear as an S-curve, of which this characteristic can also be leveraged to facilitate the

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pre-compensations just as in [32]. Consequently, for simplicity, we ignore the Doppler effect in our study.

Similar to (4), the channel allocation in space networks should satisfy

$$\sum_{q=1}^{Q} B_{S,j}^{q}\left(p\right) \leq B_{S,j}. \tag{9}$$

Considering the transmission differences between space and ground networks, such as transmission mechanisms, network protocols, etc., in our proposed resource allocation scheme, at a given scheduling period, the data of one service can only be carried by a single network to avoid the complexities of data combining. Therefore, two binary indicators, i.e., $\ell_{G,i}^{q}\left(p\right)$ and $\ell_{S,i}^{q}\left(p\right)$, are defined to denote whether service q is allocated to a ground or space network in the pth scheduling period, whose expressions are

$$\ell_{S,i}^{q}\left(p\right) = \begin{cases} 0, B_{S,i}^{q}\left(p\right) = 0 \\ 1,\ \text{otherwise} \end{cases} \tag{10}$$

and

$$\ell_{G,i}^{q}\left(p\right) = \begin{cases} 0, B_{G,i}^{q}\left(p\right) = 0 \\ 1,\ \text{otherwise.} \end{cases} \tag{11}$$

Then, in the pth scheduling period, the channel allocation for service q should satisfy

$$\ell_{G,i}^{q}\left(p\right) + \ell_{S,i}^{q}\left(p\right) \leq 1. \tag{12}$$

Since different metrics have different units, we need to conduct normalization operations to put them into a single objective utility function. The normalized data rate is given as

$$C_{X,i\to Y,j}^{q,nor}\left(p\right) = \frac{C_{X,i\to Y,j}^{q}\left(p\right) - C_{th}^{q}}{C_{\max} - C_{th}^{q}},\ \mathrm{X\,and\,Y = S\,or\,G}, \tag{13}$$

where $C_{th}^{q} = \lambda_q T_s$ is the basic data rate requirement for service q, and $C_{\max} = \max\left(C_{X,i\to Y,j}^{q}\left(p\right)\right)$ is the maximum data rate within the current network j.

BER. Similar to the metric of data rate, in wireless communications, BER is also mainly determined by the received signal quality SNR. In practice, transmitters usually fix a BER level, and then select an achievable MCS level based on the estimated SNR. Based on this observation, we directly specify the BER performance for all networks, instead of calculating them through SNR. Then, in the pth scheduling period, the normalized BER performance that service q can get from network j is assumed in (14), where $BER_{\min}^{q}$ and $BER_{\max}^{q}$ specify the BER requirement range for service q.

E2E latency. In this paper, the E2E latency we are concerned with is the total transmission time between two peers. For instance, as for a safety service, the E2E latency is the transmission time between a train and its train control center, instead of just the access time between the train and a satellite or ground RRU. Usually, the E2E latency of a routing path can be measured or estimated, and therefore we assume the E2E latency is known in this paper without significantly impacting our study. Similar to (14), the normalized E2E latency metric can be expressed as

$$D_{X,i\to Y,j}^{q,nor}\left(p\right) = \begin{cases} 1,\ D_{Y,j}\left(p\right) \leq D_{\min}^{q} \\ \frac{D_{\max}^{q} - D_{Y,j}\left(p\right)}{D_{\max}^{q} - D_{\min}^{q}},\ D_{\min}^{q} < D_{Y,j} < D_{\max}^{q} \\ 0,\ D_{Y,j}\left(p\right) \geq D_{\max}^{q} \end{cases} \tag{15}$$

where $D_{\min}^{q}$ and $D_{\max}^{q}$ specify the E2E latency requirement range for service q.

Consequently, the weighted utility function is formulated as (16) at the bottom of this page. To simplify the expression, we only use i or j to represent the indices of networks since networks along the target transportation line have been ordered in sequence in (1). $N_s = \sum_{j=1}^{m+n} N_{X,j,s}$ represents the total number of scheduling periods within the SE duration. $\gamma_{i\to j}^{q,C}$, $\gamma_{i\to j}^{q,BER}$ and $\gamma_{i\to j}^{q,D}$ are the weighting factors on data rate, BER and E2E latency, respectively, with $\gamma_{i\to j}^{q,C} + \gamma_{i\to j}^{q,BER} + \gamma_{i\to j}^{q,D} = 1$. Considering the fact that handovers consume transmission opportunities, a handover discount factor $\delta_{i\to j}^{q}$, whose value is between 0 and 1, is added in the utility function to avoid unnecessary handovers. When no handover happens between two adjacent scheduling periods, there is no discount on the obtained utility, i.e., $\delta_{i\to j}^{q} = 1$ if $i = j$. Otherwise, we set

$$BER_{X,i\to Y,j}^{q,nor}\left(p\right) = \begin{cases} 1,\ \mathrm{BER}_{Y,j}\left(p\right) \leq BER_{\min}^{q} \\ \frac{BER_{\max}^{q} - \mathrm{BER}_{Y,j}\left(p\right)}{BER_{\max}^{q} - BER_{\min}^{q}}, BER_{\min}^{q} < \mathrm{BER}_{Y,j} < BER_{\max}^{q} \\ 0,\ \mathrm{BER}_{Y,j}\left(p\right) \geq BER_{\max}^{q} \end{cases} \tag{14}$$

$$U_{S,E}^{Q} = \sum_{q=1}^{Q} \eta_q \sum_{p=1}^{N_s} \delta_{i\to j}^{q} \left(\gamma_{i\to j}^{q,C} C_{i\to j}^{q,nor}\left(p\right) + \gamma_{i\to j}^{q,BER} BER_{i\to j}^{q,nor}\left(p\right) + \gamma_{i\to j}^{q,D} D_{i\to j}^{q,nor}\left(p\right)\right) \tag{16}$$

$$\begin{aligned} &\max \sum_{q=1}^{Q} \eta_q \sum_{p=1}^{N_s} \delta_{i\to j}^{q} \left(\gamma_{i\to j}^{q,C} C_{i\to j}^{q,nor}\left(p\right) + \gamma_{i\to j}^{q,BER} BER_{i\to j}^{q,nor}\left(p\right) + \gamma_{i\to j}^{q,D} D_{i\to j}^{q,nor}\left(p\right)\right) \\ &s.t. \sum_{q=1}^{Q} B_{X,j}^{q}\left(p\right) \leq B_{X,j}, \forall p \\ &\ell_{G,i}^{q}\left(p\right) + \ell_{S,i}^{q}\left(p\right) \leq 1, \forall q,\ p \end{aligned} \tag{18}$$

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$0 \leq \delta_{i\to j}^{q} < 1$ to express the discount on the final transmission performance due to the handover overheads. Moreover, in (16), a gain factor η_q is introduced to emphasize the utility of resources that are serving safety services compared with non-safety services, which will stimulate the network to assign higher priority to safety services in resource allocation, thereby guaranteeing the transmission performance for safety services especially for the resource-shortage situations. The definition of η_q is

$$\eta_q = \begin{cases} \mu > 1, q \, \text{is a safety service} \\ 1, \text{ otherwise} \end{cases} \tag{17}$$

Based on the above analysis, the optimization problem can be formulated as (18). Based on the definitions in (13)-(15), the basic transmission performance requirements of services are implicitly contained in the optimization problem. Once the allocated resources cannot meet the basic transmission performance requirements of services, the correspondingly obtained utility will be negative, which will degrade the whole utility and stimulate the resource manager to adjust the resource allocation strategy to achieve higher utility. It can be found that this problem is a combinatorial optimization problem, which is typically NP-hard and cannot be easily solved. Besides, in conventional optimization methods, optimal results come at the cost of complicated and massive iterations, which leads to high computation latency and does not fit high-mobility scenarios.

In HSR communication systems, the available network resources along an interested transportation line can be predicted relatively accurately. Moreover, the movement patterns of trains and space satellites have strong regularity in both time and space. The network selections and corresponding channel allocation can be characterized as a Markov-decision process. Based on this observation, we use Q-learning, a common technique in reinforcement learning (RL) for solving Markov-decision problems, to solve the above problem in a low-complexity way. In fact, with the increasing of network density, heterogeneity and complexity, it is hard for network controllers to make resource allocation decisions through traditional optimization methods, and RL, as a model-free and unsupervised learning technique, has been commonly applied in solving the resource allocation problems for wireless systems [33], [34]. In our problem here, the state, action and reward of the Q-learning algorithm are defined as follows.

Agent: ground and space BBU pools. In this problem, the cloud BBU pools acting as the control center is the learning agent.

State $s_t = [p, A_{X,i}(p)]$ where $i = 1, 2, .., m + n$, the state is defined as the vector formed by the scheduling period and the properties of networks. At the scheduling period p, the properties of network i can be expressed as

$$A_{X,i}\left(p\right) = \left\{b_{(1)}, b_{(2)}, ..., b_{(B_{X,i})}, BER_{X,i}, D_{X,i}\right\} \tag{19}$$

where the channels are in descending order based on their achievable bit rate levels b with $b_{(1)} \geq b_{(2)} \geq, ..., \geq b_{(B_{X,i})}$.

Action: in this problem, an action is to select a network as well as assign channels for all queued services. Nevertheless, as the number of available channels in an access network may be large, the actions may have high dimensions if we include channel allocation into actions. Therefore, to reduce the computation complexity of the proposed algorithm, the actions are defined as the final selection of access networks. After the network is determined, the high-quality channels will be allocated to safety services according to the priority, so as to guarantee the transmission performance for safety services. Based on the above analysis, the actions of this problem can be expressed as

$$a_t = (I_1, I_2, ..., I_Q) \tag{20}$$

where $I_q \in \{1, 2, ..., m + n\}$ denotes the network selection for service q .

Reward: $U_t\left(s, a\right)$ assesses the immediate return by applying action a_t for service q at state s_t. Based on the objective function of the optimization problem in (18), the considered reward can be expressed as (21).

Q-value update: the Q-learning process attempts to find the best action a_t at state s_t in a recursive manner so as to gain the highest reward. The Q-value updating rule can be expressed as

$$\begin{aligned} &Q_t\left(s, a\right) = \left(1 - \ell\right) Q_{t-1}\left(s, a\right) \\ &+\ell \left[U_t\left(s, a\right) + r \max Q_{t-1}\left(g, a\right)\right] \end{aligned} \tag{22}$$

where g is the next scheduling period after s. When maximizing the long-term reward, we are concerned more about the recent reward than the further future ones, which is usually realized by introducing a discounting factor, denoted by r in (22). Another related parameter is the learning rate ℓ , which determines the weights of previous Q-value and the newly obtained reward. In our problem, the ε-greedy exploration is used to balance explorations and exploitations. In explorations, new actions are discovered to adapt to the possible environmental changes, while in exploitations, the best action is always selected. For clarity, the Q-learning based resource allocation algorithm is listed in Algorithm 1. In step 11, k counts the channels that have been allocated. In step 13, $L_{(i)}$ denotes the sequence of services that are sorted in descending order of the resource allocation priority $\eta_{(i)}$. The whole algorithm has two phases, i.e., network selection and channel allocation. As aforementioned, to reduce the dimensions of actions as well as the computation complexity, the Q-learning method is used to determine the access networks for services. Then, in the channel allocation part, based on the sequence of channels described in (19), to best

$$U_t\left(s, a\right) = \sum_{q=1}^{Q} \delta_{i\to j}^{q} \cdot \eta_q \left(\gamma_{i\to j}^{q,C} \cdot C_{i\to j}^{q,nor}\left(p\right) + \gamma_{i\to j}^{q,BER} \cdot BER_{i\to j}^{q,nor}\left(p\right) + \gamma_{i\to j}^{q,D} \cdot D_{i\to j}^{q,nor}\left(p\right)\right). \tag{21}$$

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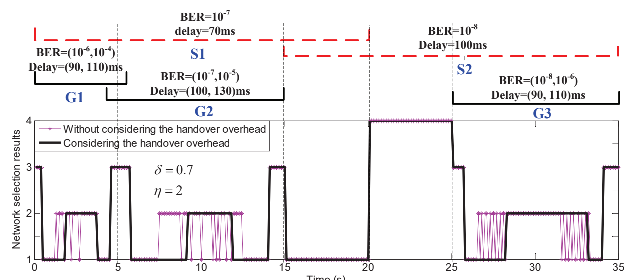
guarantee the transmission performance for safety services, the high-quality channels of the correspondingly-determined networks are preferentially allocated to safety services and then the remaining resources are given to non-safety services. Steps 12-24 present the channel allocation procedures for the case when multiple services select the same network, while steps 26-37 serve for the case that different services select different networks. Finally, the obtained utility is taken as the immediate reward for the current state and action. After enough trials, for a state, the best action that can gain the highest Q-value can be found. Different from conventional optimization methods, the computations of the Q-learning based resource allocation scheme happen in the off-line training phase. When the Q-value table is established, in the on-line application phase, by inputting the current network state, the best action can be quickly obtained through looking up the Q-value table without involving too much computation, which is a good property for high-mobility scenarios that need fast decision-making. It should be noted that in this part, our major contribution is not on the Q-learning algorithm itself, but on the safety-oriented resource allocation problem formulation and its transformation to a standard Q-learning problem for solution through the corresponding definitions for the state, action and reward in Eq. (19)-(21).

V. Performance Evaluation

In our simulation study, two typical services, i.e., the safety and non-safety services, are taken into account, whose weighting factor values on three performance evaluation metrics are listed in Table 1. Other simulation related parameter values can also be found in Table III or corresponding figures. As a case study, we set the simulation scenario with five networks, including two space networks and three ground networks, whose parameters are given in the upper part in Fig.3(a). Besides, Fig.3(a) also gives the network selection results under the proposed resource allocation algorithm. To simplify the illustrations of Fig.3(a), one-dimensional action indicator is used as the y-axis to represent the combined network selection results of the two services, whose values and their corresponding physical meanings at different time can be found in Fig.3(b). As aforementioned, in HSR scenarios, trains obey strict time schedule during their travel, based on which we assume the train in our simulations runs in a constant velocity in a relatively long time interval during the target transportation line SE, and therefore we use the time as the x-axis. As shown in Fig.3(a), owing to the introduced handover discount factor, the proposed resource allocation scheme can avoid unnecessary handovers, leading to fewer network handovers compared to the case without considering handover discounts. For clarity, in Fig.3(c), the exact numbers of handovers for the two schemes with and without considering the handover discount factor are illustrated. Fig. 3(d) gives the convergence performance of the algorithm at time=4s. Within an acceptable number of epochs, the data rates of two services fast converge to relatively stable levels that meet the transmission requirements of the safety service while maximizing the overall utility, which demonstrates the feasibility of the proposed algorithm.

TABLE III
Parameter Settings

Parameters	Values
Duration of SE	35s
MCS levels	[1 2 4 6 8] bits
$B_{S,j}$	5
$B_{G,j}$	10
Weighting factors of safety service	$\left[\gamma_{i\to j}^{safety,C}, \gamma_{i\to j}^{safety,BER}, \gamma_{i\to j}^{safety,D}\right] = [0.2, 0.4, 0.4]$
Weighting factors of non-safety service	$\left[\gamma_{i\to j}^{non,C}, \gamma_{i\to j}^{non,BER}, \gamma_{i\to j}^{non,D}\right] = [0.6, 0.2, 0.2]$
Safety service requirements	$[C_{th}, BER_{\min}, BER_{\max}, D_{\min}, D_{\max}] = [3.4Mbps, 10^{-8}, 10^{-6}, 70ms, 100ms]$
Non-safety service requirements	$[C_{th}, BER_{\min}, BER_{\max}, D_{\min}, D_{\max}] = [12.6Mbps, 10^{-6}, 10^{-4}, 90ms, 120ms]$
Space state update period	300ms
Ground state update period	1ms
Q-learning discount	$r = 0.1$
Exploration rate	$\varepsilon = 0.2$
Learning rate	$\ell = 0.4$
Velocity of trains	$v = 360km/h$



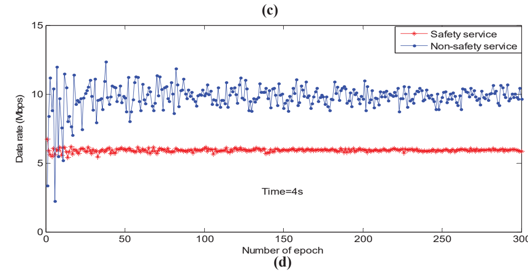
(a)

	Time (0, 5)s	Time (5, 15)s	Time (15, 20)s	Time (20, 25)s	Time (25, 35)s
Result=1	Safety→S1 Non-safety→G1	Safety→S1 Non-safety→G2	Safety→S1 Non-safety→S2	—	Safety→S2 Non-safety→G3
Result=2	Safety→G1 Non-safety→S1	Safety→G2 Non-safety→S1	Safety→S2 Non-safety→S1	—	Safety→G3 Non-safety→S2
Result=3	Safety→S1 Non-safety→S1	Safety→S1 Non-safety→S1	Safety→S1 Non-safety→S1	—	Safety→S2 Non-safety→S2
Result=4	Safety→G1 Non-safety→G1	Safety→G2 Non-safety→G2	Safety→S2 Non-safety→S2	Safety→S2 Non-safety→S2	Safety→G3 Non-safety→G3

(b)

	Time (0, 5)s	Time (5, 15)s	Time (15, 20)s	Time (20, 25)s	Time (25, 35)s
With δ	4	4	0	1	5
Without δ	10	6	0	1	18

(c)



(d)

Fig. 3. Performance of safety-oriented resource allocation scheme: (a) Network selection results, (b) lookup table of network selections, (c) number of handovers, (d) convergence performance.

Under the same simulation conditions as in Fig. 3, Fig.4 presents the data rate, BER and E2E latency of the two services in the proposed resource allocation scheme,

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respectively. Due to the guaranteed priority of the safety service in the resource allocation algorithm, at any situations, the achieved performance of three metrics can always meet the corresponding transmission requirements for the safety service. With regards to the non-safety service, at the area with high-performance resources, its transmission requirements on the three metrics can be completely satisfied. Nevertheless, at the area with limited network resources, such as during the time from 20s to 25s in Fig.4(a) where no terrestrial network exists, since the safety service is given priority to using high-performance resources, the remaining resources allocated to the non-safety service cannot meet its data rate requirements, which is consistent with the practical considerations of railway industry that safety always comes first.

To guarantee the resource allocation priority for the safety service, we use a gain factor η to emphasize the achieved utility of resources serving safety services. In Fig. 5, the transmission performance of the safety service under different values of η is shown. When η is increased from 1 to 2, due to the fact that higher utility can be produced by the safety services with larger η, high-performance resources are firstly allocated to the safety service, thereby bringing in the transmission performance improvements for the safety service. For the cases with $\eta = 5$ and $\eta = 10$, their performance is almost the same. The reason is that when $\eta = 5$, the safety services have acquired enough high-performance resources and achieved the best transmission performance. In this situation, if still more resources are allocated to the safety service, the performance degradation of the non-safety service will decrease the whole utility instead. Therefore, further increasing η from 5 to 10 does not bring in performance improvement for the safety service.

In space-ground integrated networks, data services can be allocated to diverse network resources for transmissions. Nevertheless, in practice, even though the space and ground

Algorithm 1: the Q-learning based resource allocation scheme

Initialize: $t = 0, Q(s,a) = 0, p = 1$;
network selection:
  generate a random number r between 0 and 1;
  if $(r < \varepsilon)$
    randomly select an action
  else
    select the action a_t that has the maximum $Q(s_t, a_t)$
  end if
  execute a_t
channel allocation:
  k=0;
  if $I_i = I_j =, ..., I_q$ with $i, j, ..., q \in \{1, 2, ..., Q\}$
    sort the service levels $L_{(i)} > L_{(j)} >, ..., L_{(q)}$ with $\eta_{L_{(i)}} > \eta_{L_{(j)}} >, ..., \eta_{L_{(q)}}$;
    while k< B_{X,I_i} do
      for $L = L_{(i)}, L_{(j)}, ..., L_{(q)}$
        if $C^L_{j \to I_i}(p) < C^L_{th}$
          $C^L_{j \to I_i}(p) = C^L_{j \to I_i}(p) + b_{(k)}$
          k=k+1;
        else
          break;
        end if
        $\mathrm{BER}^L_{j \to I_i}(p) = BER_{I_i}; \mathrm{D}^L_{j \to I_i}(p) = D_{I_i}$
      end for
    end while
  else
    for $q = 1, 2, ..., Q$
      while k< B_{X,I_q} do
        if $C^q_{j \to I_q}(p) < C^q_{th}$
          $C^q_{j \to I_q}(p) = C^q_{j \to I_q}(p) + b_{(k)}$
          k=k+1;
        else
          break;
        end if
      end while
      $\mathrm{BER}^q_{j \to I_q}(p) = BER_{I_q}; \mathrm{D}^q_{j \to I_q}(p) = D_{I_q}$
    end for
  end if
end channel allocation
  calculate immediate reward R_t through (13)-(15) and (21)
  observe the next state $s_{t+1} = p + 1$
  update the Q-value table: $Q_t(s,a) = (1-\ell) Q_{t-1}(s,a) + \ell \left[R_t(s,a) + d \max Q^i_{t-1}(g,a) \right]$
  set $s_t = s_{t+1}$
end network selection

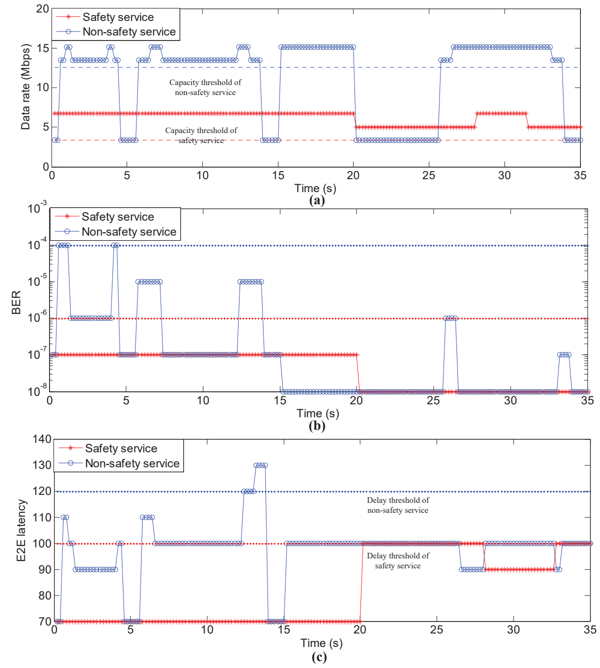

Fig. 4. Performance of safety-oriented resource allocation scheme: (a)data rate, (b) BER, (c) E2E latency.

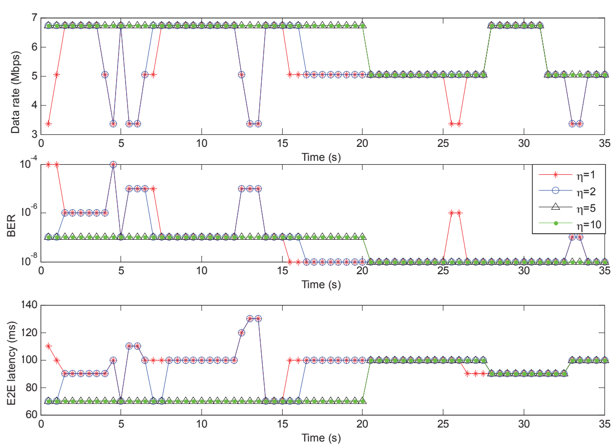

Fig. 5. Performance of safety service under different η: (a) data rate, (b) BER, (c) E2E latency.

networks are unified, they may still run different protocols and use different physical layer technologies to adapt to their specific communication environments. Consequently, during the data transmissions of one service, handovers between two networks may bring in capacity degradation due to the signaling exchanges and data combinations. Based on this observation, in the proposed scheme, a handover discount factor is introduced to avoid unnecessary handovers. As the transmission performance for the safety service is always our main concern, Fig. 6 displays the data rate of the safety service under different network handover discount values. In the case with $\delta = 1$, no discount is added to the final utility, and therefore handovers happen more frequently, resulting in data rate decreases. For the cases with $\delta = 0.5$ and $\delta = 0.6$, due to the considered handover discounts, some unnecessary network handovers are avoided, thereby achieving higher data rate performance. Nevertheless, when further decreasing the value of δ to 0.2, that is, the discount percentage of a handover is increased to 80%, the data rate of the safety service declines again. This is because in this situation, even when the transmission performance of current networks degrades to unacceptable levels, the high handover discount still prevents services from switching to other networks and keep them in the low-performance network, resulting in the lower data rate. Based on these results, in practical network operations, we need to carefully set the handover discount value to balance the handover gains and costs.

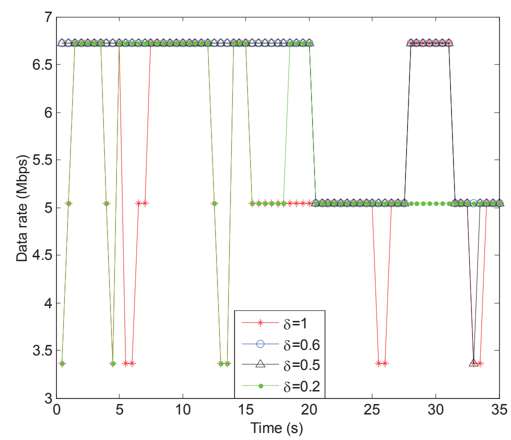

Fig. 6. Data rate of safety service under different δ.

Finally, Fig.7 presents the data rate comparisons of the safety service under the proposed, the greedy, and the random resource allocation schemes. Since till now, there are few literatures on the resource allocation for space-ground integrated HSR networks, especially from the perspective of preferentially guaranteeing the safety services, we only compare the proposed scheme with the intuitive greedy and random resource allocation schemes. In the conventional greedy allocation scheme, the gain factor and the handover discount factor are not considered, that is, the safety and non-safety services are view as the same, handover costs are not taken into account, and the only purpose of the strategy is to maximize the overall utility. While in the random allocation scheme, the resources are randomly allocated to the two services without following any rules. The results demonstrate that within the whole transportation line, the proposed scheme can always outperform the conventional schemes in terms of guaranteeing the transmission performance for the safety service. Without giving the resource allocation priority to the safety service in the conventional two schemes, the data rates of the safety service under the random allocation scheme are even as low as zero at some points. Besides, in Fig.7, the transmission performance of the safety service under the situation without space networks to supplement the coverage holes of ground systems is also depicted. In the simulation scenario shown in Fig. 3(a), during the time from 15s to 25s, there is no terrestrial network coverage and therefore the safety

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service cannot be transmitted, causing railway transportation safety concerns. While this problem is well addressed by the space-ground integrated network.

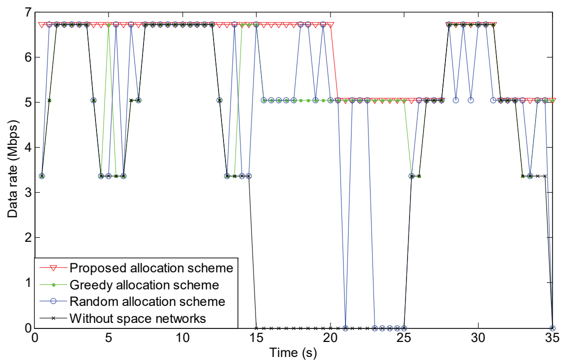

Fig. 7. Data rate of safety service under different schemes.

VI. Conclusions and Prospectives

Building on the C/U-plane decoupling and C-RAN technologies, we design a space-ground integrated cloud network to achieve seamless accesses for HSR where the transportation lines cross diverse terrains. The whole network includes the space and ground cloud layers, where the cloud BBU pools containing all LEO BBUs are deployed in GEO satellites. To improve the mobility support, we establish an additional handover-free BS-C-plane between trains and GEO satellites to benefit from the stable and ultra-wide terrestrial coverage of GEO satellites. Then, under this framework, we propose a safety-orientated resource allocation scheme, in which a gain factor and a handover discount factor are introduced to offer the resource allocation priority for safety services and to balance the costs and gains due to network handovers, respectively. Our simulation results have demonstrated that our proposed scheme can guarantee the transmission performance for safety services even under the situations with limited network resources. With diverse network resources, owing to the introduced handover discount factor in this scheme, the unnecessary network handovers and resulting resource costs are avoided. Note that although in this paper our study focus is on HSRs, the proposed space-ground integrated cloud network and the safety-oriented resource allocation scheme can also be utilized in other transportation industries. With regards to the network design, how to coordinate the common C-plane and the newly-added BS-C-plane to improve the network mobility support is still a remaining but worthwhile research problem. As software defined network (SDN) and network function virtualization (NFV) technologies have gradually become the major drivers of network architectural design and technological developments, SDN/NFV-enabled space-ground communication system integration and corresponding E2E resource allocation algorithms are promising research directions. Besides, not only in 5G millimeter wave communications, but also in future space access networks, massive antenna arrays will play an important role, and the resource management under this background will be another worthy research topic.

References

[1] R. He, C. Schneider, B. Ai, G. Wang, D. Dupleich, R. Thomae, M. Boban, J. Luo, z. Zhong, and Y. Zhang, "Propagation channels of 5G millimeter wave vehicle-to-vehicle communications: Recent advances and future challenges," *IEEE Vehicular Technology Magazine*, 2019, early access.

[2] R. He, B. Ai, G. L. Stber, G. Wang, and Z. Zhong, "Geometrical-based modeling for millimeter-wave MIMO mobile-to-mobile channels," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 4, pp. 2848–2863, Apri. 2018.

[3] R. He, B. Ai, G. Wang, K. Guan, Z. Zhong, A. F. Molisch, C. Briso-Rodriguez, and C. P. Oestges, "High-speed railway communications: From GSM-R to LTE-R," *IEEE Vehicular Technology Magazine*, vol. 11, no. 3, pp. 49–58, Sep. 2016.

[4] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, "Space-air-ground integrated network: A survey," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, pp. 2714–2741, Fourthquarter 2018.

[5] G. Maral, J. Restrepo, E. del Re, R. Fantacci, and G. Giambene, "Performance analysis for a guaranteed handover service in an LEO constellation with a "satellite-fixed cell" system," *IEEE Transactions on Vehicular Technology*, vol. 47, no. 4, pp. 1200–1214, Nov 1998.

[6] M. Chowdhury, R. Agarwal, V. Sekar, and I. Stoica, "A longitudinal and cross-dataset study of internet latency and path stability," 2014, Technical Report No. UCB/EECS-2014-172. http://www.eecs.berkeley.edu/Pubs/TechRpts/2014/EECS-2014-172.html.

[7] R. Goyal, S. Kota, R. Jain, S. Fahmy, B. Vandalore, and J. Kallaus, "Analysis and simulation of delay and buffer requirements of satellite-atm networks for tcp/ip traffic," 1998, https://arxiv.org/abs/cs/9809052.

[8] TR 38.811 V1.0.0 (2018-06), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on New Radio (NR) to support non terrestrial networks.

[9] L. Yan, X. Fang, and Y. Fang, "Control and data signaling decoupled architecture for railway wireless networks," *IEEE Wireless Communications*, vol. 22, no. 1, pp. 103–111, Feb. 2015.

[10] L. Yan, H. Ding, L. Zhang, J. Liu, X. Fang, Y. Fang, M. Xiao, and X. Huang, "Machine learning-based handovers for sub-6 GHz and mmWave integrated vehicular networks," *IEEE Transactions on Wireless Communications*, vol. 18, no. 10, pp. 4873–4885, Oct. 2019.

[11] L. Yan, X. Fang, and Y. Fang, "Stable beamforming with low overhead for C/U-plane decoupled HSR wireless networks," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 7, pp. 6075–6086, Jul. 2018.

[12] V. W. S. Wong, R. Schober, D. W. K. Ng, and L. Wang, *Key Technologies for 5G Wireless Systems*, Cambridge University Press, 2017.

[13] L. Boukhatem, D. Gaiti, and G. Pujolle, "A channel reservation algorithm for handover issues in LEO satellite systems based on a satellite-fixed cell coverage," in *Proceeding of* IEEE VTS 53rd Vehicular Technology Conference (VTC), Rhodes, Greece, vol. 4, May 2001, pp. 2975–2979 vol.4.

[14] Y. Shi, Y. Cao, J. Liu, and N. Kato, "A cross-domain SDN architecture for multi-layered space-terrestrial integrated networks," *IEEE Network*, vol. 33, no. 1, pp. 29–35, Jan. 2019.

[15] J. Liu, Y. Shi, L. Zhao, Y. Cao, W. Sun, and N. Kato, "Joint placement of controllers and gateways in sdn-enabled 5g-satellite integrated network," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 2, pp. 221–232, Feb. 2018.

[16] Y. Cao, Y. Shi, J. Liu, and N. Kato, "Optimal satellite gateway placement in space-ground integrated network for latency minimization with reliability guarantee," *IEEE Wireless Communications Letters*, vol. 7, no. 2, pp. 174–177, Apri. 2018.

[17] S. Zhou, G. Wang, S. Zhang, Z. Niu, and X. S. Shen, "Bidirectional mission offloading for agile space-air-ground integrated networks," *IEEE Wireless Communications*, vol. 26, no. 2, pp. 38–45, Apri. 2019.

[18] Y. Peng, T. Dong, R. Gu, Q. Guo, J. Yin, Z. Liu, T. Zhang, and Y. Ji, "A review of dynamic resource allocation in integrated satellite and terrestrial networks," in *Proceeding of* International Conference on Networking and Network Applications (NaNA), Xi'an, China, Oct. 2018, pp. 127–132.

[19] X. Zhu, C. Jiang, W. Feng, L. Kuang, Z. Han, and J. Lu, "Resource allocation in spectrum-sharing cloud based integrated terrestrial-satellite network," in *Proceeding of* International Wireless Communications and Mobile Computing Conference (IWCMC), Valencia, Spain, Jun. 2017, pp. 334–339.

[20] T. K. Saini, M. Kumar, and M. K. Dhaka, "Experimental validation of TCP performance in GEG satellite link conditions," in *Proceeding of* IEEE International Advance Computing Conference, Patiala, India, Mar. 2009, pp. 597–602.

[21] R. Wang, S. Horan, S. Kota, and B. Sun, "WLC40-2: An experimental evaluation of SCPS-TP over lossy GEO-space links," in *Proceeding of* IEEE Global Communications Conference (GLOBECOM), San Francisco, CA, USA, Nov. 2006, pp. 1–5.

[22] J. Zhang, E. Björnson, M. Matthaiou, D. W. K. Ng, H. Yang, and D. J. Love, "Multiple antenna technologies for beyond 5G," 2019, https://arxiv.org/abs/1910.00092.

[23] C. Li, Q. Luo, G. Mao, M. Sheng, and J. Li, "Vehicle-mounted base station for connected and autonomous vehicles: Opportunities and challenges," *IEEE Wireless Communications*, vol. 26, no. 4, pp. 30–36, August 2019.

[24] C. Huang, A. F. Molisch, Y. Geng, R. He, B. Ai, and Z. Zhong, "Trajectory-joint clustering algorithm for time-varying channel modeling," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 1, pp. 1041–1045, Jan 2020.

[25] Z. Sheng, H. D. Tuan, H. H. Nguyen, and Y. Fang, "Pilot optimization for estimation of high-mobility OFDM channels," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 10, pp. 8795–8806, Oct. 2017.

[26] I. Chlamtac, Y. Fang, and H. Zeng, "Call blocking analysis for PCS networks under general cell residence time," in *Proceeding of* IEEE Wireless Communications and Networking Conference (Cat. No.99TH8466), New Orleans, LA, USA, vol. 2, Sep. 1999, pp. 550–554 vol.2.

[27] R. Aggarwal, M. Assaad, C. E. Koksal, and P. Schniter, "Joint scheduling and resource allocation in the OFDMA downlink: Utility maximization under imperfect channel-state information," *IEEE Transactions on Signal Processing*, vol. 59, no. 11, pp. 5589–5604, Nov 2011.

[28] J. Francis and N. B. Mehta, "EESM-based link adaptation in point-to-point and multi-cell OFDM systems: Modeling and analysis," *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 407–417, January 2014.

[29] R. He, Z. Zhong, B. Ai, G. Wang, J. Ding, and A. F. Molisch, "Measurements and analysis of propagation channels in high-speed railway viaducts," *IEEE Transactions on Wireless Communications*, vol. 12, no. 2, pp. 794–805, Feb. 2013.

[30] E. Lagunas, S. K. Sharma, S. Maleki, S. Chatzinotas, and B. Ottersten, "Resource allocation for cognitive satellite communications with incumbent terrestrial networks," *IEEE Transactions on Cognitive Communications and Networking*, vol. 1, no. 3, pp. 305–317, Sep. 2015.

[31] J. Talvitie, T. Levanen, M. Koivisto, T. Ihalainen, K. Pajukoski, and M. Valkama, "Positioning and location-aware communications for modern railways with 5G new radio," *IEEE Communications Magazine*, vol. 57, no. 9, pp. 24–30, Sep. 2019.

[32] J. Li, Y. Zhang, Y. Zhang, W. Xiong, Y. Huang, and Z. Wang, "Fast tracking Doppler compensation for OFDM-based LEO Satellite data transmission," in *2016 2nd IEEE International Conference on Computer and Communications (ICCC)*, Oct. 2016, pp. 1814–1817.

[33] C. Qiu, H. Yao, F. R. Yu, F. Xu, and C. Zhao, "Deep Q-learning aided networking, caching, and computing resources allocation in software-defined satellite-terrestrial networks," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 6, pp. 5871–5883, Jun. 2019.

[34] M. Feng and S. Mao, "Dealing with limited backhaul capacity in millimeter-wave systems: A deep reinforcement learning approach," *IEEE Communications Magazine*, vol. 57, no. 3, pp. 50–55, Mar. 2019.

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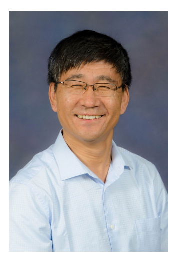

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