INTERLINK: A Digital Twin-Assisted Storage Strategy for Satellite-Terrestrial Networks

(Article begins on next page)

INTERLINK: A Digital Twin-Assisted Storage Strategy for Satellite-Terrestrial Networks

Liang Zhao, Chengcheng Wang, Kanglian Zhao, Daniele Tarchi, Shaohua Wan, and Neeraj Kumar

***Abstract*—Recently, low-orbit satellite networks have gained lots of attention from society due to their wide coverage, low transmission latency, and storage and computing capacity. Providing seamless connectivity to users in different areas is envisioned as a promising solution, especially in remote areas and for marine communication. However, when jointly used with terrestrial networks composing satellite-terrestrial networks (STNs), the satellite moving speed is much faster than the ground terminal, which can cause inconsistent service from a single satellite, and therefore lead to frequent satellite handover. Moreover, due to the dynamic and time slot visibility of satellites, the topology of an intersatellite changes frequently, which results in loops during satellite handover, thereby reducing the utilization of links. To address these problems, we propose a digital twin-assisted storage strategy for satellite-terrestrial networks (INTERLINK), which leverages the digital twins (DTs) to map the satellite networks to virtual space for better communication. Specifically, we first propose a satellite storage-oriented handover scheme (ASHER) to minimize the handover frequency by considering the limited access time and capacity constraints of satellites. Then, a multiobjective optimization problem is formulated to obtain the optimal satellite by genetic algorithm. Finally, considering the timing visibility of satellite links, a digital twin-assisted intersatellite routing scheme (ITO) is introduced to improve the quality of data delivery between satellites. Simulation results demonstrate that the proposed INTERLINK can reduce both handover times and average propagation delay compared with its counterparts. Meanwhile, benefitting from integrated DT, both the quality of data delivery and the delay of intersatellite links are considerably improved.**

***Index Terms*—Satellite-terrestrial network, digital twins, satellite handover, intersatellite routing, multiobjective optimization.**

I. Introduction

The 6G cellular communication is now developing [1] as future technology to provide ubiquitous broadband connectivity to users everywhere. Although the traditional terrestrial network mostly covers urban areas [2], it is unrealistic to deploy base stations and other communication infrastructures in remote areas, such as deserts and oceans [3]. Due to the increasing demand for data in these regions, satellite-terrestrial networks (STNs) are an effective solution [4] for 6G. An STN is a novel network architecture that fully utilizes the advantages of a low transmission delay and a wide coverage of low earth orbit (LEO) constellations to supplement terrestrial networks [5]. The data service requested by terrestrial users in different regions can be delivered anytime and anywhere by satellites. Currently, it has been widely used for post-disaster reconstruction, navigation, and intelligent transportation [6].

However, in STNs, the high mobility of LEO satellites always causes frequent satellite handover [7], because the satellites may move away from users before a service is complete. In general, a user's call duration [8] is usually longer than the service time that satellites can provide, resulting in a single satellite that is unable to provide continuous services for the users. Therefore, the user will select an alternative satellite to continue receiving the requested services when the connection with the current satellite is broken. In an STN, there is more than one satellite in the LEO constellation that can provide services to users at a certain time [9]. In addition, when users communicate with satellites, they inevitably need to access the storage resources of satellites. However, the total dosage of various radiation received by satellites in the universe is distinctive, as the satellites are not simultaneously launched into space. The damage degree of a satellite's hard disk is also distinguishing, which causes different access times and capacities for satellite storage. The access times reflect the number of times a satellite can be interacted with, and the capacities limit the storage and access of data content on a satellite. As a result, achieving more efficient satellite handover to ensure that a user's requested services continue is needed to solve.

Recently, many handover strategies have been proposed and most of them focus on single metrics such as the maximum elevation angle [10], the maximum service time [11], and the nearest location [12] when selecting alternative satellites. However, in practice, some satellite-related metrics, such as access times, also have a substantial impact on satellite service capabilities. Therefore, to meet the needs of continuous services and minimal handover times, it is necessary to design an effective handover strategy that can comprehensively utilize more features in STNs. A satellite handover refers to a new satellite selected to continuously provide services to users. Transmitting the content from the current satellite to the alternative satellite has also been a crucial problem.

The content delivery process can be explained as multihop

Liang Zhao is with School of Computer Science, Shenyang Aerospace University, China, and Digit Fujian Internet-of-Things Laboratory of Environmental Monitoring, Fujian Normal University, PR China; Chengcheng Wang are with Shenyang Aerospace University, China; (e-mails: lzhao@sau.edu.cn, wccwb1@outlook.com)

Kanglian Zhao is with School of Electronic Science and Engineering, Nanjing University, China; (e-mail: zhaokanglian@nju.edu.cn)

Daniele Tarchi is with Department of Electrical, Electronic, and Information Engineering, University of Bologna, Italy; (e-mail: daniele.tarchi@unibo.it)

Shaohua Wan is with School of Information and Safety Engineering, Zhongnan University of Economics and Law, Wuhan 430073, China. (e-mail: shaohua.wan@ieee.org)

Neeraj Kumar is with the Department of Computer Science and Engineering, Thapar Institute of Engineering and Technology, Patiala, India; (e-mail:neeraj.kumar@thapar.edu)

Shaohua Wan is the corresponding author.

TABLE I
LIST OF ACRONYMS

5G	$5^{th} generation$	6G	$6^{th} generation$
AI	artificial intelligence	ASHER	satellite storage-oriented handover
ACK	acknowledge character	CDR	content delivery ratio
DRL	deep reinforcement learning	DT(s)	digital twin(s)
DTN(s)	digital twin network(s)	GA	genetic algorithm
GPS	global position system	INTERLINK	digital twin-assisted storage strategy for satellite-terrestrial networks
IoV	Internet of Vehicles	ISL(s)	intersatellite link(s)
ITO	digital twin-assisted intersatellite routing	LEO	low earth orbit
LSN	low earth orbit satellite network	MARL	multi-agent reinforcement learning
MaRST	maximum remaining service time	MAT	maximum access times
MEC	mobile edge computing	MiRST	minimum remaining service time
MSC	maximum storage capacity	PD	propagation delay
PL	path length	QoS	quality of service
SDSN	software-defined satellite network	SSN(s)	small satellite networks
STN(s)	satellite-terrestrial network(s)	STK	System Tool Kit

routing from a source to a destination (i.e., from the current satellite to the selected satellite), which is a problem for routing decisions in satellite networks. Intersatellite links (ISLs) are the basis of satellite communication [13] and their establishment relies on the time slot visibility between satellites. In the STN, the highly dynamic nature of satellites makes frequent changes in the topology of intersatellite networks, which may cause repeated end-to-end ISL paths and long communication delays. Therefore, reasonably scheduling ISLs to overcome these weaknesses has become an urgent problem.

Utilizing the digital twin (DT) technology is a promising way to solve the aforementioned problems. As an emerging concept, DT has attracted significant attention in both academia and industry [14]. It is formally put forward for the first time in [15], encompassing three elements, including physical object in physical space, virtual object in virtual space, and data link between two spaces. DT has been applied in many domains, such as intelligent transportation system and healthcare, but there is no existing research on the combination of DT and satellite networks.

It is well known that the satellites are launched in orbit, therefore, the satellite orbit parameters can be easily obtained. However, due to the high-speed movement of satellites in space and the limitation of communication, some key data of satellites, such as the memory usage of satellites and the power of the battery on satellites, cannot be obtained in real-time. By introducing DT to satellite networks, the known data can be used to reproduce the operation state of satellites for providing auxiliary decision-making, meanwhile, preventing the expansion and deterioration of abnormalities and problems and improving the probability of satellite fault detection. Moreover, by constructing DT of physical satellite network, neighbouring satellites can collaborate for realizing a group of digital twin networks (DTNs). During the phrase of content delivery, we can derive the optimal routing path by pruning the network topology and carrying out virtual routing in advance in DTNs to calculate and verify a routing path before assigning it into real space. In addition, some prediction approaches can be implemented to express future network statuses and provide additional functionalities in DTNs.

As illustrated above, in this paper, we propose an effective handover and routing strategy in STN, known as digital twin-assisted storage strategy for satellite-terrestrial networks (INTERLINK), which involves two aspects. First, to minimize the handover frequency, we propose a satellite storage-oriented handover scheme (ASHER) to optimize intermediate satellite selection by considering limited access times and storage capacity constraints of the satellites jointly. We model it as a multiobjective optimization problem and apply the genetic algorithm (GA) to find its optimal solution. Second, targeting the content delivery process among satellites, we introduce a digital twin-assisted intersatellite routing scheme (ITO) to efficiently re-route user's data by verifying all potential routing paths in advance when handover happens. All the efforts made in this paper are focused on more continuous service and more efficient routing.

The main contributions of this paper are as follows.

- In STN, a handover and routing strategy, INTERLINK, is introduced with the advantages of (i) reducing handover frequency and delay, and (ii) improving the efficiency of routing throughout durations of communication.
- In order to minimize the handover times for better service continuity, we propose a satellite storage-oriented handover scheme (ASHER) by taking storage capacity, access times, and maximum remaining service times of satellites into consideration. The selection of optimal satellites is formulated as a multiobjective optimization problem and it is further settled based on the genetic algorithm.
- We introduce a digital twin-assisted intersatellite routing scheme (ITO), based on which efficient routing is realized. A time-varying graph is designed to find and verify all potential routing paths from the source satellite to the destination, in which the optimal one is further applied to the physical satellite network.

The rest of this paper is organized as follows. In Section II, we provide a literature review regarding the related work. Section III describes the system model construction and formulates the related problems. The proposed solutions are described in Section IV. In Section V, the simulation result is presented. Finally, we conclude this paper and highlight further directions of research in Section VI. For convenience,

TABLE II
DISCUSSION OF RELATED SOLUTIONS

Category	Objective(s)	Ref. No.	Scenario	Technique(s)	Considered factors
satellite handover	minimizing handover times	[8]	STN	multi-attribute decision making	channel quality, remaining service time, number of users served, power allocated by satellites
		[20]			receiving signal strength, remaining service time, satellites' idle channels
		[16]		real-time handover	trace angle, service time
		[21]		graph-based path finding	elevation angle, the number of free channels
		[24]		user-centric handover	satellite cluster, the length of handover window
		[25]		MARL-based handover	elevation angle, service state, channel budget
		[23]	SDSN	potential game-based handover	bipartite graph, available channels, userspace
	reducing call blocking probability	[17]	STN	Doppler-based prioritization	doppler shift, terminals' geometric characteristics
		[22]		channel assignment	available channels, mission priority
	handover scenario analysis	[18]		common coverage area based handover	service time, distance, number of idle channels
		[19]	satellite network	cross-layer handover	instantaneous elevation angle, handover rate
inter-satellite routing	improving routing adaptability	[26]	satellite network	ISL state information based routing	logical topology, satellite link state information, actual location information, delay
	reducing routing overhead	[27]		memory-efficient routing	location prediction, network recovery, flooding
		[28]		area-based hierarchical routing	satellite grouping, handover region size, neighbor
	avoiding data overcommitment	[29]		network-layer routing	the information about the schedule of future contacts between network nodes, satellite motion
	routing arrival	[31]		evolving graph	link connectivity prediction, the earliest path
	balancing delay and bandwidth	[32]		bandwidth-delay satellite routing	delay, bandwidth, weight factor of satellite links
	optimizing throughput	[33]		network coding based multipath cooperative routing	network coding, ACK, packet batch size, transmission times
	ensuring transmission QoS	[34]		storage time aggregated graph	flow-maximizing, the shortest path
	saving energy consumption	[36]		set of power model	link cost, recharge/discharge cycle number
		[37]		DRL-based energy-efficient routing	energy consumption, delay
	reducing computation complexity	[35]	SSN	netgrid-based shortest path routing	discrete netgrids, packet drop rate
digital twin	reducing offloading cost	[39]	vehicular edge computing	distributed multi-agent learning	cooperation gain, service matching, resource utilization
	minimizing offloading latency	[40]	MEC	mobile offloading	service migration, user mobility, rate failure rate
	reducing system cost	[41]	wireless network	digital twin wireless network	digital twin association, training data batch size, bandwidth allocation
	sensor validation	[42]	industry	machine learning architecture	temporal correlation, number of layers
	improving energy efficiency	[43]	air-ground	digital twin drone-assisted ground network	time-varying status of entities, reputation value, weighing benefits and costs, accuracy, energy
		[44]	air-assisted IoV	Stackelberg game-based incentive mechanism	resource scheduling and allocation, vehicle satisfaction, energy

the acronyms of this paper are listed in Table I.

II. RELATED WORK

In this section, we discuss the existing work from the perspectives of satellite handover, inter-satellite routing, and digital twin, and illustrate their distinctive characteristics in Table II.

A. Satellite Handover

Existing literature such as [8] [16]–[25] studied several problems related to satellite handover. Zhang *et al.* [8] jointly optimized the channel quality, the remaining service time, the number of users served, and the power allocated by satellites based on the bipartite graph. Wu *et al.* [16] utilized GPS and satellite diversity to enable the management of real-time handover for LEO satellite networks. Papapetrou and Pavlidou [17] proposed a Doppler-based dynamic handover strategy, whose effectiveness was proven by a queueing model. Papapetrou *et al.* [18] proposed an effective handover strategy based on the existing common coverage area between adjacent satellites, while also considering the maximum service time, the minimum distance, and the maximum number of idle channels. Bottcher and Werner [19] selected alternative satellites with the maximum elevation angle. However, this method did not achieve ideal results, because they found that it was not worth trying to maximize the instantaneous elevation when the "best" satellite relative to the selected strategy was not covered. Miao *et al.* [20] presented a multi-attribute joint handover by considering the received signal strength, remaining service time, and the number of satellite idle channels. Wu *et al.* [21] constructed a directed graph based on the coverage period of satellites for the satellite handover. The weights of the graph are assigned regarding various handover standards.

El Houda Hedjazi *et al.* [22] evaluated several LEO satellite constellation channel allocation strategies and simulated the impact of handover on the probability of call blocking. A satellite handover strategy based on the potential game of mobile terminals in the LEO network is presented [23]. It achieved Nash equilibrium between users and satellites in some cases. Li *et al.* [24] proposed a user-centered and ultradense LSN handover scheme based on satellite clusters. He *et al.* [25] proposed a satellite handover strategy based on Q-learning to minimize the average satellite handover times. Although existing work [16]–[25] proposed different schemes on satellite handover in LEO satellite networks, including single-parameter and multiparameter measurements, they do not consider the impact of access times and capacity constraints on satellite handover.

B. Inter-satellite Routing

The satellites selected by handover strategies directly determine the source and destination of intersatellite routing. At present, due to the high dynamics of satellites, research on intersatellite routing is in the development stage. The current existing routing algorithms are mostly based on the ISLs' time-evolving graphs [13]. For instance, Zhang *et al.* [26] proposed an improved routing algorithm based on the state information of ISLs, which helped them make decisions according to the link state and network topology between satellites. Pan *et al.* [27] proposed the shortest path first routing of path prediction. Zhang *et al.* [28] presented a region-based hierarchical routing to reduce routing overhead. Lowe *et al.* [29] proposed a routing strategy named Spae to achieve efficient data routing in a store-carry-forward fashion. In addition, Dijkstra, as a typical single-source shortest path algorithm, has been widely utilized in satellite networks to optimize routing [30]. Wang *et al.* [31] presented an evolving graph model and leveraged the Dijkstra algorithm to find the earliest arrival path. Zhang *et al.* [32] proposed a combinatorial satellite routing algorithm comprehensively considering both delay and bandwidth.

Tang *et al.* [33] proposed a source-based and destination-based multipath cooperative routing algorithm based on the network coding and adopted a novel ACK mechanism to accelerate the data transmission. Zhang *et al.* [34] leveraged the storage time aggregated graph to construct an on-demand mission model and simplified it to a multiple flow-maximizing problem to guarantee the mission QoS. Also, in [35], Li *et.al* developed a netgrid-based routing to search the optimal path in SSNs, where satellites are located by discrete netgrids rather than coordinates. Besides, considering the impact of battery energy on satellite lifetimes viewpoint, Yang *et al.* [36] routed traffic flows properly and switched relative sleep mode and Liu *et al.* [37] proposed a novel DRL-based energy-efficient routing to save energy consumption, respectively. The above literature verifies the routing performance based on a certain fixed policy on some indicators. However, it cannot guarantee the advantages of the corresponding scheme in all indicators. Accordingly, in this paper, we introduce digital twins to satellite networks to select the optimal routing path by verifying the performance of all potential paths with corresponding indicators rather than relying on a specific scheme.

C. Digital Twin

Recently, the digital twin (DT) has attracted great research attention in both academia and industry, especially focusing on manufacturing, healthcare, and intelligent transportation. For instance, Darvish *et al.* [38] comprehensively review the state-of-the-art about DT starting from the original definition with the manufacturing industry, including the concept, characteristic, and applications in its expanded field of the Internet of Things. Zhang *et al.* [39] incorporated DT and artificial intelligence (AI) into vehicular edge computing to improve task offloading efficiency, in which each roadside unit collects the computing capabilities and communication topology of its surrounding vehicles and shares the collected information to form the vehicular edge DTN. Sun *et al.* [40] introduced DT into mobile edge computing networks to leverage DTs to assist the mobile offloading decision by estimating the states of edge servers and providing deep reinforcement learning agent training data. In [41], Lu *et al.* proposed the DT-based wireless networks, then applied the blockchain and federated learning for collaborative computing.

Considering the unreliability of sensors, Minerva *et al.* [42] proposed a machine learning-based architecture for sensor validation to pave the way to reliable digital twins, which detected and identified the abnormal sensors, meanwhile, adjusted them with estimated data. Sun *et al.* [43] introduced digital twin and federated learning into the air-ground network to capture the time-varying status of entities. Wang *et al.* [44] conducted the digital twin of air-assisted Internet of Vehicles and used the Stackelberg games to maximize energy efficiency. At present, most existing literature on digital twins concentrated on employing it in 5G, 6G, federated learning, or mobile edge computing. However, there is no existing research on the combination of DT to satellite networks.

III. SYSTEM MODEL AND PROBLEM FORMULATION

Given the description of the previous sections, our goal is to find an effective handover scheme to reduce the amount of handovers of satellite-terrestrial networks and consider intersatellite routing to improve the content delivery ratio, reducing delays. In this section, we introduce the considered system model and the problem formulas.

A. System Model

As shown in Fig.1, in this paper, we consider a satellite handover and content delivery scenario for terrestrial users, consisting of a terrestrial layer and a space layer. The space layer is an LEO satellite constellation, which is used to provide a satellite backhaul system. The satellite constellation

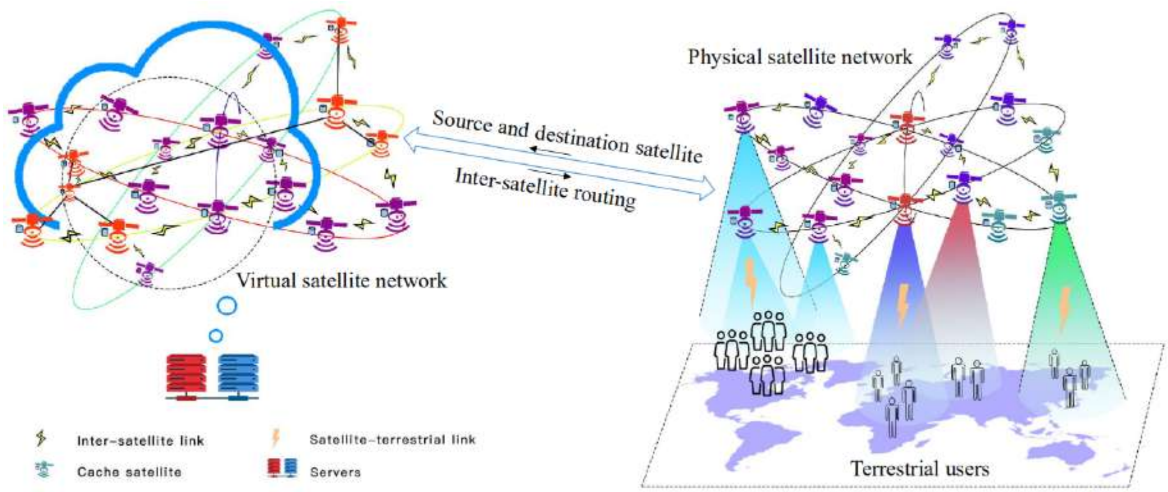

Fig. 1. The system scenario.

is composed of multiple LEO satellites in different orbits. The satellites, denoted by $\mathcal{S} = \{s_1, s_2, \cdots, s_N\}$, realize global coverage. We denote with N the total number of satellites. Each satellite is equipped with caching and processing capacities, and satellites in the same orbit have the same orbital altitude and inclination. The terrestrial layer consists of massive amounts of users denoted by $\mathcal{U} = \{u_1, u_2, \cdots, u_M\}$. M represents the number of users. We assume that users directly communicate with satellites and are stationary relative to the satellites. The notations frequently mentioned in this paper are presented in Table III.

The dynamics of satellites always lead to intermittent connections with users. However, in general, a user can build connections with more than one satellite at the same time because the satellite covers a wide-area. Once the elevation of the current satellite is approximately lower than the minimum elevation, it is necessary to select another satellite and reconstruct the satellite-user link for continuous service. The access satellites' choices directly determine the source point and destination point of intersatellite data transmission. In intersatellite networks, the routing strategies design always struggles with the dynamics of satellites and the time slot visibility. Thus, in this paper, we introduce digital twins (DTs) into the existing satellite network (left side of Fig. 1) to assist in making routing decisions. A digital twin network (DTN) is constructed by providing an accurate digital copy of real-world objects across multiple-intensity levels. It mainly contains physical objects in real space, virtual objects in virtual space, and data connections between two spaces. Note that this connection is bidirectional and enables real-time data interaction.

TABLE III
NOTATIONS

Notation	Definition
$\mathcal{S}$	satellite node set
$\mathcal{S}_\mathcal{C}$	candidate satellite node set
s_i	satellite node number
$\mathcal{U}$	user node set
u_j	user node number
Arr_i	service time matrix of satellite i
$T^b_{s_i}$	start service time of satellite i
$T^e_{s_i}$	end service time of satellite i
$\mathcal{T}^{re}_{s_i}$	remaining service time of satellite i
$G = (s_i, e)$	topological map composed of satellite i
e	edges in topology G
$\mathbb{Q}_{ij,t}$	the service quality of satellite i to user j at time t (obtained by joint optimization)
$\mathcal{A}_i$	the access time of satellite i
$\mathcal{C}_i$	the storage capacity of satellite i

B. Problem Formulation

1) satellite handover

As shown in the satellite handover process on the left side of Fig. 2, a user may be covered by multiple satellites. When the satellite connecting to the user moves away before service is completed, the user must select another satellite satisfying the conditions to rebuild the connection for continuous communication. Therefore, the selection of alternative satellites has a great impact on communication quality. To reduce handover times and delays, we propose a satellite storage-oriented handover scheme (ASHER) with limited access times and capacity constraints, which also considers the maximum remaining service time, the access times, and the satellites' storage capacities. Among them, the remaining service time plays a vital role, which directly determines the handover frequency.

In the single-user scenario, the remaining service time $\mathcal{T}^{re}_{s_i}$ is expressed as follows.

$$\mathcal{T}^{re}_{s_i} = T^e_{s_i} - T_h \tag{1}$$

where T_h is the time that the handover occurs and $T^e_{s_i}$ is the deadline for the satellite to provide services to the user. The selected alternative satellite only provides services for the user. The remaining service time, the access time, and the storage capacity of the satellite are not consumed by other users. Therefore, the calculation is relatively simple.

In the multi-user scenario, connections for communication are established between a satellite and multiple users, as

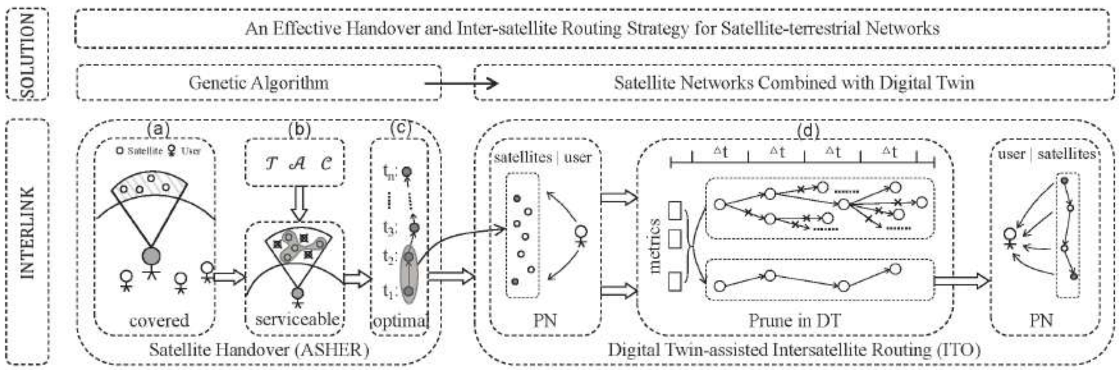

Fig. 2. The proposed INTERLINK in STN. (a) and (b) show the selection process of satellites with the capacity for coverage and service. (c) The optimal satellite for continuous communication is selected. (d) The DT-assisted routing scheme that aims to apply the optimal scheme among all potential routing paths to the physical satellite networks.

the satellite resources are shared by users. Therefore, it is necessary to calculate the relevant parameters of all candidate satellites by traversing their connected users and further select the most satisfying satellite. The three criteria for selecting the optimal alternative satellite are calculated as follows.

First, for the remaining service time $\mathcal{T}_{s_i}^{re}$ of satellite i, we have

$$\mathcal{T}_{s_i}^{re} = T_{s_i}^{e} - T_h - \sum_{j=1}^{M} T_{u_j}^{need} \quad (2)$$

where $T_{u_j}^{need}$ represented the service time required by user j. We need to consider whether all users connected to satellite i need corresponding service and the time they need.

Second, for the access times $\mathcal{A}_i^{re}$ of satellite i, we have

$$\mathcal{A}_i^{re} = \mathcal{A}_i - \sum_{j=1}^{M} \mathcal{A}_{u_j}^{need} \quad (3)$$

where $\mathcal{A}_i$ is the current access times of satellite i and $\mathcal{A}_{u_j}^{need}$ represents the amount required by user j.

Third, for the storage capacity $\mathcal{C}_i^{re}$ of satellite i, we have

$$\mathcal{C}_i^{re} = \mathcal{C}_i - \sum_{j=1}^{M} \mathcal{C}_{u_j}^{need} \quad (4)$$

where $\mathcal{C}_i$ is the current storage capacities of satellite i and $\mathcal{C}_{u_j}^{need}$ represents the requirement by user j.

Based on these analyses, for continuous connection to satellite-terrestrial links, it is essential to select the efficient optimal alternative satellites. Hence, in this paper, the problem with satellite handover is modeled as a multiobjective optimization problem, which can be formulated as follows.

$$\arg\max_{i} \mathbb{Q}_{ij,t} = \zeta(\mathcal{T}_{s_i}^{re}, \mathcal{A}_i^{re}, \mathcal{C}_i^{re}) \quad (5)$$

$$\begin{aligned} s.t. \quad & \mathcal{T}_{s_i}^{re} > 0 \\ & 0 < \mathcal{A}_i^{re} < A_{threshold} \\ & 0 < \mathcal{C}_i^{re} < C_{threshold} \end{aligned}$$

where $\mathbb{Q}_{ij,t}$ is the service quality of satellite i for user j at time t. ζ represents the joint optimization of the three achieved by assigning corresponding weights to the remaining service time $\mathcal{T}_{s_i}^{re}$, access times $\mathcal{A}_i^{re}$, and storage capacities $\mathcal{C}_i^{re}$ of satellites for selecting the optimal alternative satellite. $\mathcal{A}_{threshold}$ and $\mathcal{C}_{threshold}$ are the upper limits of access times and storage capacity of satellites, respectively.

2) intersatellite routing

The alternative satellites selected by the ASHER mentioned above directly determine the source and destination of intersatellite routing. Intersatellite links (ISLs) are the basis of satellite networks, and their establishment depends on the visibility between satellites. As the number of satellites increases, the visible relationships in satellite networks become more complex. Meanwhile, the highly dynamic nature of satellites makes frequent changes in the topology of intersatellite networks, thereby causing repeated end-to-end ISL paths and long communication delays. To address this problem, we introduce the concept of DT to satellite networks to assist intersatellite routing.

As shown on the right of Fig. 2, we construct DTNs in space according to the real-time satellite network status. We assume the neighbouring satellites can collaborate and build a distributed computing service for realizing DTNs. A DTN has the same number of entities (satellites and users) and related information as the real satellite network. Moreover, prediction approaches can be implemented for constructing DTNs to express future network statuses and provide additional valuable functionalities. In the intersatellite content delivery stage, a large number of loops may exist due to the dynamics and time slot visibility of satellites, which will lead to a low link utilization and a long delay. We prune the network topology to derive the optimal path by carrying out virtual routing in advance in DTNs to calculate and verify a routing path before assigning it into the real space. As a result, the communication delay is reduced, improving the content delivery ratio. Specifically, when a user communicates to a satellite, we can obtain the end service time of the satellite. For the routing in DTNs, due to the periodic motion of satellites, we can also predict the satellite trajectories and obtain all alternative satellites in the next handover time. Meanwhile, we apply the GA to select the optimal candidate satellite and conduct routing planning to apply this route to the physical satellite network.

IV. SOLUTIONS

In this section, we elaborate on the solutions for satellite handovers and intersatellite routing. We first apply the genetic algorithm (GA) to directly solve the problem with satellite handovers. Second, we introduce DT, an accurate digital copy of real-world objects, to satellite networks to assist in routing decisions for better content delivery.

A. Solution to The Problem with Satellite Handovers

Under ideal conditions, users always wish to connect to the satellite with the longest remaining service time, the maximum access times, and the maximum storage capacity as the alternative satellite. However, in reality, it is almost impossible for any satellite to simultaneously meet the three conditions. To select better alternative satellites for continuous communication, in this paper, the problem is modeled as a combinatorial optimization issue (as shown in Equation (5)), which has been proven by NP-hard. We transform this problem into a single-objective optimization problem and find its optimal solutions using the genetic algorithm (GA). The satellite with the maximum $\mathbb{Q}_{ij,t}$ is selected each time as the alternative satellite. The reason for choosing GA to solve the problem is that it can handle all types of objective functions and constraints. GA also does not involve the derivative and differential process of the objective function value, because in practice, many objective functions are difficult to derive, and there is no derivative. In addition, it avoids the algorithm falling into the local optimum through mutation mechanisms and has a strong searchability. In the most intelligent search algorithms, its global optimization probability is the largest. Although the convergence speed of GA is relatively slow, this limitation can be ignored compared with the remaining time of satellite during the handover intermittent. The pseudocode of applying GA to select alternative satellites is described in Algorithm 1.

We initially set the value of $\mathbb{Q}_{ij,t}$ to a minimal negative number and the candidate satellite is set as $\mathcal{S}_\mathcal{C}$ = $\emptyset$ (Line 1). Then, according to the handover time T_h, we calculate all satellites satisfying the cover condition when handover occurs and add them to the candidate satellite set $\mathcal{S}_\mathcal{C}$ (Lines 2-8). Whether the satellite covers the user depends on whether the handover time T_h is within the serviceable time of the satellite. The service time matrix of s_i is represented as follows.

$$Arr_i = \begin{bmatrix} T^b_{s_{i,1}} & \cdots & T^b_{s_{i,k}} \\ T^e_{s_{i,1}} & \cdots & T^e_{s_{i,k}} \end{bmatrix}_{2\times k} \tag{6}$$

where k is the number of visible time slots between satellites and users during the simulation period. If T_h is between $T^b_{s_{i,k}}$ and $T^e_{s_{i,k}}$, we can say satellite i covers user j at time t.

Next, we traverse all candidate satellites and calculate the service time, access times, and storage capacity required by users connected to them to obtain the final parameters of satellites (Lines 10-16), and select the satellite with service capacity by comparing the resource threshold (Line 17). Finally, we use GA to calculate the fitness value of the current function (corresponding to satellite i) and compare them to obtain the satellite with the best $\mathbb{Q}_{ij,t}$ (Lines 20-25).

Algorithm 1: GA-based ASHER Scheme

Input: satellite number N, $\mathcal{S}$, user number M, $\mathcal{U}$, $\mathcal{S}_\mathcal{C}$, and Arr_i
Output: s_i with the maximum $\mathbb{Q}_{ij,t}$, $T^b_{s_i}$, and $T^e_{s_i}$

1 Initialize $\mathbb{Q}_{ij,t} = -\infty$, $\mathcal{S}_\mathcal{C} \leftarrow \emptyset$;
2 Get the handover_time T_h;
3 **for** i = *1 to* N **do**
4   **for** j = *1 to* k **do**
5   **if** $T^b_{s_{i,j}} \leq T_h \leq T^e_{s_{i,j}}$ **then**
6       $\mathcal{S}_\mathcal{C}$ = $\mathcal{S}_\mathcal{C} \cup \{s_i\}$;
7   **else**
8   continue
9 **for** s_i, $\forall s_i \in \mathcal{S}_\mathcal{C}$ **do**
10   $\mathcal{T}^{re}_{s_i} = T^e_{s_i} - T_h$;
11   **for** u_M, $\forall u_M \in \mathcal{U}$ **do**
12   **if** s_i *covers* u_M *and* u_M *needs service of* s_i **then**
13   Calculate $T^{need}_{u_M}$, $\mathcal{C}^{need}_{u_M}$, and $\mathcal{A}^{need}_{u_M}$;
14   Calculate $\mathcal{T}^{re}_{s_i}$, $\mathcal{C}^{re}_i$, and $\mathcal{A}^{re}_i$;
15   **else**
16   continue;
17   **if** $\mathcal{T}^{re}_{s_i} < 0 \ || \ \mathcal{A}^{re}_i < \mathcal{A}_{threshold} \ || \ \mathcal{C}^{re}_i < \mathcal{C}_{threshold}$ **then**
18   continue;
19   **else**
20   Call GA to calculate the fitness value of s_i;
21   **if** *fitness value* $> \mathbb{Q}_{ij,t}$ **then**
22   Record the s_i, $T^b_{s_i}$, $T^e_{s_i}$, and other parameters.
23   (The population size P is 100; The maximum evolution algebra E is 500; The crossover parameter is 0.7; The mutation probability is 0.01.);
24   **else**
25   continue;

As stated above, this algorithm is divided into two parts, candidate satellite discrimination and optimal satellite selection. The former is realized by judging whether the satellite has the service capability for the current user when handover happens. The algorithmic complexity is $O(Nk)$. The latter is to select the optimal one from all candidate satellites, which involves the consumption of variable computation and GA application. The algorithmic complexity is $O(c(M+PE))$, in which c is the number of candidate satellites. Therefore, the algorithmic complexity of the proposed GA-based approach is $O(Nk + c(M+PE))$.

B. Solution to The Problem with Intersatellite Routing

When the current satellite connected to the user moves away before a service is completed, another satellite is needed to rebuild the connection for continuous service. In this situation,

Algorithm 2: Time-based Topology Generation

Input: s_i, $T^b_{s_i}$, T_{s_i},s_j, $T^b_{s_j}$, T_{s_j}, satellite number N
Output: satellite visibility topology G
1 Initialize: L_s = [s_i,], L_d = [ ];
2 $t = T^e_{s_j} - T^e_{s_i}$, $t_{up} = T^e_{s_i}$;
3 Divide t into m time slots, $\Delta t = t_{m+1} - t_m$;
4 **for** $p = 1$ *to* m **do**
5 $\quad t_{now} = t_{up} + \Delta t$;
6 $\quad$ **for** $\forall s_k,\ s_k \in L_s$ **do**
7 $\quad\quad$ **for** $l = 1$ *to* N **do**
8 $\quad\quad\quad$ **if** $l \neq k$ **then**
9 $\quad\quad\quad\quad$ **if** *s_k and s_l are visible in time slot (t_{up}, t_{now})* **then**
10 $\quad\quad\quad\quad\quad L_d[\,] \leftarrow s_l$;
11 $\quad\quad\quad\quad\quad$ add_edge(s_l, s_k);
12 $\quad\quad\quad\quad\quad$ Set the weight of the edge of (s_l, s_k) to m;
13 $\quad\quad\quad\quad$ **else**
14 $\quad\quad\quad\quad\quad$ continue;
15 $\quad\quad\quad$ **else**
16 $\quad\quad\quad\quad$ continue;
17 $\quad L_s[\,]$ $\quad L_d$;
18 $\quad L_d$ = [ ];
19 $\quad t_{up} = t_{now}$;
20 return G;

Algorithm 3: The Process of Routing Discovery

Input: G', s_i, s_j, m, N
Output: route $[s_i, \cdots, s_k, \cdots, s_j]$
Initialize S_v = [ ], Q_v = [ ];
for $k = 1$ *to* m **do**
$\quad$ **for** $l = 1$ *to* N **do**
$\quad\quad$ **if** *there is an edge between s_i and s_l and $weight == k$* **then**
$\quad\quad\quad S_v[\,] \leftarrow s_l$;
$\quad\quad$ **else**
$\quad\quad\quad$ continue;
$\quad$ **if** $k == m$ **then**
$\quad\quad$ **if** *s_j in S_v* **then**
$\quad\quad\quad$ route[s_i,] $\leftarrow$s$_j$; //one valid routing
$\quad\quad\quad k = k - 2$, $S_v = [\,]$;
$\quad\quad\quad$ Delete the last two elements of the route;
$\quad\quad\quad$ **if** *the tuple with the last element of current route and k is in Q_v* **then**
$\quad\quad\quad\quad$ delete the tuple in Q_v and continue traversing;
$\quad\quad\quad$ **else**
$\quad\quad\quad\quad k = k - 1$;
$\quad\quad\quad\quad$ delete the last element of route;
$\quad\quad$ **else**
$\quad\quad\quad k = k - 1$, S_v = [ ];
$\quad\quad\quad$ Delete the last element of route;
$\quad\quad\quad$ Traversal Q_v, and find the first tuple with the last element in the route as the source node and the weight is k in Q_v;
$\quad\quad\quad$ **if** *there is no tuple* **then**
$\quad\quad\quad\quad k = k - 1$;
$\quad\quad\quad$ **else**
$\quad\quad\quad\quad$ Delete the tuple and find the next hop with its end node as the source node, and add it to the route as the new s_i.
$\quad$ **else**
$\quad\quad$ Add the S_p to the route, and add others to Q_v in the form of tuple [s_s, s_d, $weight$] in turns; //s_p is the first element of S_v;
$\quad\quad s_i = s_p$;
$\quad\quad S_v = [\,]$;
$\quad$ **if** $Q_v = NULL$ **then**
$\quad\quad$ break;
$\quad$ **else**
$\quad\quad$ continue;

transmitting the content on the current satellite to the alternative satellite is crucial and involves the intersatellite routing. However, due to the dynamics and visibility of satellites, the topology of the intersatellite changes more frequently which results in repeated end-to-end paths, thereby reducing the routing efficiency. Therefore, in this paper, we introduce DT to satellite networks to assist with routing decisions. The specific work is illustrated in the following.

First, according to satellite visibility, we propose an intersatellite topology based on time series. As shown in Algorithm 2, we divide the total time (the service time interval between the source and the destination satellites) into m time slots (Line 3) and continuously update the topology by considering the visibility of satellites in each time slot (Lines 4-19). Among them, the weight of edges (visible satellite pairs) in topology is set as the corresponding time slot (Line 12). In addition, the topology is stored in an adjacency table, which is expressed as follows.

$$M_x = \begin{bmatrix} [0,1,\ldots] & \cdots & [0,1,4,\ldots] \\ \vdots & \ddots & \vdots \\ [0,2,3,\ldots] & \cdots & [0,3,4,\ldots] \end{bmatrix}_{N\times N} \tag{7}$$

where the abscissa and ordinate of the matrix represent the satellite number, and the values in the matrix correspond to the visibility between satellites in the relevant time slots.

We can only build intersatellite topology according to the visibility of satellites in the current time slot. However, in reality, there may be some candidate satellites that are still visible in subsequent time slots. This may lead to satellites that have better service capability being forcibly replaced, reducing the routing performance. Therefore, we need to find satellites with better continuous visibility and further prune and update the built topology. Second, we traverse the modified topology and find all valid routing paths from the source to the destination. The pseudocode is shown in

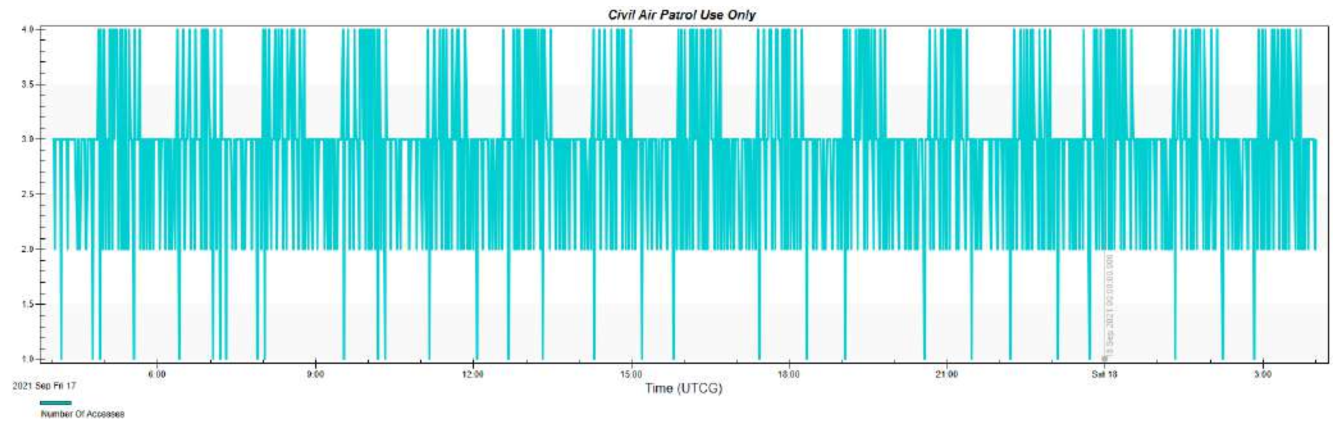

Fig. 3. Analysis of constellation coverage.

Algorithm 3.

The routing discovery process is an iterative process with continuous fallback. If the last time slot has not arrived, we need to continue traversing later slots (Lines 27-29). Otherwise, we determine whether the destination satellite is one of the currently visible satellites. If the destination satellite exists, a valid routing is found (Lines 10); otherwise, we need to return to the previous time slots and continue traversal (Lines 19-25). Whether the routing path is found or not, we need to return to continue searching all of the valid paths (Lines 11-25). When there are no traversable nodes, the algorithm ends (Lines 30-33). Finally, we will obtain L potential routing paths. Then, we verify all routing paths by DT and select the optimal path.

V. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

This section is devoted to the performance evaluation of our proposed ASHER and ITO content delivery scheme. First, we introduce the simulation settings, including basic settings and descriptions, evaluation metrics, and solutions for comparison. Second, experimental simulations and corresponding evaluations are conducted.

A. Simulation Setup

1) basic settings and parameter descriptions

The visibility of satellites and users is affected by a constellation and an on-board scanning angle. In general, the smaller the on-board scanning angle is, the more satellites are required for continuous coverage. In our simulation, we developed a simulation platform using Python 3.8 and generated an LEO constellation using the System Tool Kit (STK). The scanning angle of satellites is set to $45°$. Through the adjustment of Walker in STK, we found that it could provide continuous coverage when the constellation scale is 12×12. However, only one or two satellites can provide services once; thus, it is not necessary to optimize satellite selection. Therefore, considering the number of visible satellites and the need for continuous coverage, we opted for the constellation with a scale of 15×15. The coverage relation between satellites and users during the simulation in STK is shown in Fig. 3. The simulated LEO constellation is shown in Fig. 4. More simulation parameters are listed in Table II. In addition, we have made our simulation source available at https://github.com/NetworkCommunication/interlink-wcc.

TABLE IV
SIMULATION PARAMETERS

Parameter	Value
simulation time	24 hours (2021/9/8 - 2021/9/9 04:00)
type of satellites	LEO
altitude	1000 km
inclination	52°
cone half angle	45°
number of planes	15
number of satellites per plane	15
inter plane spacing	1
call duration	600, 1200, 1800, 2400, 3000 s
time interval size	200 s
content size	1 $\sim$ 10 GB
number of content	1000
access times	0 $\sim$ 7000
storage capacity	150 $\sim$ 500 GB
speed	3×10^8 m/s

2) evaluation metrics

We introduce the following metrics to evaluate the simulation performance:

(a) Handover times are the total number of satellites that establish a communication connection with the user in throughout corresponding call duration. Generally, low handover frequency can maintain long and stable communication.

(b) Communication delay is the total time that data content is transmitted in satellite-terrestrial links, which depends on the distance between satellites and users, as well as the speed of transmission. Here, a smaller delay denotes a better quality of communication service. In this paper, speed is defined as the speed of light.

(c) Path length (PL) indicates the content transmission distance from the source satellite to the destination satellite in ISLs, calculated by the sum of the distance between every two hops. The distance of the route indirectly determines the delay in the space layer.

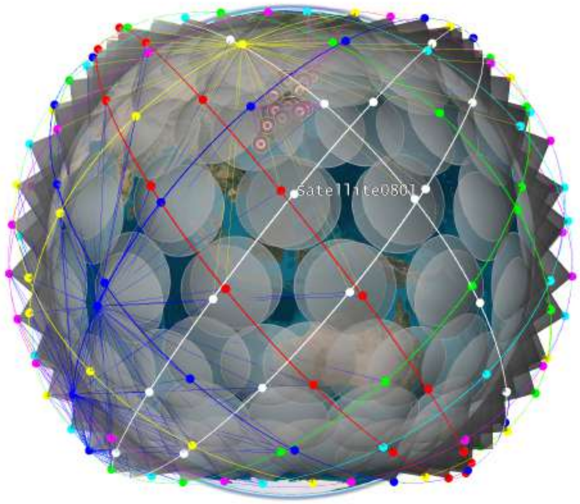

Fig. 4. The simulated LEO constellation in STK (the circular curves wrapping the earth represent different orbits, the solid dots on the curves represent satellites, the texts like "Satellite0801" represent satellite numbers, the gray circle shadows indicate the coverage of on-board sensors, and the yellow and blue lines connecting satellites indicate that satellites are visible to each other in the current time slot).

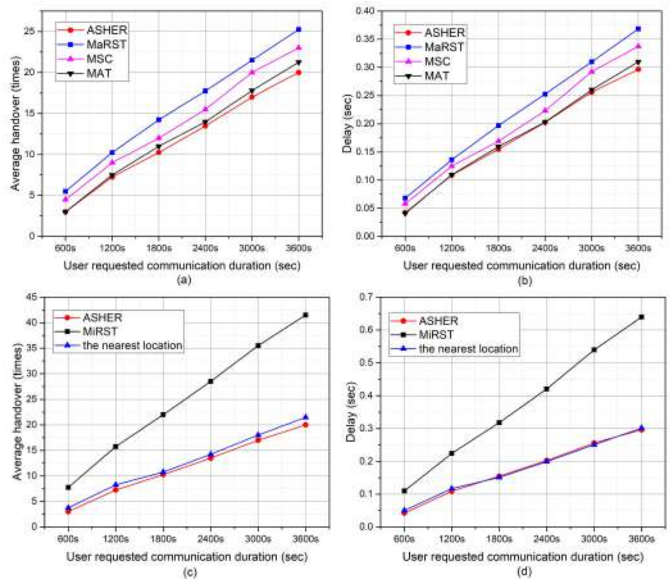

Fig. 5. Performance Comparison in single-user scenario. (a) and (b) are the comparative analysis of the proposed scheme and its single influence factor in terms of handover times and delay, respectively. Accordingly, (c) and (d) are the comparisons between our proposed scheme and other handover schemes.

(d) Propagation delay (PD) is a vital component of end-to-end delay, which is determined by the path length and propagation speed. When the speed is constant, the longer the path length is, the larger the propagation delay is.

(e) Content delivery ratio (CDR) is defined as the probability of successful data delivery from source to destination.

To better evaluate the proposed scheme, we consider scenarios with different request communication durations of users. Specifically, we set up six groups of experiments with a different call duration from 600 to 3000, with an interval of 600.

3) solutions for comparison

In this paper, the comparisons are divided into two parts. First, for satellite handover, we compare the performance in handover times and delay of our proposed ASHER scheme with five different algorithms, maximum remaining service time-based handover, MaRST, maximum storage capacity-based handover, MSC, maximum access times-based handover, MAT, minimum remaining service time-based handover, MiRST, and the nearest location-based handover [12].

(a) MaRST and MiRST are introduced as a common and simple handover schemes in satellite-terrestrial networks, which completely depend on the remaining time of satellites. The remaining time of satellites directly determines the handover frequency. During satellite handover, the former selects the satellite with the largest remaining service time to take over the service. However, the latter selects the satellite with the smallest remaining service time.

(b) MSC and MAT are satellite storage-oriented handovers, which fully consider the condition that satellites are not simultaneously launched into space.

(c) The nearest location-based handover scheme depends on the location of satellites and users, in which the satellite with the shortest distance to users is selected each time.

Second, for intersatellite routing, we compare the performance in the content delivery ratio of our proposed ITO with the scheme based on Dijkstra [30] and the nearest location [12]. Dijkstra's algorithm, as one of the shortest path algorithms, was initially widely used in intersatellite routing. It chooses the shortest path from all of the paths. The nearest location-based scheme selects the node that is closest to it as the next-hop each time to construct the route.

B. Simulation Results and Performance Evaluation

1) comparative analysis of satellite handover scheme

Fig. 5 and Fig. 6 illustrate the average handover times and communication delay for varying communication durations ranging from 600 seconds to 3600 seconds in single-user and multi-user scenarios, respectively.

(i) single-user scenario

Fig. 5(a) and Fig. 5(c) show the comparison of different handover schemes in terms of handover times under a single-user scenario. With increasing call duration, the average handover times of all schemes linearly increase. This tendency occurs because the longer the request call duration is, the more frequent information exchange and access to satellites, which is in line with actual results. The comparison of the proposed ASHER with MaRST, MSC, and MAT is shown in Fig. 5(a). It is clear that our proposed handover scheme based on ASHER has the minimum handover times under the same duration since we consider the three single impact factors.

Fig. 5(c) illustrates the changes in average handover times under different call durations of our proposed ASHER with MiRST and the nearest location-based handover scheme. By comparison, we find that the MiRST-based scheme has the maximum handover times, which can be explained by the fact

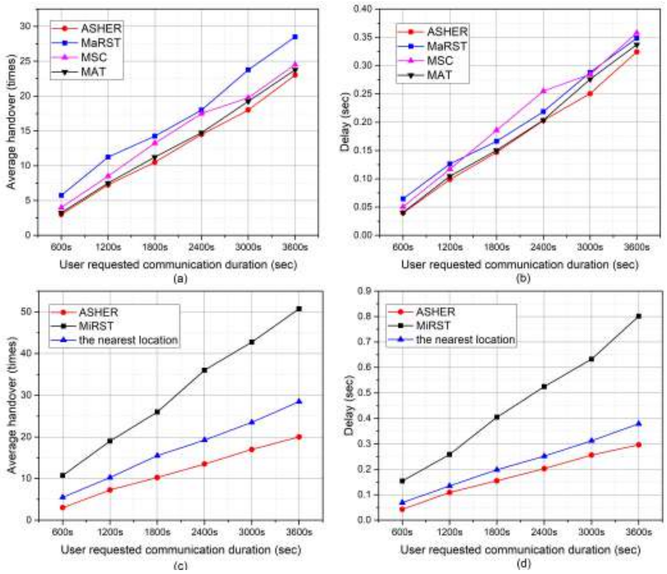

Fig. 6. Performance Comparison in multi-user scenario. (a) and (b) are the comparative analyses of the proposed scheme and its single influence factor in terms of handover times and delay, respectively. Accordingly, (c) and (d) are the comparisons between our proposed scheme and other handover schemes.

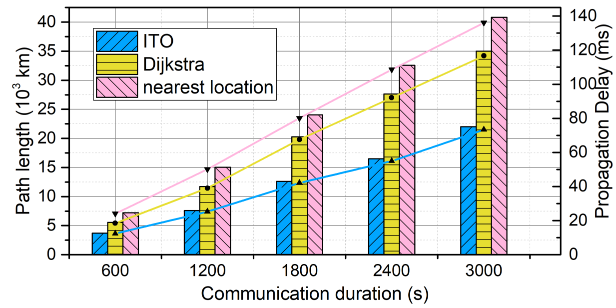

Fig. 7. Influence of different routing schemes on path length and propagation delay.

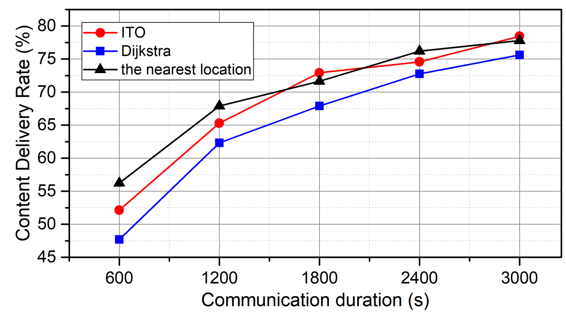

Fig. 8. Influence of different routing schemes on the content delivery ratio.

that the remaining satellite service time directly determines the handover times between users and satellites. The shorter the remaining service time is, the more frequent handover times are. Compared with the nearest location-based scheme, although the gap is small, our strategy still has a slight tread.

Fig. 5(b) and Fig. 5(d) show the effect of different call durations on the delay. As the call duration increases, the delay of all schemes increases, and our proposed scheme has the lowest delay. Meanwhile, the delays of ASHER, MAT, and the nearest location-based scheme are roughly similar, which can be explained by the following: (1) in reality, we cannot acquire accurate information about the access times of hard disks on satellites, and (2) the relative position relationship between satellites and users is the main impact factor of delay. For the former, we can only make a rough estimation. For the latter, the closer the relative position, the smaller the delay. However, even in this situation, we can prove the superiority of our proposed scheme.

(ii) multi-user scenario

The comparison of ASHER, MaRST, MSC, and MAT for evaluating the average handover times over varying call durations under a multi-user scenario is shown in Fig. 6(a). The results show that as the call duration increases, the average handover times of the four schemes increase. However, compared with the single-user scenario, the impact of different schemes on handover times remains relatively larger. The reason for this is that in the multi-user scenario, other users also access the service of satellites. If only a single factor is considered, it certainly has an impact on the total transmission. Nevertheless, our proposed ASHER still has the lowest handover times, which expresses the stability of the ASHER.

Fig. 6(c) demonstrates the results of ASHER, MiRST, and the nearest location-based scheme in terms of handover times. We found that, as the call duration increases, our proposed ASHER has a lower handover frequency. Thus, the advantage is expanding because we fully consider multiple satellite impact factors. Meanwhile, compared with the single-user scenario (as shown in Fig. 5(c)), the effect is more intuitive.

Fig. 6(b) and (d) illustrate the delay of different schemes for varying call durations in the multi-user scenario. With the increase in call duration, the delay brought by all schemes also increases. As shown in the analysis in Fig. 6(a), due to the access of satellites by other users, the curves in Fig. 6(b) also exhibit relative fluctuations. However, the final results are the same which denotes our proposed ASHER has a better performance. The results in Fig. 6(d) also further expand the advantage of our proposed scheme.

2) comparative analysis of intersatellite routing

For intersatellite routing, we evaluate our proposed schemes in terms of path length and content delivery ratio.

(i) evaluation of PL and PD

The relationship between routing distance, propagation delay, and call durations is shown in Fig. 7. As a result of the increase in call durations, the PL of all three schemes shows an upward trend. This tendency occurs because, throughout a long call duration, more satellites are likely to be accessed. Compared with Dijkstra, the scheme based on the nearest location has the longest routing distance, because it selects the closest candidate satellite as the next hop each time, which cannot guarantee the shortest total routing distance from the source to the destination. In our proposed ITO scheme, the intersatellite topology has been pruned and updated and routing paths have been extensively evaluated in parallel digital twin networks before being deployed. Thus, the proposed scheme displays an acceptable performance in PL. Meanwhile, we can also see that, as the call duration increases, the PD of all three schemes still increases, which is because when the speed is constant, the distance determines the propagation delay. That is, the longer the path length is, the larger the propagation delay we can have. Therefore, as shown in Fig. 7, the results tend of the three schemes in terms of PL and PD are consistent.

(ii) evaluation of CDR

Fig. 8 illustrates the changes in the content delivery ratio under varying call durations. As shown, with an increasing period of call durations, the CDR of all three schemes almost shows an upward trend. This is because, in short call duration, the alternative routing paths and the storage capacity of satellites are limited, while experiencing a long duration, the situation is greatly improved. We can find that the ITO scheme has better CDR because the routing is trained in DTNs in advance, especially in the long call duration. However, as shown in Fig. 8, there are some close overlapped points. This can be explained by the fact that during content delivery, the storage capacity of satellites is a vital factor. It cannot be excluded that the same CDR can be obtained under some routing paths.

VI. Conclusion

In this paper, we presented a satellite storage-oriented handover scheme (ASHER) with limited access times and capacity constraints for STNs, while also considering the maximum remaining service time, the access times, and the storage capacity of satellites. We formulated the handover issue as a multiobjective optimization problem and found its optimal solution by the genetic algorithm (GA). The alternative satellites selected by ASHER directly determine the source and destination of intersatellite routing. However, due to the satellites' dynamics, the topology of the intersatellite changes frequently which results in loops during satellite handover, thereby reducing the routing efficiency. Therefore, we construct INTERLINK and propose the digital twin-assisted intersatellite routing scheme (ITO) to better plan the routing and ensure that the content required by users is always maintained above users. Simulation results have shown that the proposed ASHER can effectively reduce handover times and communication delays. Meanwhile, the content delivery ratio can be improved by applying ITO.

In future work, we will extend current research to further investigate some applications under the direction of combining digital twin and satellite networks, such as computational offloading and content caching, to explore additional harvest.

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Liang Zhao (Member, IEEE) is a Professor at Shenyang Aerospace University, China. He is a member of IEEE INGR SatCom and IEEE ComSoc SSC. He received his Ph.D. degree from the School of Computing at Edinburgh Napier University in 2011. Before joining Shenyang Aerospace University, he worked as associate senior researcher in Hitachi (China) Research and Development Corporation from 2012 to 2014. His research interests include ITS, VANET, WMN and SDN. He has published more than 120 papers. He served as the Chair of several international conferences and workshops, including 2021 IEEE TrustCom (Program Co-Chair), 2019 IEEE IUCC (Program Co-Chair), and 2018-2021 NGDN workshop (founder). He is Associate Editor of Frontiers in Communications and Networking and Journal of Circuits Systems and Computers. He is/has been a guest editor of IEEE Transactions on Network Science and Engineering, Springer Journal of Computing, etc. He was the recipient of the Best/Outstanding Paper Awards at 2015 IEEE IUCC, 2020 IEEE ISPA, and 2013 ACM MoMM.

Chengcheng Wang received the B.S. degree in computer science and technology from Shenyang Aerospace University, Shenyang, China. She is currently working toward the master's degree in Computer Science, Shenyang Aerospace University. Her research interests mainly include SDN, DT, and satellite networks.

Kanglian Zhao received his B.S. degree in Electronic Science and Technology and his Ph.D. degree in Circuits and Systems, both from Nanjing University, Nanjing, China in 2003 and 2014 respectively. He has been with School of Electronic Science and Engineering, Nanjing University since 2003, where he is currently an Associate Professor in the Department of Communications Engineering and the Institute of Space-Terrestrial Intelligent Networks, Nanjing University. He was with K.U. Leuven and IMEC as an International Scholar from Aug. 2009 to Aug. 2010. His current research interests include network architectures and protocols for space internetworking, delay/disruption tolerant networking, and satellite-terrestrial integrated communications. He is currently a member of Subcommittee on Space Data and Information Transfer of National Technical Committee on Space Technology and Operation, Standardization Administration of China (SAC/TC425/SC3).

Daniele Tarchi (Senior Member, IEEE) received his M.Sc. degree in Telecommunications Engineering and Ph.D. degree in Informatics and Telecommunications Engineering from the University of Florence, Italy, in 2000 and 2004, respectively. Since 2019 he is an Associate Professor at the University of Bologna, Italy. He is the author of around 130 published articles in international journals and conference proceedings. His research interests are mainly on Wireless Communications and Networks, Satellite Communications and Networks, Edge and Fog Computing. Prof. Tarchi is an IEEE Senior Member since 2012. He is Editorial Board member for IEEE Wireless Communications Letters, IEEE Transactions on Vehicular Technology and IET Communications.

Shaohua Wan (Senior Member, IEEE) received the Ph.D. degree from the School of Computer, Wuhan University in 2010. Since 2010, he has been an associate professor with the School of Information and Safety Engineering, Zhongnan University of Economics and Law. From 2016 to 2017, he was a visiting professor at with the Department of Electrical and Computer Engineering, Technical University of Munich, Germany. His main research interests include deep learning for Internet of Things and edge computing. He is an author of over 100 peer-reviewed research papers and books, including over 40 IEEE/ACM Transactions papers such as TII, TITS, TOIT, TNSE, TMM, TCSS, TOMM, PR, etc., and many top conference papers in the fields of Edge Intelligence.

Neeraj Kumar (Senior Member, IEEE) received his Ph.D. in CSE from SMVD University, Katra (J & K), India, and was a postdoctoral research fellow in Coventry University, Coventry, UK. He is a Professor in the Department of Computer Science and Engineering, Thapar Institute of Engineering & Technology, Patiala (Pb.), India since 2014. He is an internationally renowned researcher in the areas of VANET & CPS Smart Grid & IoT Mobile Cloud computing & Big Data and Cryptography.