A Survey on Laser Space Network: Terminals, Links, and Architectures

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ABSTRACT Due to the high directionality and short wavelength of laser transmission in space, satellite laser communication can achieve high speed, wide bandwidth, high precision, and high security with no electromagnetic spectrum constraints. It has become a promising direction to construct the laser space network. Recently, relative products, on-orbit demonstrations, and researches have been conducted on laser space networks. Considering this network as a graph, this paper presents a comprehensive survey from nodes, edges, to architectures of this graph, corresponding to laser communication terminals, laser space links, and laser space network architectures. For each content, current achievements are introduced and future trends are analyzed accordingly. Through this survey paper, we aim to present the prospect to develop laser space networks in the next space generation and provide potential research directions to interested researchers or engineers.

INDEX TERMS Laser space network, laser communication terminal, laser space link, software-defined satellite network.

I. INTRODUCTION

In order to break the regional limitation of satellite-ground transmission, building global satellite networks with intersatellite connections has become the development trend for the next generation of space networks. The intersatellite communication used radio frequency (RF) waves for transmission in the early time, whose transmission rate was limited and could not support the increasing transmission and access demands of clients. Due to the higher directionality and shorter wavelength compared with RF communication, laser communication has a higher data transmission rate, a higher security level, and is more robust to the communication environment, which is a promising direction to support intersatellite connections [1]. International ''Kuiper'' [2], ''Telesat'' [3], ''Starlink'' [4], ''Xingyun'' [5] constellations have adopted laser communication as one of their backbone transmission carriers, illustrating that the space network is transformed from ''radio era'' to ''laser era''.

Considering the laser space network (LSN) as a graph, it is composed of nodes, edges, and architectures. The

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nodes of LSN represent laser communication terminals (LCTs); the edges represent laser space links (LSLs); and the architectures comprehensively describe the organization of these nodes and edges, indicating the typologies and routing protocols of LSNs. Although the explorations of laser space networks have begun in the 1990s [6], it has aroused wide attention for the last five years. Thus, we mainly survey and present the latest achievements of LSN terminals, links, and architectures since 2015 in this paper. The development trends are accordingly analyzed for these three parts from their recent advances with respect to time. The paper organization is shown in Fig. 1. For the convenience of readers, we have provided summary tables, illustrations, and conclusion subsections in each section for clarification.

Since the LSN has been researched in the past few years, there have been several survey papers discussing this area. The papers [7]–[11] mainly survey challenges and potential solutions to free-space optical (FSO) communication systems on the ground. They have provided potential key features of FSO communications in the space domain, while there is lacking in a comprehensive survey of laser space networks. On the contrary, the survey [12] summaries the achievements
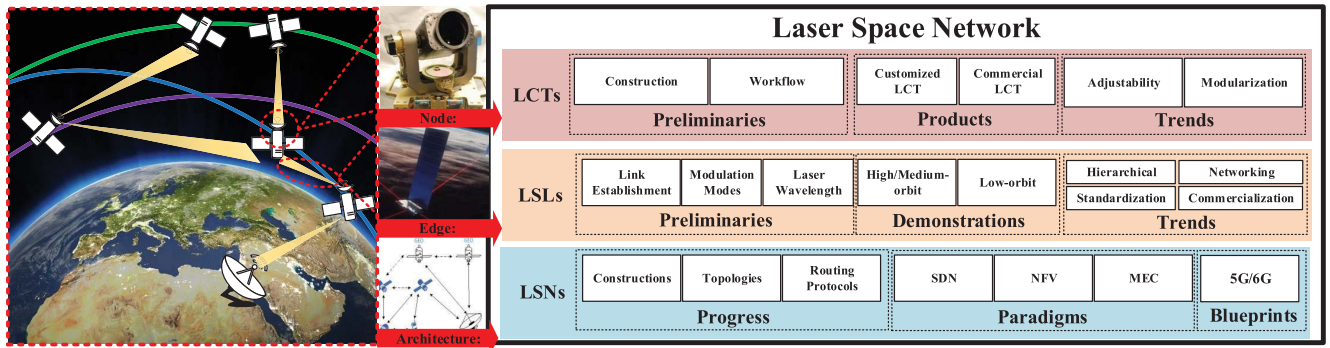
FIGURE 1. Paper organization.

in optical intersatellite communication, but until the year 2010. The paper [7], [13] discusses the recent advances of intersatellite optical links and challenges which would sway the performance. Compared with these survey papers, the scope of our survey paper is more extensive. It comprehensively introduces the progress and analyzes the future tendency of LSNs from the terminals, links, to architectures. The surveyed contents of our paper are more up-to-date, which can represent the latest development tendency of LSN.

In a word, the main contributions of our survey paper can be summarized as:

1) This paper comprehensively considers the key components of LSNs from the view of graph construction, including terminals, links, and architectures of this network. It is expected to provide a global view on the main research aspects in LSN to readers.

2) This paper selects and introduces a number of recent advances in academic or industrial areas of LSN, together with surveys and analysis on future plans. Thus readers can grasp both the progress and the development trends of LSN with respect to time.

3) This paper further provides explorations to adopt the latest techniques of software-defined network (SDN), network function visualization (NFV), and mobile edge computing (MEC) in LSNs. Their benefits and feasibility are demonstrated, which would be promising development directions for the next generation of LSN architecture, especially work for the large-scale satellite strategic deployment goals.

The rest of this paper is organized as follows. Sec. II introduces LCTs, denoted as the nodes of LSNs. Existed LCT products are surveyed from the customized and commercial types, and the progress tendency of LCTs is analyzed in this section. Sec. III presents the preliminary knowledge, on-orbit demonstrations, and development trends of LSLs, as the edges of LSNs. Sec. IV mainly introduces LSN architectures. It firstly surveys existing LSN architectures. Then it demonstrates the advantages and challenges to adopt techniques of SDN, NFV, 5G/6G LTE, and MEC in LSNs, and finally provides a vision of the future LSN architecture. In the end, Sec. V concludes the paper and points out the

prospects of LSNs for the next space generation. For the reading convenience, we summarize all abbreviations and their corresponding full names in Tab. 1.

II. LASER COMMUNICATION TERMINALS

In the graphs of LSNs, LCTs are considered essentially as nodes that carry out laser intersatellite communications. This section first introduces some preliminary knowledge about LCTs, including their constructions and workflows. Then it surveys on some typical LCT products. The development trends of LCTs are analyzed next according to the survey of these terminals.

A. THE PRELIMINARY KNOWLEDGE OF LCTS

One satellite can deploy multiple LCTs. In general, four terminals will be respectively placed in the front, back, left, and right directions of the satellite. A laser terminal, for example, is composed of an optical communicator, a pointing-acquisition-tracking (PAT) host, and a PAT electronic control unit. The former two modules are connected through optical fiber components, and the latter two modules are connected through cable components.

The optical communicator provides the modulation and demodulation of high-speed laser signals. As shown in Fig. 2, the communicator will modulate the high-speed baseband signals onto the optical carrier, amplify and transmit them. The optical signals are then received and demodulated to recover the base-band signals. At the transmitting end (the upper subfigure), the baseband signal is input into the electronic-optical modulator after differential coding and then loaded on the optical carrier through a phase change. Then this signal light is amplified and transmitted via an erbium-doped fiber amplifier (EDFA). At the receiving end (the lower subfigure), the received optical signal is amplified first by the pre-EDFA and then processed by the matched filtering to reduce noises. Finally, the signal is demodulated with the help of a Doppler frequency shift compensation device through the optical coupling interference on two channels [14], [15].

The PAT host and PAT electronic control unit perform as the executor and the controller of the high-precision tracking and aiming mechanism respectively. The PAT host mainly

TABLE 1. Acronyms table.

| Abbreviation	Full Name	Abbreviation	Full Name
LSN	Laser Space Network	SOTA	Small Optical TrAnsponder
LCT	Laser Communication Terminal	OSA	Optical System Assembly
LSL	Laser Space Link	EB	Electronic Box
FSO	Free-Space Optical	DWDM	Dense Wavelength Division Multiplexer
SDSN	Software-Defined Satellite Network	OOK	On-Off keying
NFV	Network Function Visualization	MEC	Mobile Edge Computing
RF	Radio Frequency	PPM	Pulse-Position Modulation
PAT	Pointing-Acquisition-Tracking	ASK	Amplitude-Shift Keying
EDFA	Erbium-Doped Fiber Amplifier	PSK	Phase-Shift Keying
CPA	Coarse Pointing Assembly	BPSK	Binary Phase Shift Keying
FPA	Fine Pointing Assembly	QPSK	Quadrature Phase Shift Keying
PAA	Point-Ahead Assembly	DPSK	Differential Phase Shift Keying
LEO	Low Earth Orbit	ITU	International Telecommunication Union
MEO	Middle Earth Orbit	HydRON	High-throughput optical network system
GEO	Geosynchronous Orbit	HIT	Harbin University of Technology
GTO	Geoschronous Transfer Orbit	SIOM	Shanghai Institute of Optical Mechanics
SSO	Sun Synchronous Orbit	CAST	China Academy of Space Technology
GND	Ground	CASC-5	The Fifth Institute of China Aerospace Science and Technology Corporation
JDRS	Japan Data Relay System	DRTS	Data Relay Test Satellite
LCRD	Laser Communications Relay Demonstration	OCSD	Optical Communications and Sensor Demonstration
CLICK	CubeSat Laser Infrared CrosslinK	O2O	Orion Artemis II Optical communications system
TBIRD	Terabyte Infrared Delivery	DSOC	Deep Space Optical Communication
LUCAS	Laser Utilizing Communication System	SDA	Space Development Agency
ILLUMA-T	Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal	DTN	Delay Tolerant Network
DLR	Deutsches Zentrum fur Luft- und Raumfahrt	SDN	Software-Defined Network
NICT	National Institute of Information and Communications Technology	QoS	Quality-of-Service
ESA	Europe Space Agency	JAXA	Japan Aerospace Exploration Agency
HTS	Heat Transport System	R&D	Research and Development
MIMO	Multiple Input Multiple Output	NFVI	Network Function Virtualization Infrastructure
VNF	Virtual Network Function	MANO	Management Automation and Network Orchestration
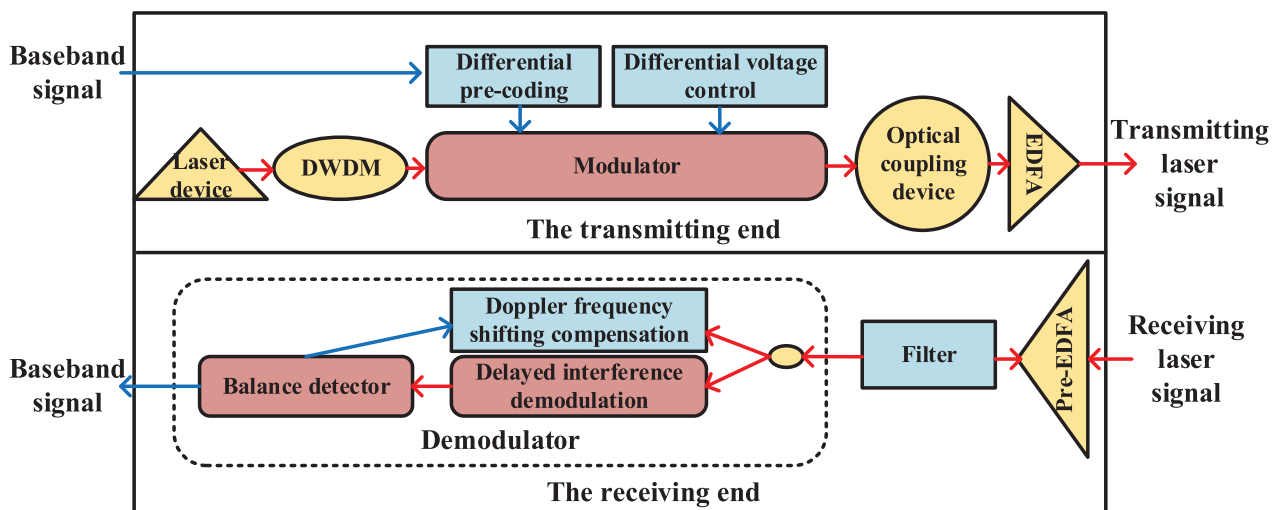
FIGURE 2. The illustration of an optical communicator.

completes the transmission and reception of space optical signals. And the electronic control unit controls the PAT host for initial pointing, scanning, and real-time tracking. These two modules can resist potential satellite platform vibration and intersatellite motions in the laser pointing stage, so as to maintain the communication stability of point-to-point links [16]. More specifically, they can be divided into

four parts: optical antenna and relay optical path, coarse pointing assembly (CPA), fine pointing assembly (FPA), and point-ahead assembly (PAA). The optical antenna and the relay optical path together construct the optical system, which is in charge of the optical signal transmission and receiving. The CPA, FPA, and PAA are cooperated to provide relatively accurate acquisition results through the large-scale coarse

scanning and the small-scale fast scanning between two finer points [14], [17].

B. LCT PRODUCTS

Nowadays, LCTs can be categorized into customized and commercial types. The customized terminals are mainly adopted in present on-orbit technology verification projects, which are designed for particular communication requirements in these projects. While in order to support the deployment of large-scale constellations in the next generation of space networks, commercial aerospace technology companies in various countries, such as TESAT, Mynaric, Hyperion Technology, Thales Alenia Space, MOSTCOM, and NICT, began to launch laser terminal products with higher transmission rate, smaller mass volume, and lower power consumption. These terminal products can meet the generalized needs of satellite communication tasks, which greatly reduce the communication cost of the terminal deployment. In this section, we will investigate the models and parameters of some typical LCT products, which are summarized in Tab. 2.

Note that transmission distances in Tab. 2 are partially represented by satellite orbits. Different satellite orbit refers to different heights of the satellite above the ground and different angles between the satellite orbit and the equatorial plane, including the low earth orbit (LEO), middle earth orbit (MEO) and geosynchronous orbit (GEO), geosynchronous transfer orbit (GTO), and sun-synchronous orbit (SSO), etc. The LEO, MEO, GEO, and SSO are circular orbits, where the LEO is also called the near-earth orbit, ranging about 200-1200km above the ground; the SSO is 800km above the ground; the MEO is 1200-36000km above the ground; the GEO is also called the highland orbit, ranging about 36000km above the ground. The GTO, on the contrary, is an elliptical orbit with a 200km close range above the ground and a 36000km long-range above the ground [18].

1) CUSTOMIZED LCTS

The terminals are customized for specific satellites and missions in the earlier stage. Several typical customized laser communication terminals are surveyed in this subsection, including the EDRS-A LCT delivered for satellites in the first version of European Data Relay System (EDRS); LUCAS for satellites in Japan Data Relay System (JDRS); CubeSat Laser Infrared CrosslinK (CLICK); Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal (ILLUMA-T) for the Laser Communications Relay Demonstration (LCRD); Terabyte Infrared Delivery (TBIRD) demonstrations of America; and OSIRIS LCTs in German.

After the 2016 in-orbit test campaign of the Eutelsat-9B satellite, the EDRS-A LCT is proposed by TESAT Spacecom to build the LEO-GEO laser communication with a 1.8Gbps data relay rate. The EDRS-A LCT is designed based on the generic LCT design. It consists of data electronic units for transmission and receiving, laser and fiber amplifiers with corresponding driver circuits, and a computer for operation,
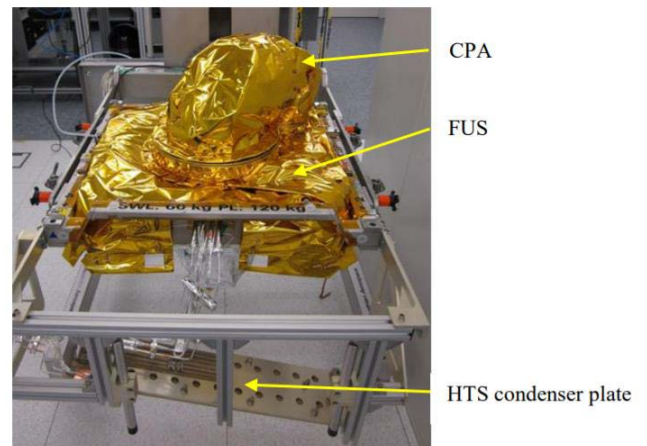

FIGURE 3. EDRS-A LCT flight model [19].

monitoring, and controlling. These subunits are implemented on a single frame unit system. Together with the CPA module, the EDRS-A LCT flight model is shown in Fig. 3. Customized adaptations are required on this terminal to be fit for its hosting satellite. The tubing and shape of the heat transport system (HTS) condenser plate, the electrical interface, and the data bus interface are adapted to the actual parameters of the hosting satellite [19].

In 2020, the NEC Corporation announced two types of LCTs developed for the Laser Utilizing Communication System (LUCAS) in outer space, where one is for GEO satellites and another is for LEO satellites. LUCAS LCTs support an up to 1.8Gbps data transmission rate between satellites. The GEO LUCAS LCT is launched on the JAXA's optical data relay satellite in November, and the LEO LCT is planned to be boarded on ALOS-3 and ALOS-4 satellites [20].

National Aeronautics and Space Administration (NASA) plans to develop the ILLUMA-T, which is expected to be launched to the international space station in early 2022. This terminal will establish a two-way communication link between GEO and LEO, and realize the hybrid space networking. The terminal uses photon integration technology instead of traditional electronic units to reduce the weight, volume, and power consumption of the laser communication terminal, thus improving the reliability of space laser communication [21].

The CLICK-A terminal is jointly developed by the Massachusetts Institute of Technology (MIT), the University of Florida, and NASA Ames Research Center. It includes a laser transmitter and a precision pointing PAT system. At present, the assembly test of CLICK-A has been completed and the overall assembly of the spacecraft has been delivered. The CLICK-B/C, which is expected to be launched in mid-2022, inherits the CLICK-A mission but adds new elements to the payload, including beacon lights and detector systems required for communication. The CLICK-B/C can support the full-duplex interconnection and a more than 20Mbps communication rate among satellites [22]. In almost the

same timestamp, the TBIRD terminal will demonstrate a new 200Gbps downlink with only $18 \times 10 \times 10 cm^3$ volume and a less than 2.25kg mass [23].

Besides, the Deutsches Zentrum fur Luft- und Raumfahrt (DLR) has developed experimental optical terminals for small satellites, that is the OSIRIS series. The development of OSIRIS began with two launch missions with the payload of OSIRISv1 and BiROS (OSIRISv2) in 2016 and 2017 respectively. The OSIRIS 4 Cubesat was subsequently launched in the fourth quarter of 2018, and the OSIRISv3 was installed on the Airbus DS Bartolomeo platform on the international space station in 2019. The fourth-generation OSIRIS-4 is currently developing a miniaturized version, whose size is less than $10 \times 10 \times 3 cm^3$. Coupled with the low power consumption of only 8W during operation, this terminal series can be loaded on almost every cube satellites [24], [25].

2) COMMERCIAL LCTS
The commercial LCTs have lower costs, higher research and development (R&D) efficiency, and a large-scale payload production capability. With the development of the space network, these terminals can satisfy the requirements for global satellite layout and the construction of large-scale constellations. We have surveyed commercial terminal products proposed by six typical corporations: TESAT, Mynaric, Hyperion Technology, Thales Alenia Space, MOSTCOM, and NICT. The characteristics and corresponding parameters of these terminals are presented as follows.

1) **TESAT Laser Terminals:** TESAT corporation has proposed laser terminals for communication tasks in various scenarios. For LEO laser communication missions, TESAT has launched SmartLCT terminals, as shown in Fig. 4. Its lightweight design can dramatically save weight and space when being deployed on smaller and lighter satellites, whose weight is only about 30kg. The data transmission distance of SmartLCT is up to 45000km, and its speed can achieve 1.8Gbps with safety and failure-free characteristics.

   In the field of microsatellites, TESAT also proposes lightweight Tosiris and CubeLCT laser product series. Their data transmission rates to the ground station are 10Gbps and 100Mbps respectively. Tosiris weighs only 8kg and its downlink rate is adjustable. CubeLCT with an edge length of 10cm weighs only 0.397kg. By constructing the earth data backbone network through laser terminals, the products of TESAT contribute to realizing almost real-time global data transmission [26].

   As planned to be launched in 2021, the TESAT corporation proposes the ConLCT terminal. It can provide quite high-speed laser communication (up to 10Gbps) and a 6000km transmission distance. On the contrary, the LCT135 terminal proposed by TESAT supports the farther laser transmission (80000km), and a 1.8Gbps transmission rate for GEO-GEO, GEO-LEO,

FIGURE 4. SmartLCT terminal model [26].

FIGURE 5. CONDOR Mk3 terminal model [27].

GEO-Airborne, and GEO-ground laser communication. It has become a core element of the operational service for the EDRS.

2) **Mynaric Laser Terminals:** Mynaric was founded in 2009 by the former employees of the German Aerospace Center. It aims to promote wireless laser communication in the commercial aerospace field. Since 2012, Mynaric has completed several space-to-ground and space-to-space demonstrations and verifications, who has achieved product-level maturity.

   In 2014, Mynaric proposed CONDOR MK2 laser terminal, which can provide up to 1.25Gbps data transmission rate with a 5000km transmission distance. Further improved in 2017, this corporation proposed an enhanced version in CONDOR series as CONDOR Mk3 laser terminal shown in Fig. 5. This terminal increases its data transmission rate and distance to 10Gbps and 8000km. The terminal can support 1553nm/1536nm wavelength laser, 2W emission power, and 7-year service life. Both of these two terminals have adopted modular designs, which are mainly composed of optical and electronic units. The volumes of the optical and electronic units in CONDOR Mk3 are slightly smaller than the ones of CONDOR Mk2, which are $35.1 \times 21 \times 17 cm^3$ and $16.1 \times 33.6 \times 25.5 cm^3$ [27].

3) **Thales Alenia Space Laser Terminals:** Thales Alenia Space promotes multiple beam antenna concepts for satellites applications. The Optel-μ LCT is one of the

examples to establish a powerful direct detection laser communication system for microsatellite communication from LEO to the ground. This terminal consists of three main units: optical, electronic, and laser units. Based on a 1550nm wavelength and an 8U volume, the system can guarantee a higher daily downlink capacity with a 2Gbps data transmission rate and a lower space-borne volume [28], [29].

4) **Mostcom Laser Terminals:** The SOT terminal series launched by Mostcom can be used not only for intersatellite communication but also for space-to-ground communication. Two terminals in this series, SOT-90 and SOT-150 both adopt a unified optical transceiver path and service information exchange protocol, which is suitable for a variety of application scenarios. They can all support high-speed communication requirements where the SOT-150 can even support an up to 50000km communication distance. In addition, these two terminals support hemispherical viewing areas and stable two-way communication. Quantum key distribution and video monitoring systems are also considered to increase the diversity of terminal functions [30].

5) **NICT Laser Terminals:** The National Institute of Information and Communications Technology (NICT) of Japan has launched a variety of terminals suitable for different tasks [31]. They launch the Small Optical TrAnsponder (SOTA) terminal with a total weight of 6kg. This terminal is deployed on SOCRATES, a 50kg advanced space optical communication research satellite. The optical communication experiments leveraging SOTA are mainly carried out at the Tokyo Koganei ground station. It is verified that SOCRATES can realize the photon-level information exchange with the ground station based on SOTA.

Another sub-miniature optical terminal launched by NICT is VSOTA. The laser signal transmitter in VSOTA supports a compact dual-band with both 980nm and 1550nm wavelengths. It is carried on the international scientific experiment satellite RISESAT at present, which is a 50kg earth observation microsatellite currently being developed by the Space Robot Laboratory of Northeastern University. RISESAT with VSOTA has been selected as part of the innovative satellite technology demonstration program for the Japan Aerospace Exploration Agency (JAXA). With the help of VSOTA, RISESAT can realize the unidirectional laser communication from LEO to the ground [32].

The NICT also proposes the Hicali terminal, which is deployed on the ETS-IX satellite. The composition of Hicali is more refined, including the optical transmitter, receiver, amplifier, data conversion module, communication module, telescope, and coarse acquisition and fine tracking mechanism of ground target positioning. Hicali uses a near-infrared laser with a wavelength of 1550nm. Because this wavelength is widely used

in optical fiber communication on the ground, it is more suitable to migrate devices and systems used in ground optical communication networks to space optical communication [33].

6) **Hyperion Technology Laser Terminals:** The CubeCat terminal launched by Hyperion Technology is a space-to-ground laser communication terminal. This terminal is also a lightweight terminal. It has a less than 15W power consumption, a less than 1.33kg mass, and only a 1U volume. But it can realize a 1Gbps downlink rate and a 200kbps uplink rate suitable for cube stars [34]. It is expected to be delivered in 2021 and serve cube satellites in the future.

C. THE DEVELOPMENT TRENDS OF LCTS

The above-investigated LCTs have been summarized in Tab. 2. It can be seen that most LCTs are designed and developed in the direction of high speed, lightweight, small volume, full-duplex, automatic on-orbit calibration, and automatic link establishment. From the perspective of orbits, the medium- and high-orbit satellite LCTs mainly develop towards higher rate, longer service life, and higher reliability, while the low-orbit satellite LCTs mainly develop towards smaller volume, higher speed, and lower power consumption.

From the perspective of LCT types, we find that customized LCTs have corresponding parameters adapted to their hosting satellites, while commercial LCTs have relatively generalized parameters and lower costs, thus can be launched on more satellite types and welcomed by the market nowadays. Furthermore, we summarize another two potential development trends for commercial LCTs, including adjustability and modularization.

1) **Adjustability:** The adjustability refers to an adjustable terminal configuration. The transmission rate, wavelength, power, and other parameters, can be flexibly adjusted according to task requirements. For example, the speed ranges of LCTs in the Condor MK series are adjustable. The transmission rate of CONDOR Mk2 can be adjusted from 100Mbps to 1.25Gbps, and the rate of CONDOR Mk3 can even be adjusted to the maximum of 10Gbps.

2) **Modularization:** The modularization refers to the highly modular design of LCTs. Most LCTs at present tend to be composed of optical system assembly OSA) and independent electronic boxes (EBs). Compared with the integrated design of LCTs, the modular design can dramatically reduce the complexity and the cost of manufacturing and maintenance of each LCT. If the satellite needs multiple OSAs, such a highly modular design can also help to reduce the mass of LCTs. Each satellite can also customize its own LCTs with the free combination of these modules. As shown in Tab. 2, ConLCT, CONDOR Mk2, and CONDOR Mk3 adopt the independent modular design of OSA and EB, which makes it possible for module redundant backup.

TABLE 2. The summary of laser terminals (the transmission rate refers to the two-way transmission rate if not specifically mentioned and for volume, $1U = 10 \times 10 \times 10 cm^3$).

Type	Institution /Corporation	Name	Transmission Rate	Transmission Distance	Volume (cm^3)	Power (W)	Mass (kg)	Delivery Time
Customized	TESAT	EDRS-A LCT	1.8Gbps	>45000km	60×60×70	160	56	2016
	NEC/JAXA	LUCAS	1.8Gbps	GEO version: 36000km LEO version: 1000km	-	-	-	2020
	NASA/MIT/ the University of Florida	CLICK-A	20Mbps	400km	1.2U	-	-	2018
		CLICK-B/C	>20Mbps	25-580km	1.3U	-	-	2022
		TBIRD	Downlink: 200Gbps Uplink: 5Kbps	LEO-GND	18×10×10	-	2.25	2022
	NASA	ILLUMA-T	Downlink: 1.244Gbps Uplink: 51Mbps	LEO-GND	-	3	-	2022
	DLR	OSIRISv1	200Mbps	600km	-	26	1.3	2017
		OSIRISv2	1Gbps	LEO-GND	-	37	1.65	2016
		OSIRISv3/4	10Gbps	LEO-GND	-	150	9	2021
		OSIRIS 4 CubeSat	100Mbps	LEO-GND	9.5×9.5×3.0	10	0.39	2021
Commercial	TESAT	TOSIRIS	Downlink: 1.25/2.5/5/10Gbps Uplink: 1Mbps	LEO-GND	28.0×20.0×15.0	40	8	2019
		SmartLCT	1.8Gbps	45000km	<35.0×35.0×20.0	150	30	2020
		CubeLCT	Downlink: 100Mbps Uplink: 1Mbps	LEO-GND	9.0×9.5×3.5	10	0.397	2021
		ConLCT	10Gbps	6000km	Optical unit: 50.0×18.0×26.0 Electronic unit: 26.0×11.0×17.5	130	15	2021
		LCT135	1.8Gbps	80000km	60.0×60.0×70.0	150	53	2021
	Mynaric	CONDOR Mk2	100Mbps-1.25Gbps	5000km	Optical unit: 57.3×27.1×23.0 Electronic unit:: 34.0×25.9×16.3	-	-	2014
		CONDOR Mk3	100Mbps-10Gbps	8000km	Optical unit: 35.1×21.1×17.0 Electronic unit: 16.1×33.6×25.5	-	-	2017
	Thales Alenia Space	OPTEL-μ	2Gbps	LEO-GND	8U	43	8	2015
	MOSTCOM	SOT-90	10Gbps	5000km	45.0×30.0×38.0	60	16	2020
		SOT-150	1.25Gbps	50000km	60.0×40.0×48.0	100	50	2020
	NICT	SOTA	1M/10Mbps	LEO-GND	-	15.74	5.9	2014
		VSOTA	1kbps-1Mbps	LEO-GND	-	4.33	<1	2018
		HICALI	10Gbps	GEO-GND	-	-	-	2021
	Hyperion Technology	CubeCat	Downlink: 100M/300M/1Gbps Uplink: 200kbps	LEO-GND	1U	15	1.33	2021

D. LCT CONCLUSION

In this section, we first introduce the construction and the workflow of LCTs. Then we survey recent LCT products which are categorized into customized and commercial types. Detailed parameters of the surveyed LCTs have been summarized in Tab. 2. According to the introduction of these typical products, we analyze the development trends of LCTs next.

In the initial exploration of laser space communication, the terminals are customized for each communication mission and its host satellite. But as the technology matures, LCTs become adjustable and have highly modular designs, which improves the compatibility of LCTs on various communication requirements. It can be predicted that the mass production of commercial LCTs will become one of the main drivers to expand LSNs. Depending on the characteristics of

different terminals, it would be efficient to deploy customized LCTs on higher-orbit satellites to guarantee communication reliability, while deploying commercial LCTs on lower-orbit satellites to satisfy the broad coverage and large quantity requirements.

In order to construct large-scale constellations for the next generation of LSN, further developments on LCTs focus on increasing transmission rate while decreasing costs. However, such developments entail with several substantial challenges:

1) **Low sensitivity of components:** More complex modulation modes can provide a higher laser transmission rate. However, limited by the current production process, the sensitivity of components nowadays is not high enough to support the finer phase difference in demodulation.
2) **Low reliability and short life of components:** Due to the influence of harsh space environments such as single-particle and electromagnetic radiation, it is difficult to achieve high reliability and long life of components like ground components.
3) **Lack of LCT manufacturing standards:** The higher degree of modular designs can help to reduce LCT manufacturing costs. But there is lacking in uniform LCT manufacturing standards, which limit the mass production of modular terminals.

Correspondingly, we find several potential research directions of LCTs:

1) **Component optimization with all-optical design:** Inspired by technologies in all-optical networks [35], LCTs for spacecraft can break the bottleneck of photoelectric conversion rate through physical optimizations, and greatly improve the data transmission rate in space.
2) **Component optimization with optical phased array (OPA):** Similar to the design of microwave phased-array [36], LCTs could also realize multiple-input multiple-output (MIMO) function through OPA [37]. It has advantages of fast steering speed, flexible beam, multi-beam steering, small volume, and lightweight to further improve LCT performance.
3) **LCT manufacturing standards proposal:** The manufacturing standards could be proposed according to the summary on various laser space mission conditions and quality-of-service (QoS) requirements. The modular design of LCTs can then follow these standards.

III. LASER SPACE LINKS

Under the support of various LCTs deployed on satellites, the LSLs can then be established for laser communication. Since LCTs are considered as nodes in the graphs of LSNs, LSLs are built as edges in this graph. In this section, we first introduce some preliminary knowledge of LSLs, including the link establishment process, modulation modes, and laser wavelength. Some on-orbit demonstrations in the field of satellite laser communication are then surveyed in the next

subsection, followed by the development trend analysis of LSLs.

A. THE PRELIMINARY KNOWLEDGE OF LSLS
The satellite laser communication system is an optical-electronic-mechanical system, including three basic subsystems of optics, tracking and aiming, and communication, together with other supporting systems such as thermal control and power distribution systems. The communication subsystem is composed of a laser carrier unit, electro-optical modulation unit, optical amplification unit, and optical demodulation unit, which mainly completes the functions of optical signal modulation and demodulation, optical amplification, and signal processing. In this subsection, we correspondingly present some preliminary knowledge of LSLs, including how to establish a laser link, how to modulate a laser signal, and how to choose a suitable laser wavelength.

1) LINK ESTABLISHMENT PROCESS
As laser communication is a point-to-point communication, the key component of laser link establishment is to accurately acquire the position of the communication target. However, satellite attitude drift, relative motion between satellites, satellite platform vibration, and the interference of space background light will increase the difficulty of acquisition. Various scanning strategies are proposed for target acquisition, including rectangular scanning, spiral scanning, rectangular-spiral scanning, and complex spiral scanning with signal lights [16], [38], [39].

Rectangular scanning is a line-by-line scanning method. Although it is easy to design and implement, the scanning efficiency is relatively low. Spiral scanning follows the spiral track and starts from the area that the target will appear with the highest probability. This method has higher efficiency if the probability of the target appearing in the uncertain area follows Gaussian or Rayleigh distribution, but it will miss the target at the edge. The missed scanning probability can be reduced by increasing the scanning overlapping but at the expense of capture time. Rectangular-spiral scanning, on the contrary, combines the advantages of these two methods. This scanning also starts from the area with the maximum probability density, together with a small scanning interval overlap. So this method is easier to realize than spiral scanning and has a higher efficiency than rectangular scanning. In addition to using beacon light to capture, a complex spiral scanning with a signal light is further proposed. This scanning strategy combines coarse and fine scanning together. The two-dimensional turntable is used for large-spacing coarse scanning of the uncertain area, and the advanced galvanometer is used for small-scale fine scanning between the two points output from the coarse scanning [14], [40]–[42].

2) MODULATION MODES
In free-space optical communication, there are two main categories of modulation modes: incoherent modulation and

TABLE 3. The summary of laser communication modulation modes.

Type	Mode	Advantages	Disadvantages	Scenarios
Incoherent	OOK	Technical-simple and -mature	Low sensitivity, easily impacted by background noise and atmospheric turbulence	LEO-LEO, LEO-GND
	PPM	High sensitivity, Technical-simple, and High power efficiency	Complex detector, low bandwidth efficiency, limited transmission rate, easily impacted by background noise	LEO-GND, deep space ultra-long distance transmission
Coherent	BPSK	High sensitivity, strong anti-background interference ability	Complex receiver, Doppler frequency shift compensation, easily impacted by atmospheric turbulence, require high linewidth and frequency stability	Intersatellite, satellite-to-GND high transmission rate link
	QPSK	High sensitivity, strong anti-background interference ability, automatic compensation on atmospheric turbulence, technical-mature	Require additional differential detection module and Doppler shift automatic compensation loop	Satellite-to-GND long-distance link
	DPSK	High sensitivity, strong anti-background interference ability, Doppler shifting compensation	Require high linewidth and frequency stability	Intersatellite, satellite-to-GND high transmission rate link
	M-QAM	Higher coding efficiency, strong anti-background interference ability	Complex receiver	Intersatellite, satellite-to-GND high transmission rate link

coherent modulation. Incoherent modulation mainly adopts intensity modulation direct detection (IM-DD), which has a quite simple structure and high reliability, but the receiving sensitivity is poor. Incoherent modulation can be divided into on-off keying (OOK) and Pulse-position modulation (PPM) [43].

OOK is the simplest amplitude-shift keying (ASK) modulation. It represents digital data by the presence or absence of a carrier wave [44]. The presence of a carrier during a specific time period represents a binary one, while its absence represents a binary zero. Some variants of OOK [45] can provide further information with different lengths of the time period. The OOK modulation is simple and mature in implementation, but it has relatively low sensitivity, and can be easily impacted by background noise and atmospheric turbulence in space. So, the OOK modulation mode is mainly adopted among LEO satellites or LEO to ground communications.

Compared to OOK, the PPM modulation is primarily useful for optical communications systems, which have little or no multipath interference, and lower power consumption [46]. The principle of PPM is to divide a certain time period into M slots. If there is a pulse sent in the i-th time slot ($i \in [M]$), and there is no pulse in other time slots, it represents the binary PPM signal corresponding to value i. The PPM modulation mode has a higher sensitivity and power efficiency than OOK, together with the simple implementation, so it is widely adopted in deep space ultra-long-distance transmission and LEO-GND communications. However, it requires complex detection, and can also be impacted by background noises in space, leading to sometimes a lower bandwidth efficiency and limited transmission rate.

On the contrary, coherent communication system mainly adopts phase modulation/coherent detection mode, which has the advantages of high sensitivity, high modulation

rate, and strong anti-interference ability [47]. Phase-shift keying (PSK) modulation belongs to coherent modulation. Mathematically, the transmitted wave $s_i(t)$ ($i = 1, 2, \ldots, M-1$) through M-PSK can be represented as:

$$s_i(t) = A\cos(2\pi f_0 t + \frac{2\pi i}{M}), \qquad (1)$$

where f_0 is the carrier frequency, A is the amplitude of the signal, and $\phi = \frac{2\pi i}{M}$ represents the phase of the signal. According to the trigonometric law, we can have:

$$\begin{aligned} s_i(t) &= A\cos(2\pi f_0 t + \varphi) \\ &= A\cos(\varphi)\cos(2\pi f_0 t) - A\sin(\varphi)\sin(2\pi f_0 t) \\ &= I\cos(2\pi f_0 t) - Q\sin(2\pi f_0 t). \end{aligned} \qquad (2)$$

Thus, the PSK modulation is a digital modulation process that conveys data by changing the phase of the carrier wave. It varies its I and Q inputs at a timestamp. Different M represents specific modulation modes, including Binary Phase Shift Keying (BPSK) and Differential Phase Shift Keying (DPSK) when $M = 2$, Quadrature Phase Shift Keying (QPSK) when $M = 4$, etc.

BPSK is the simplest form of PSK. The BPSK leverages two phases which are separated by 2π, so it can also be termed as 2-PSK. The BPSK can encode each bit with one symbol [48]. It has a high detection sensitivity and anti-interference ability to the background noise. Similarly, QPSK uses four equally separated phases on the constellation diagram. The QPSK has a higher coding gain than BPSK, which can encode two bits per symbol. But the BPSK is more robust than QPSK. Both of these two modulation modes require high linewidth and frequency stability of the laser device, while the BPSK also requires Doppler frequency shift compensation. These two modulation modes both are mainly adopted in intersatellite or satellite to the ground high-speed communications.
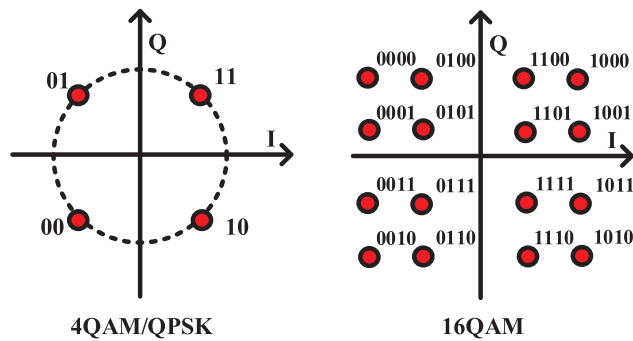
FIGURE 6. The constellation figures of 4-QAM and 16-QAM.

DPSK, however, requires lower laser linewidth on the premise of obtaining the same transmission rate and sensitivity. Different from the BPSK and QPSK which detect the phase difference with the original reference phase, the reference phase for DPSK is the phase in the previous timestamp. Thus, this modulation mode can effectively avoid the error accumulation in phase difference, which is widely adopted in satellite to ground long-distance communications.

M-QAM is the modulation mode to adjust both amplitude and phase shown in Eqn. 2. As the I and Q are orthogonal to each other, they can be represented as the x- and y-axis, so we can get the modulation constellation figures shown in Fig. 6. For M-QAM, there will be n circles in each quadrant, where $2^n = M$. It can be seen that 4-QAM is the same as QPSK [49]. The M-QAM modulation can achieve a higher coding efficiency and strong anti-background interference ability, but requires a complex receiver. Nowadays, this modulation mode is wide adopted in intersatellites and satellite to the ground high-speed communications.

The advantages, disadvantages, and potential application scenarios for all these modulation modes are summarized in Tab. 3. Because the coherent modulation has higher spectral efficiency than the incoherent modulation, the laser intersatellite links for MEO and GEO satellites that need to carry more complex and precise communication tasks are mostly modulated by the coherent modulation modes. For example, the EDRS-A [50] adopts BPSK modulation, the American LCRD [51] and the downlink transmission of JDRS [52] adopt DPSK modulation. At present, the LEO satellite laser communication and deep space exploration projects mainly adopt incoherent modulation. For example, the CLICK [22], [25] mission adopts PPM modulation for its downlink transmission, the downlink of ultra-small optical transponder VSOTA [32] and the uplink transmission of JDRS adopt OOK/PPM modulation. However, the coherent modulation requires complex modulation implementation and a local oscillator optical coherence detector. The terminal leveraging coherent modulation has relatively higher weight and power consumption. For example, the communication distance of the EDRS laser terminal deployed on GEO satellites reaches 75000km, but the mass of the terminal is up to 53kg, and the overall power consumption is 180W.

Therefore, the selection of modulation modes should be based on not only the height of the orbit but also on the specific task needs.

3) LASER WAVELENGTH

Compared with RF communication whose wavelength ranges from 30mm to 3m, the LSL adopts the near-infrared wavelength with the range of 700nm-1600nm. This thousands of times wavelength difference enables laser communication to provide higher quality satellite communication services. Firstly, satellite laser communication uses the beam as a carrier in space, which is about 5 orders of magnitude higher bandwidth than the RF. It can provide a faster and higher volume data transmission service, which satisfies the increasing number of clients [53] and a large amount of stream data [54] in the future. Secondly, compared with the spaceborne microwave frequency band strictly controlled by International Telecommunication Union (ITU), laser space communication does not need frequency application permission, which has a broader convenience space. Thirdly, the laser space link has a higher security level. Because its spectrum has a quite small laser beam diverging angle, it is not easy to be intercepted during communication. Fourthly, the laser beam is narrower than the microwave and has good directivity. Therefore, it is not easy to be disturbed by the outside world in the communication process, resulting in its good anti-interference and anti-interception ability. Finally, the laser space link has a higher power aggregation degree, leading to less power consumption than RF [55], [56].

The current space laser communications for various countries differ in the selection of communication wavelength [57], [58]. Different wavelength choices have different effects on the performance of LSLs and the sensitivity of detectors. Specifically, a shorter wavelength can bring greater antenna gain, but a higher wavelength can provide lower signal aiming attenuation [7], [59], [60]. As shown in Fig. 7, the near-infrared spectrum is internationally divided into several frequency bands according to the wavelength, from which the communication carrier of the appropriate wavelength is selected for the actual deployment environment and specific task requirements. In order to reduce the impact of solar background noise and scattering, the wavelength of space laser communication at present is mainly considered to be selected in the range of 500nm to 2000nm. Because the ground industrial laser components mostly adopt a 1550nm wavelength laser as the standard system, the migration of the communication technology from the ground to the space has a lower cost with the 1550nm wavelength selection for LSLs. Thus, the JDRS of Japan [52] and the LCRD of America [51] both adopt the 1550nm wavelength communication, and the follow-up tasks of their respective models continue to use this wavelength system. In addition, with the development of technology, the communication systems of various countries are developing in a more compatible direction, that is, they support both 1064nm and 1550nm wavelengths at the same time. For example, the European
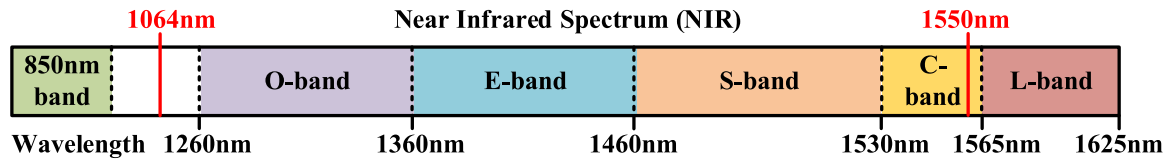
FIGURE 7. Optical wavelength distribution in the near-infrared spectrum.

EDRS-D demonstration [61] and high-throughput optical network system (HydRON) [62] planned to be launched in 2025 are compatible with 1064nm and 1550nm wavelengths. The wavelength compatible design can also serve the future hierarchical network construction.

B. ON-ORBIT LSL DEMONSTRATIONS

Multiple countries and regions have successfully completed a number of on-orbit demonstrations in the field of LSLs. These demonstrations strongly prove the feasibility of the large-scale construction and practical deployment of space laser networks. In the following subsections, we select four typical regions including Europe, the USA, Japan, and China, and survey their laser link demonstrations. According to the different orbital heights of these tasks, this paper summarizes the surveyed space laser achievements as well as future plans with respect to the launch time and shown in Tab. 4. The next subsections introduce their technical details, and further analyze the development status and trends of LSLs.

1) HIGH/MEDIUM-ORBIT LASER LINK DEMONSTRATIONS

In Europe, EDRS is a space laser relay system based on the GEO satellite platform. It carries both laser and Ka-band communication payloads, which can provide GEO-LEO and GEO-GND high-speed communications [63]. The EDRS has launched the A and C mission in 2016 and 2019 respectively, and plans to launch the D mission in 2025.

EDRS-A carried out the space laser communication with LEO satellite "Sentry-1A". It achieved a 1.8Gbps transmission rate with BPSK coherent modulation mode for relay services to around 40 LEO satellites every day [50]. The LCT of EDRS-C is set up on the platform developed by Small-GEO, which is successfully launched to GSO 31E position [61], [64]. The capability of EDRS is further improved in EDRS-D, which is expected to communicate with multiple satellites synchronously. The EDRS-D is predicted to contain 3 LCTs and achieve an up to 80000km transmission rate. Different from A and C missions, the EDRS-D plans to be compatible with both 1064 and 1550nm wavelengths. It is expected to transmit data from the Asia-Pacific region to Europe to realize the global data relay service [65], [66].

In order to solve the system-level problem of introducing a large number of optical technologies into satellite communication systems, Europe Space Agency (ESA) has prepared an innovative project proposal, namely HydRON. In HydRON, the satellite payload is divided into the network part and application part, which is equivalent to the backbone part and access part of the ground optical fiber network. Through the aggregation with new optical technologies, HydRON is expected to reach Tbps transmission rate with an "all-optical load", thus can provide the connection to the real space optical fiber network [62].

In the USA, LCRD is a high-speed space optical communication demonstration carried out by NASA and MIT. The purpose is to verify the space laser communication link and network technology. It is an important reference for establishing the space laser communication and network of the next-generation tracking and data relay satellite in US [51]. LCRD is expected to be launched with the space experimental satellite STPSat-6 in 2021, mainly carrying out the dual communication between GEO-GND and ISS-GEO through ILLUMA-T LCT [21]. The modulation of GEO-GND is the combination of both coherent and incoherent modes, and the one of ISS-GEO is the DPSK coherent mode. The laser wavelength selected by LCRD is 1550nm and this project can reach the maximum 2.88Gbps downlink transmission rate for the GEO-GND scenario.

In Japan, the JDRS satellite is jointly developed by JAXA and the Japanese government. This high-orbit satellite is responsible for faster data transmission between Japanese satellites to ground stations. It is especially suitable for promoting data transmission when the satellite cannot clearly see the ground station. JDRS-1 launched in 2020 is a Japanese data relay satellite with dual military and civilian tasks, replacing the "Kodama" data relay test satellite (DRTS) launched in 2002. Its transmission rate is up to 1.8Gbps, which consists of two LCTs. The Lucas payload allows the JDRS-1 to transmit data seven times faster than the S-band and Ka-band of DRTS [52], [67].

In China, the "Shijian-13" satellite developed by The Fifth Institute of China Aerospace Science and Technology Corporation (CASC-5) was successfully launched in 2017. It carried out a two-way 5Gbps high-speed laser communication between SSO and GND. The communication distance is 45000km and the modulation mode is IM/DD, which was the highest data rate of high-orbit satellite-ground laser communication in the world at that time [68].

The "Shijian-20" satellite launched in 2019 was equipped with an LCT developed by CASC-5. It established a QPSK-modulated laser communication link with LiJiang optical ground station in China, with a rate of 10Gbps [69].

2) LOW-ORBIT LASER LINK DEMONSTRATIONS

With the collaboration of US Aerospace and MIT, NASA has launched and planned a number of low-orbit laser

TABLE 4. The summary of on-orbit laser link demonstrations and future plans.

| Orbital Altitude	Launch Time	Project Name	Country /Region	Research Institute	Transmission Rate	Modulation Mode	Wavelength
GEO-GEO GEO-LEO GEO-GND	2016	EDRS-A	Europe	ESA	1.8Gbps	BPSK	1064nm
	2017	Shijian-13	China	CASC-5	5Gbps	IM/DD	-
	2019	EDRS-C	Europe	ESA	1.8Gbps	BPSK	1064nm
	2019	Shijian-20	China	CASC-5	10Gbps	QPSK	-
	2020	JDRS	Japan	JAXA/NICT	Uplink: 50Mbps Downlink: 1.8Gps	Uplink: IM/DD Downlink: RZ-DPSK	Uplink: 1560nm Downlink: 1540nm
	2021	LCRD	America	NASA/MIT	GEO-GND: Uplink: 622Mbps Downlink: 2.88Gps ISS-GEO: Uplink: 51Mbps Downlink: 1.244Gbps	GEO-GND: DPSK+PPM ISS-GEO: DPSK	1550nm
	2025	EDRS-D	Europe	ESA	3.6Gbps-10Gbps	BPSK	1064nm/1550nm
	2025	HydRON	Europe	ESA	100Gbps	-	1064nm/1550nm
LEO-LEO LEO-GND	2011	Ocean-2	China	HIT	504Mbps	IM/DD	-
	2016	Mozi	China	SIOM	Uplink: 20Mbps Downlink: 5.12Gbps	Uplink: PPM Downlink: DPSK	-
	2016	Tiangong-2	China	CAST	Downlink: 1.6Gbps	IM/DD	-
	2015/2017	OCSD	America	NASA/ US Aerospace	Uplink: 10Kbps Downlink: 5-200Mbps	OOK/PPM	1064nm
	2018	CLICK-A	America	NASA/MIT	20Mbps	PPM	1537nm/1563nm
	2020	Xingyun-2	China	Aerospace Cloud Technology Co.	100Mbps	-	-
	2020	OSIRISv3/4	Europe	DLR	10Gbps	IM/DD	1550nm
	2021	TBIRD	America	NASA/MIT	Uplink: 5Kbps Downlink: 200Gbps	PPM	1550nm
	2022	CLICK-B/C	America	NASA/MIT	>20Mbps	PPM	1537nm/1563nm
	2022	O2O	America	NASA	Uplink: 20Mbps Downlink: 80-250Mbps	PPM	1550nm
	2022	DSOC	America	NASA	-	-	1550nm
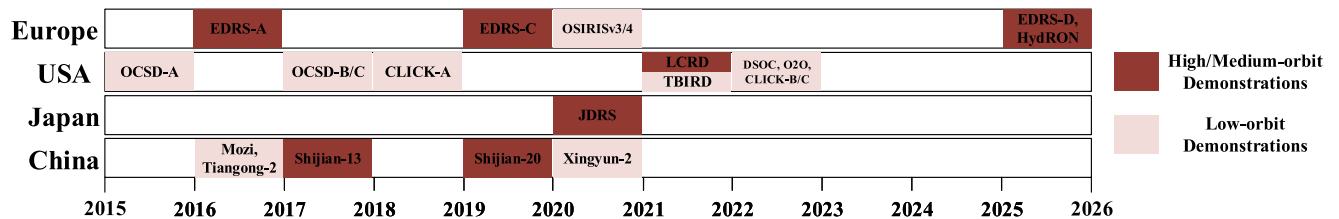
FIGURE 8. The timeline of space laser communication demonstrations and planning from 2015 to 2025.

link demonstrations. The Optical Communications and Sensor Demonstration (OCSD) was designed to validate the capability of microsatellites to provide low-orbit high-speed laser communication. The OCSD-A satellite was launched in October 2015 and the OCSD-B/C satellite was launched in November 2017. They have verified a 5-200Mbps LEO-GND laser communication rate [70]. The projects carrying CLICK-A/B/C and TBIRD LCTs as introduced in Sec. II-B1 are also low-orbit demonstrations. All these demonstrations utilize the PPM modulation mode, while the wavelength selected by the CLICK series is either 1537 or 1563nm, and the one for TBIRD is 1550nm [23].

Subsequently, NASA plans to promote more LSL demonstrations. Among them, Orion Artemis II optical communications system (O2O) plans to support real-time 4K video transmission through a two-way optical communication for Orion spacecraft in the lunar orbit. The modem on the Orion spacecraft will convert data into optical signals and transmit them from the lunar surface to the receiver on the earth. The same equipment will also be able to receive

optical signals from the earth and convert them into data for spacecraft analysis [21]. Another Deep Space Optical Communication (DSOC) flight demonstration is planned for 2022. The system will provide a deep-space optical platform and ground data system for flight, which consists of ground laser transmitters and receivers with existing assets. The communication between space and ground will use advanced lasers in the near-infrared region to improve the laser communication performance by 10 to 100 times without increasing the mass, volume, or power of the satellite [71].

In addition to demonstrations in America, China and Europe also develop their low-orbit laser link projects. As the first satellite-to-ground laser communication demonstration in China, the Ocean-2 satellite was successfully launched in 2011. It was equipped with an LCT developed by Harbin University of Technology (HIT). Its laser communication distance is 2000km, and the transmission rate can reach 504Mbps with the IM/DD modulation mode. The launch of Ocean-2 fills the gap in the Chinese satellite-to-ground laser communication area.

The "Mozi" quantum satellite was successfully launched in 2016, carrying an LCT developed by the Shanghai Institute of Optical Mechanics (SIOM). The satellite has carried out the first high-orbit satellite-to-ground high-speed coherent laser communication demonstration in China. It can achieve a 20Mbps uplink transmission rate with the PPM modulation mode, and a 5.12Gbps downlink rate with the DPSK modulation mode. The communication distance of its laser link is 1200km, which can support encrypted multimedia data stream transmission [72].

In the same year, another high-speed space laser communication demonstration is carried out by the "Tiangong-2" satellite, developed by the China Academy of Space Technology (CAST). The downlink transmission rate of multiple scientific load services is 1.6Gbps and the communication mode is IM/DD. This payload realizes daytime laser communication, which has comparable performance at night [73].

"Xingyun-2" satellites are further conducted in 2020. The compact T5 LCT developed by Laserfleet corporation is mounted on these microsatellites with a 100Mbps communication rate [74].

In Europe, the projects carrying OSIRIS LCTs choose the IM/DD modulation mode and 1550nm wavelength to achieve a 10Gbps transmission rate in low orbits [24], [25]. The timeline of these demonstrations from 2015 to 2022 is shown in Fig. 8. It can be seen that LSLs have aroused wide attention to international communities in different orbits and scales. Their performance has validated the capabilities of LSLs to construct the next generation of global satellite systems.

C. THE DEVELOPMENT TRENDS OF LSLS

From the investigation of the above development status and future plans of LSLs, their development trends can be analyzed as: hierarchical, networking, standardization, and commercialization.

1) HIERARCHICAL

The investigated space laser communication demonstrations have covered various heights of orbits, including GEO-GEO, GEO-LEO, GEO-GND, LEO-GND, etc. The transmission rate ranges from Mbps to Gbps, and is even expected to reach Tbps. At the same time, the wavelength of space laser communication is mostly 1064nm or 1550nm, which is similar to the development of ground optical communication. And the modulation modes involve both incoherent and coherent modes. These various demonstrations can be used as the basis for the construction of future hierarchical LSNs.

2) NETWORKING

On-orbit laser communication demonstrations are changing from single link function verification to space network verification. Different orbital satellites are connected with each other and each satellite carries multiple laser inter-satellite links to verify the networking technology. This composed space network is expected to provide high-speed data transmission, global mission planning and response, information encryption and decryption, and other comprehensive information support capabilities in the next space network generation.

3) STANDARDIZATION

U.S. space development agency (SDA) has proposed to build the space "transport layer" based on space laser links, which will be the backbone of the future space defense architecture of the United States [75]. In order to improve the deployment efficiency of LSLs, SDA issued the standard documents of laser intersatellite links and LCTs. These standards unify the laser space link system and performance indicators of the next space generation. The determination of standardization helps to promote and expand satellite coverage and spatial relevance for the large-scale development trends of the next laser space generation.

4) COMMERCIALIZATION

As mentioned in Sec. II-B2, commercial aerospace companies in various countries have entered the track to launch various LCT products. The adjustability of commercial LCTs can be adapted to various requirements of missions, and the modular design of these LCTs is suitable for more satellite platforms, which can bear the platform vibration and frequent temperature change. Thus, LSL demonstrations in recent years prefer to deploy commercial LCTs to reduce costs, making commercialization one of its development trends.

D. LSL CONCLUSION

In this section, we first introduce some preliminary knowledge of LSLs, including the link establishment process, modulation modes, and various laser wavelengths. Then we have surveyed recent on-orbit LSL demonstrations as well as future launch plans from 2015 to 2026 in four typical regions: Europe, USA, Japan, and China. These demonstrations have been classified by different orbits and summarized with respect to time in Tab. 4. The development trends of LSLs are accordingly analyzed from four aspects: hierarchical, networking, standardization, and commercialization.

The LSL is mainly established through the PAT mechanism. It can be modulated by both incoherent and coherent modes, where incoherent modes are technically simple and mature, and coherent modes have higher sensitivity and strong anti-interference ability. The selection of modulation modes depends on specific task needs on different orbits. Nowadays, most space laser communications adopt 1550nm wavelength similar to ground optical communication, and the compatibility of multiple wavelengths is further valued. According to the surveyed demonstrations and plans in different regions, future hierarchical and large-scale LSNs can be realized by standard LSLs and commercial LCTs.

The current performance on LSLs is limited by the following challenges:

1) **Satellite platform vibration:** During the attitude adjustment process of the satellite platform, the satellite

platform will vibrate [76]. Slight vibration will reduce the LSL transmission rate or even interrupt it.

2) **Harsh space environment:** Harsh space environment such as interference from macroscopic particles, solar radiation, plasma, and large ambient temperature difference [77] will greatly affect the LSL stability.

Thus, to increase the performance of LSLs, we find several potential research directions of LSLs:

1) **Link establishment optimization:** In order to increase the link establishment efficiency, the future LSLs could adopt fast automatic calibration techniques [78].

2) **PAT mechanism optimization:** The PAT mechanism can be optimized by aggregating multi-source and multi-modal sensing data, such as gyroscope, star sensor data, or Global Navigation Satellite System (GNSS) signals. The optimized PAT mechanism helps to avoid interference caused by satellite platform vibration.

3) **Anti-solar radiating:** The solar radiating disturbance is eliminated by adding shade glass nowadays. Some filtering algorithms on signal processing could deal with such disturbance and shorten the duration of link unavailability in the future.

IV. LASER SPACE NETWORK ARCHITECTURE

The LSN can be constructed through LCTs and LSLs introduced above, and the architecture of LSNs presents how these nodes and edges are organized. In this section, we first present existing LSN architectures, introducing in detail how these LCTs and LSLs are integrated and managed. In order to build efficient LSNs, we found some techniques that can be borrowed from ground networks, such as SDN, NFV, 5G/6G LTE, and MEC. Their feasibility and potential challenges when adopted in LSNs will be discussed in this section. Finally, we will provide a potential blueprint for the next generation of LSN with the participation of these techniques.

A. EXISTING LSN ARCHITECTURES

LSN architectures have both single-layer and multi-layer forms, according to different orbital heights. The single-layer LSN consists of satellites with the same orbital heights through inner-orbit LSLs, so it can be further divided into LEO LSN, MEO LSN, and GEO LSN. On the contrary, the multi-layer LSN is composed of satellites with different orbital heights through intra-orbit LSLs, such as a two-layer LEO-MEO LSN [79], LEO-GEO LSN [80], and a three-layer LEO-MEO-GEO LSN [81]. Compared with a single-layer LSN, a multi-layer LSN can provide stronger data transmission and computation capabilities. With the development of space communication technology and the improvement of mission requirements, the construction of multi-layer LSNs has become the main trend for future space networks.

The satellite constellation determines the topology design of the LSN. Currently, there are two main constellations designed for LSNs: Walker delta and Walker star [82],

corresponding to the tilted constellation LSN and polar-orbit constellation LSN. The tilted constellation LSN can evenly cover the world, thereby establishing relatively permanent intra-orbit and inter-orbit LSLs. And the polar-orbit constellation LSN has a dynamic topology with two polar gaps. Due to the strict law of orbital motions of satellites, the satellite network topology presents periodicity and predictability. The present LSN topology control strategies include virtual topology strategies [83], [84], virtual node strategies [85], [86], and coverage area division strategies [87]. The virtual topology strategy divides a system cycle into multiple time slices, where the topology in each time slice remains unchanged. The virtual node strategy regards each node in the network as a virtual node, which can provide services to the nearest satellites. Thus the topology of the LSN is fixed without considering the specific movements of satellites. The coverage area division strategy divides the surface of the earth into multiple cells at equal intervals, and each cell is served by the nearest satellite. The above three topology strategies perform in a stable manner, which is not satisfactory for the future diversified mission requirements.

In present LSNs, each LCT node has both hosting and routing functions. Corresponding to different topologies of LSNs, their routing protocols can also be divided into single-layer and multi-layer routing technologies. There are three main routing protocols of LSNs. The early LSNs mainly adopt a connection-based routing protocol. This protocol uses a virtual topology method to discretize the continuous time-varying satellite network into a series of static topology, then selects the best path from the path set according to different optimization goals [83]. However, this protocol fails to deal with traffic congestion and satellite invalidation problems. Since LSLs have long transmission delays and are susceptible to interference, the delay-tolerant network (DTN)-based routing protocol becomes another important routing mode to provide network robustness [88], [89]. For example, a distributed contact graph routing protocol is one of the effective DTN-based schemes. This protocol utilizes the predictability of LSNs and proposes a heuristic algorithm to dynamically calculate the optimal path. Once each node on the path receives the bundle, it recalculates the best path to the destination node thereby determining the next hop [90]. In recent years, cognitive-based routing protocols have aroused wide attention in LSNs [91]. Cognitive algorithms can achieve link optimization through adaptive rate changes with learning. These routing protocols can improve the robustness and the resource scheduling capability of the LSNs based on past data predictions.

From the discussion of existing LSN architectures, their deficiencies can be summarized in the following aspects:

1) Most LSNs use static or periodic parameter configurations. But such architectures are inflexible for the increasing demands of satellite services and applications.

2) The LCTs in present LSNs are responsible for both routing and data forwarding functions, which have a lower efficiency on intersatellite communication. And the

update of routing protocol will cause dramatic overheads and face incompatible challenges in LSNs.

3) The present LSNs only support the inter-connection inside the constellation, while the inter-constellation connection is difficult to be achieved.

B. POTENTIAL TECHNOLOGY PARADIGMS FOR LSNs

The LSN can be regarded as a special case of the optical network in space. With deeper insights, we found several technology paradigms researched in the ground network that has the feasibility to be adopted in the future LSNs, including the SDN, NFV, and MEC.

1) SDN

In existing LSNs, the control and forwarding planes are tightly coupled. They are integrated into boxes and scattered on each LCT of the network, making it inflexible to control the global network situation. On the contrary, the control layer in the software-defined network (SDN) [92] is separated from the physical hardware and virtualized by the network layer. Therefore, the physical resources in the whole network can be aggregated in a resource pool to satisfy the needs of various tasks. The SDN allows users to dynamically configure the network through programming, which increases the flexibility of network management. For example, the controller is programmed to divide tasks into clusters based on their distinctions and connections. Each cluster will construct its own service system when operating. The control plane will acquire the global resource information and assign it to these service systems according to their requirements. The google B4 network is one of the successful SDN use cases [93]. It was implemented in 2010 and initially completed in 2012. It adopts distributed controller architecture, which increases the utilization of WAN links between dense and complex data centers from 30% to nearly 100%.

Depending on the adjustability and modular designs of LCTs, the SDN paradigm can be considered to improve the performance of the LSN, leading to the software-defined satellite network (SDSN) architecture [94], [95]. The SDSN takes partial satellites as data forwarding nodes responsible for data forwarding, and others as control nodes for global network nodes management. It centralizes the management layer for global information acquisition, which can efficiently realize optimal resource scheduling, information routing, congestion control, and other functions [96].

The SDSN architecture can be divided into satellite-ground cooperative architecture and layered satellite architecture. As shown in Fig. 9, the satellite-ground cooperative architecture is the integration of the space-based network and the ground-based network, where SDN controllers are installed on the ground facilities and the satellite layer is only responsible for data forwarding [97]. On the contrary, the layered satellite architecture carries the control plane on different orbits of satellites. In recent advances, one layered SDSN contains GEO, MEO, and LEO three layers, where
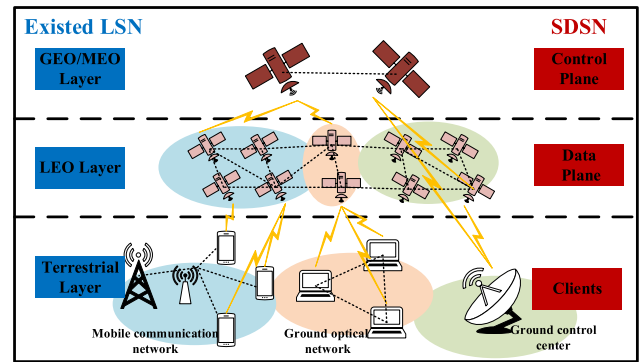

FIGURE 9. The architecture of SDSN.

the LEO layer is responsible for data forwarding, and MEO/GEO satellites carrying controllers are responsible for data exchange management [98], [99]. Another layer SDSN proposed in [100] places the control layer on GEO satellites and the forwarding layer on LEO/MEO satellites. The management center of this SDSN is placed in the ground backbone network to be responsible for decision-making and resource management. According to emergency tasks, a dynamic SDN controller placement strategy is proposed to divide ad-hoc networks with mission requests [101]. In the dynamic strategy, the control plane is composed of the ground management control center, GEO master controllers, and LEO slave controllers. Similar to [99], [102], this multi-layer control plane can provide more powerful computation capability.

From the above introductions, the features of SDSN can be summarized into three aspects: flexible, programmable, and logistically centralized. The SDSN has advantages on the high utilization rate of network resources and low operation and upgrading costs. Specifically, due to the separation of the forwarding layer and control layer, the network is more flexible to upgrade each layer independently. The programmability allows the SDSN to dynamically configure resources as needed. And the logistically centralized controller has a global network resource view, so it can decide the optimal routing and effectively control the access of the node. Due to the unified interface, the configuration of parameters and the management of devices in the SDSN could be easier.

2) NFV

The concept of NFV is to apply standardized network functions to unified hardware [103]. Specific equipment is used to realize its special function. With the proposal of NFV, the control plane of equipment is separated from specific equipment based on the virtual machine [104]. Whenever enterprises need to deploy new businesses, they only need to create corresponding virtual machines and install software packages of corresponding functions, without the need to rely on specific hardware implementations. Huawei FusionSphere [105] is one of the NFV use cases. It can realize the comprehensive virtualization of computing, storage,

and network resources. And it can uniformly manage, monitor, and optimize the virtualization resources of physical hardware.

In LSNs, the paradigm of NFV is in line with the adjustability tendency of LCTs. For example, NFV can make the routing function of LCTs no longer rely on the hardware of special satellites, but can flexibly adapt to the changing needs of future LSNs through later software configuration and parameter adjustment. This method is called network function virtualization. The NFV paradigm consists of three parts: network function virtualization infrastructure (NFVI), virtual network function (VNF), and Management automation and network orchestration (MANO):

1) **NFVI:** NFVI provides basic function mapping to hardware devices and supports the software and container management platform required by network applications. This part corresponds to the software-defined satellites or the operating system in LSNs.

2) **VNF:** VNF is a software application that realizes network functions. It usually refers to the software of network devices such as routers, firewalls, and load balancing. Various VNFs gain generality on the basis of standardized NFVI. This part corresponds to the software on each satellite in LSNs.

3) **MANO:** MANO is a unified framework for managing VNF and NFVI, which is convenient to arrange business and manage equipment. This part corresponds to satellites responsible for controlling in LSNs.

Since NFV decouples software functions with hardware equipment [106], NFV brings many advantages to satellite networks [103]:

1) **Flexible services:** On the one hand, VNFs running on cloud satellites or server satellites can speed up the update of network functions and applications whenever the requirements of LSNs change. On the other hand, there is no need to establish a special experimental environment when testing new satellite network functions. A new virtual machine can be requested or released to start or stop such experiments, providing a more flexible way for network function testing.

2) **Lower costs:** The adoption of NFV can transform the LSN entity into a virtualized satellite network function. It enables a single satellite to run multiple satellite network functions at the same time, thus reducing the number of satellites for networking, realizing resource integration, and reducing the overhead of physical space and power consumption. Besides, the basic network architecture can be quickly updated through software reorganization with NFV, thus can avoid equipment redundancy caused by satellite service changes.

3) **Avoid vendor lock-in:** NFV enables different network functions to be deployed on the unified hardware. It can avoid a certain function being locked by a specific satellite supplier and reduce the service cost on the maintenance of satellite network equipment.

3) MEC

Considering the limited computation resources on satellites, MEC is another promising technology paradigm that can be adopted in LSNs. The core idea of MEC is to transfer network functions, contents, and resources closer to mobile users [107], where on-orbit satellites and mobile devices on the ground requesting laser communication are mobile users in LSNs. The MEC can be realized in a multi-tiered architecture of LSNs, where the device layer contains client satellites, the fog layer contains satellites performing edge servers, and the cloud layer contains satellites performing central servers. This multi-tiered architecture is constructed according to different mission requirements and conditions of LCTs and LSNs, such as the bandwidth, energy resource, or computational capability. With the help of MEC, the transmission and computation burden for previous server satellites can be relieved [53]. Specifically, MEC brings advantages to LSNs [107]:

1) **Transmission latency reduction:** Since the data processing and storage processes are moved close to clients, the transmission latency can be significantly reduced, especially for the multi-media data stream, such as images or videos captured by remote sensing satellites.

2) **Bandwidth saving:** The data is pre-processed and partially stored in the MEC architecture. Thus, compared with the original data transmission, the bandwidth in LSN can be saved. Researches on the ground have shown an up to 67% bandwidth saving quantity [108], which seems promising to bandwidth-hungry LSNs.

3) **Full utilization of context information:** The MEC server deployed in a multi-tiered architecture can obtain detailed context information, including both LCT and LSL conditions on different orbits. The network resources can be efficiently managed and allocated with the known of this information.

C. THE NEXT GENERATION LSN BLUEPRINT

The proliferation of the next generations of the network, *i.e.*, 5G/6G network, aims to provide faster and more reliable communications in a larger scale [109], [110]. Although the global 6G development is still in the early research stage, it requires comprehensive performance improvement on the basis of 5G. For example, The 6G network tends to provide lower transmission delay and make the delay connected to the edge mobile terminal less than 10ns. At the same time, it provides higher network coverage density, reaching 107 network device connections per square kilometer [109].

As one of the compositions of the next generations of the network, LSN plays a significant role as a complementary solution for ubiquitous coverage, broadcast/multicast provision, and emergency/disaster recovery [111]. With the development of satellite technology and space communication technology, more commercial, civil, and military services will be carried out by LSNs, such as weather reporting, disaster relief, localization and navigation, space exploration, or international communication [112].

Since more and more large-scale constellations are going to be constructed in the future, a more flexible and efficient network management strategy should be researched to guarantee the QoS of LSNs. The technology paradigms mentioned above could be considered in this strategy. Specifically, the hierarchical LSN will be constructed and managed by the SDN in a centralized manner. The MEC provides computational capabilities to partial satellites in the lower layer closer to the client. And the NFV technology can support one satellite to realize different functions, for example, the flexible role switching from data forwarding to controlling or processing. With the help of these technologies, LSNs in the future can support global interconnection and realize the interconnection of any terminal at anytime, anywhere in the world, which is also an initiative for 5G/6G networks.

D. LSN CONCLUSION

In this section, we first introduce exiting LSN architectures from the network construction, topology, and routing protocol aspects, together with their deficiencies. To deal with these problems, we then survey several potential technology paradigms popular on the ground, including SDN, NFV, and MEC. With the help of these technologies, we propose a predicted blueprint for the next generation of LSNs, which can support the large-scale interconnections all over the world as promoted in 5G/6G network concepts.

The adjustability of LCTs and hierarchical LSLs and LSN architectures provide the feasibility to adopt SDN, NFV, and MEC paradigms. The SDN decouples the data forwarding and controlling planes. The NFV virtualizes all satellite network resources. And the MEC brings computation resources closer to the client. With the help of these three paradigms, the LSN in the future can provide more efficient and reliable global data transmission on a larger scale.

Designing a reasonable LSN architecture is necessary to realize the proposed LSN blueprint, while the mature network architecture on the ground cannot be directly applied to satellite networks [113]. It encounters various challenges:

1) **Network heterogeneity:** As we surveyed above, satellites on different orbits or launched by different regions provide different networking capabilities with different wavelengths, transmission rates, modulation modes, etc. An efficient LSN architecture in the future should deal with such heterogeneity.
2) **Network dynamism:** Different from the static terrestrial network, the LSN is much like the mobile network where network nodes are dynamic and the network topology is changed with respect to time.
3) **Network complexity:** The future large-scale LSNs tend to deal with massive communication tasks with diverse requirements. The real-time network situations like network traffic volume, link situations, and temporary communication requirements are quite complex and require to be managed and responded in a short time.

Correspondingly, we find several potential research directions:

1) **SDSN architecture design for large-scale satellite constellations:** With the increasing amount of satellites in the future space network, the architecture design especially on the control layer and forwarding layer should be carefully decided. In view of the diversified task requirements of large-scale constellations, it is necessary to study the redundancy of the network, the deployment mode of the controller, and the suitable coverage for each ad-hoc sub-network [114]–[116].
2) **NFV implementation with standard satellite system:** The virtualization through NFV depends on standard satellite hardware equipment. It is necessary to propose the standard for both hardware equipment and communication.
3) **QoS-related data processing strategy with MEC:** The QoS indicators of LSNs include throughput, error rate, end-to-end delay, delay jitter, etc. Different communication missions have different requirements for these indicators. Considering limited computational resources on satellites, the QoS-oriented data processing strategy should be considered with the MEC architecture [117], [118].

V. CONCLUSION

Compared with RF-based satellite communication, laser space communication can provide a higher information transmission rate and stronger channel robustness. With the increasing maturity of laser communication technology, it will play an extremely important role in space network communication. This survey paper presents the latest development of the LSN from three aspects: terminals, links, and architectures. We also analyze the future trends from their progress. LCTs in the future will have more generalized parameters and lower costs, which will gain their adjustability and modularization. LSLs are developing towards hierarchical, networking, standardization, and commercialization trends. And these trends make it feasible to adope SDN, NFV, and MEC paradigms in the future LSN, leading to a more efficient and reliable data transmission on a larger scale. At the end of each section, we further present various challenges and potential research directions that are needs for their developments.

The era of global information interconnection has come. Full-time and full-coverage information interaction cannot only improve our quality of life, but also provide important support in maintaining national security and stable development. Compared with the ground network subject to geographical characteristics and high construction cost, the LSN is easier to realize an omni-directional and wide-coverage networking communication. This paper aims to provide references to the design and optimization of the LSN in the future.

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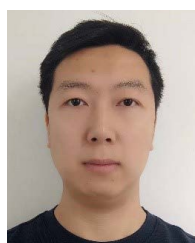
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