Technologies and applications of free-space optical communication and space optical information network

MA Jing, TAN Liying, YU Siyuan

Freespace Optical Communication Technology Research Center, National Key Laboratory of Science and Technology on TunableLaser, Harbin Institute of Technology, Harbin 150001, China

Abstract: Free-space optical communication and space optical information network offer many more superiorities over optical fiber, RF, or microwaves communication techniques, with higher data transfer rate, smaller platforms to launch and lower costs. A comprehensive overview on the architectures of the space high-speed optical information network was provided. In fundamental system, networking approach and operation mechanisms of the space optical information network were fully emphasized to be discussed a lot. The interactions of light waves and microwave network have been outlined. A blueprint for space optical information network technology is presented to be used in various communication fields in the future.

Key words: free space optical communication, space information network, wavelength assignment

Citation: MA J, TAN L Y, YU S Y. Technologies and applications of free-space optical communication and space optical information network[J]. Journal of communications and information networks, 2016, 1(1): 61-71.

1 Introduction

The increases in data transfer demand, limited spectral allocations, and emphasis on smaller spacecraft platforms to reduce launch costs, are forcing researchers to develop free-space optical communications and space optical information network, which are usually considered as the next generation space-ground and inter-satellite communication links^[1]. We have already established the ground high-speed information network system by using of optical fiber (wired optical communication). However, the space optical information network system has not been established in space yet.

The space optical information network means that aircrafts and users can be linked for transmitting information through the “cables” laid in space, with combination of the information processing technology, space internet technology and laser communication technology between aircrafts. The capacity of communication between aircrafts is about 2~10 Gbit/s. Therefore, the high-speed/real-time interconnection can be achieved between satellites in support of military tactics, strategy and space-based intelligence, surveillance and reconnaissance. Finally, the space optical information networks and ground communication networks can be linked to construct a space-earth integrated high-speed information network^[2]. Intense

efforts have already been devoted to study the space information networks technology, especially since 2000. The first high-rate lasercom link was achieved in the STRV-2 and GeoLITE experiments during the years 2000 and 2001. In 2008, the first in-orbit test (NFIRE) of inter-satellite lasercom has been carried out between the German satellite TerraSAR-X and the US LEO satellite. From October to November 2013, NASA, LLC (Lunar Laser Communication Demonstration) has successfully build a lasercom link between a lunar-orbit satellite and ground stations on the Earth. The lasercom link distance was the longest achieved yet, measuring about 3.8×10^5 km, with maximum downlink data rate of about 622 Mbit/s. In addition, recently, NASA has also performed lasercom link between an International Space Station and Ground Station in 2014, and by 2017, has planed to establish the optical communication links in a geostationary orbit (Laser Communications Relay Demonstration, LRCRD), with data rate up to 2.88 Gbit/s^[3,4].

The first inter-satellite optical link between TDRS (ARTEMIS) and the LEO satellite (SPOT-4)—SILEX experiment, was carried out by European Space Agency (ESA) in 2001. The link distance was 4.5×10^4 km with 50 Mbit/s data rate link at 800–850 nm wavelengths. ESA has also engaged in the coherent inter-satellite link and satellite-to-ground link campaign. In July, 2013, ESA's latest GEO telecommunication satellite Alphasat was launched, with two different data speed of 600 Mbit/s and 1.8 Gbit/s. The satellite-to-ground experimentation phase with OGS began in the spring of 2014 and LEO-GEO inter-satellite links were conducted after the commissioning phase of the LEO satellite Sentinel-1A. Alphasat's lasercom is a precursor to ESA's EDRS (European Data Relay System) program. EDRS will perform large-quantities data relay services with reduced time, and its infrastructure will comprise of two GEO payloads, a ground system comprising a satellite control center, a mission operations center, a payload control

center, and a dedicated network of ground station antennas^[5,6].

In addition, China has also strived to develop satellite lasercom technology in the past twenty years, and the first satellite-to-ground lasercom experiment was successfully performed in 2011. The lasercom link works by the way of synchronous dual-wavelength transmission, and the maximum data transfer rate was up to 504 Mbit/s.

The immense progress demonstrated above has provided us a possibility to develop high-speed space optical information network. Therefore, the present review aims to provide an overview of the architectures and examine critically the novel characteristics of the space high-speed optical information network. We have emphasized on fully discussing the fundamental systems, networking approaches and operation mechanisms of the space optical information network, as well as the possible interactions of light waves and microwave network. The review gives us a promising blueprint for space optical information network technology to be used in various communication fields in the near future.

2 Architecture of space optical information networks

2.1 The basic architecture of space optical information networks

Before examining the networking approach and operation mechanisms of space optical information networks. It is instructive to address the basic architecture of space optical information networks. The space optical information network layers are usually composed of the following four parts.

1) Satellite optical communication network

The satellite optical communication network is established by using laser communication satellites. At the same time, ground optical communication relay

stations are connected to the space-based optical communication network through satellite-to-ground laser links, forming a high-speed communication system of space-earth integrated network.

2) Ground optical communication relay stations

Ground laser communication relay stations are information forwarding nodes between the ground communication systems and satellite optical communication networks. The ground optical communication relay station works like the mobile ground receiving station, and then the space-ground integrated communication networks will be established. A variety of ground communication terminals can be connected to the station by means of point-to-point or microwave laser communication. Meanwhile, the satellite-to-ground laser link can also be built through ground optical communication relay stations as well as satellite laser communication network.

3) Ground microwave communication terminals

Ground microwave communication terminals are mobile terminals at disaster areas with which ground laser communication relay stations are connected.

4) Point-to-point laser communication ground terminals

Point-to-point laser communication ground terminals are usually used in areas where large-capacity data transmission is needed. The ground terminals connected with the ground optical communications relay station by the way of atmospheric optical communication.

2.2 The operation mechanisms of space-earth integrated high-speed/real-time dynamic network

Generally, space optical information networks should possess the merits of integrated high-speed/real-time dynamic performances. The typical space-earth integrated high-speed/real-time dynamic network structure based on space optical communication technology is demonstrated in Fig.1, which is mainly comprised of two types of links: the forward informa-

tion and the back information link.

Figure 1 The architecture of space-earth integrated high-speed information network

1) The forward information link

Ground microwave communication terminal and point-to-point laser communication ground terminal are in accordance with a particular need, and the information is transmitted to the ground laser communication relay station via microwave and atmospheric laser channels. The information received by ground laser communication relay stations is converted to transmission signals, which are suitable for satellite laser link, by inserting, multiplexing and encoding conversion. The ground laser communication relay stations are responsible for transmitting information to the satellite laser communication network via satellite-to-ground laser uplinks. The satellite optical communication network determines routing in terms of the sink position. The information is passed to the ground laser communication terminal at the rear of the command center by the satellite-to-ground laser downlinks.

2) The back information link

The information from the command center is transferred to satellite laser communication network via ground laser communication terminal and the satellite-to-ground laser uplink. The satellite optical communication network determines routing in terms of the sink position. The information is passed on to the vehicle laser communication terminal relay sta-

tion of each war zone by the satellite-to-ground laser downlinks. The network can achieve high-speed and bidirectional information transmission.

2.3 The networking approach for satellite high-speed/real-time dynamic information network

There should have several types of satellite communication networks. The basic networking structure of the satellite high-speed/real-time dynamic information network has been demonstrated in Fig.2.

Figure 2 The basic networking structure of the satellite communication network

As shown in the Fig.2, the satellite high-speed/real-time dynamic information network can be consisted of the following parts.

1) LEO (Low Earth Orbit) satellite laser/microwave communication network

Generally, about 60~80 satellites will be needed to achieve global coverage. Once the inter-satellite laser link of LEO-LEO is established, the laser signals will be transferred in a baton-type manner along the optimum path in terms of routing protocol. Each satellite contains not more than 5 laser communication terminals. Four of them are network holding terminals, which establish inter-satellite laser communication links with neighboring LEO laser communication satellites. While one of them is responsible for networks connecting terminals, which can establish laser links with relay satellite laser communication terminals, with which users can access LEO satellite commu-

nication network. Besides, the network connecting terminal can also establish inter-satellite laser link with the relay satellite laser communication terminal. Therefore, the LEO satellite laser communication network is connected to the relay satellite laser communication network.

2) Relay satellite communication network

There are at least three satellites that can achieve global coverage. It should be noted that GEO (Geostationary Earth Orbit) laser communication network is the auxiliary network of laser communication. On the basis of information transmission between LEO and GEO, a capacity expansion of LEO laser communication network can be achieved, when it is under the condition of high load. Ground users can also directly access the network for data transmission. The links between GEO and GEO satellites are built according to the routing protocol and laser signals transmitted between the relay satellites by way of chain transmission.

In addition, every relay satellite should have at least three laser communication terminals. Two of them holding terminals for the network, which are used to establish inter-satellite laser communication link with the neighboring GEO laser communication satellites. Another one is responsible for networks connecting terminals to build a laser link with relay satellite laser communication terminals, and users can access the GEO satellite communication network. Meanwhile, inter-satellite laser link with LEO laser communication terminals can be also be formed, and then LEO satellite laser communication network can access the relay satellite laser communication network.

3) Ground user terminal

The satellite-ground laser links are also organized between ground laser user terminals and LEO/GEO laser communication terminals. Thus the ground information can access a satellite laser communication system. The loaded platforms include the foundations, ships, vehicles and other ground systems. There-

fore, high-speed real-time communication between any two points of the world can be achieved by satellite-to-ground laser link.

3 The superiorities of space optical information networks

Space optical information networks have lots of advantages, such as high data rate, low probability of intercept, strong ability of anti-interference and so on. So it plays an 'irreplaceable' role in the process of establishing a high-speed and real-time space-earth integrated high-speed information network. Compared to the traditional microwave communication system, satellite laser communication system provides larger capacity and flexible styles of network connection for the existing emergency communication technology, for example^[7]:

- 1) The frequency of carrier wave is more than 10^5 times over the microwave communication systems and thus huge data can be transmitted within a single channel.
- 2) The terminal is of a smaller size, weightless, consumes lower power and is of higher integration.
- 3) The ground system can easily access the networks to build space-based information highway with global coverage.
- 4) Wave band is used, and there is no need to apply for communications band.
- 5) It has strong anti-interference ability and higher security.

4 Wavelength assignment and requirements in space optical information network

4.1 Wavelength assignment principles

Ideally, for space optical information networks, the same wavelength should be applied for both transmis-

sion and reception, and it is of convenience for users to access. However, the same wavelength will lead to crosstalk of transmission, reception and large light energy losses. Particularly, performance will worsen for the long-distance communication. Thus the same wavelength assignment strategy is usually not recommended.

The satellite optical communication terminals can be classified into two types: Type I and Type II, according to the networking requirements. The only difference between Type I and Type II is the method of coating the optical antennas. The Type I transmits A-band and receives B-band, while Type II transmits B-band and receives A-band. In the high-speed satellite communication network, communication link can be established between the different types of terminals on different platforms. And the same type of terminals located on the same platform can be used to back up each other. In general, if we install four optical communication terminals on each satellite: two Type I and two Type II, diversity in networking can be achieved (Fig.3).

Figure 3 The optical network components of two-wavelength mechanism

4.2 Development paths

There are several development paths to build a space high-speed optical information network.

- 1) Path 1: the key technologies of communication unit

The unit technologies of satellite optical communication terminals include high precision pointing, acquisition, tracking, and communication. PAT technique is extremely important, which is directly related to the success or failure of networking.

2) Path 2: the key technologies of laser link unit

As previously mentioned, the space laser communication networks consist of satellite-to-ground laser link and inter-satellite laser link. Therefore, in order to achieve high-speed networking, the primary task is to achieve a breakthrough in two-unit link technology. Space in-orbit tests can be carried out to verify the performances of laser communication terminals and links, by developing experimental terminals according to the satellite-to-ground and inter-satellite links.

3) Path 3: the study on high-speed networking optical communication terminals

According to network settings, we can develop a networking satellite step-by-step. On the basis of laser communication terminals designed, install and then launch satellites in terms of plans. Finally, we can build a high-speed communication network in space.

4) Path 4: make a breakthrough in the Space Networking space

The work of this section explains the following aspects, including: feasible networking blueprint, routing selecting strategy, and completing the space laser high-speed networking protocols.

4.3 The operation mechanisms

In satellite optical networks, if the network communication request, from the requested source node to the target node, is not assigned to a free lightpath to complete the communication process within the queuing delay time, we call the communication request is blocked (here, the lightpath illustrates the path between network nodes and an available communication wavelength on the path). In ground optical networks, if there are no available lightpaths when communi-

cation request reaches the network, it will enter the queue, waiting for a free lightpath to release. The queue waiting time can be adjusted according to the users' needs. If the user does not need the high quality of real-time communication, the queuing time can be set in a few minutes or even several hours. In other words, if the request queuing delay time is infinite, it means no blocked requests will happen^[8].

However, for satellite optical networks, satellite nodes are in a state of continuous relative motion with respect to ground users. Therefore, the communication connection requests of ground users can not be queued for a long time. Generally, in LEO satellite networks, the overhead time (i.e., communication time) of ground station is about 100~300 s. In order to ensure that communication request is not blocked, the queuing time of request in satellite optical network should be as short as possible.

The queuing delay is a very important parameter in optical satellite networks, which represents the time needed from optical communication request reaching satellite to being assigned to a free lightpath. Therefore, although longer queuing delay time can avoid network congestion, there are very strict restrictions on the actual queuing delay time with relations to the high-speed motion of sub-satellite point and real-time requirements. The limit of the queuing delay time can be called blocking threshold, which determines the blocked time of network tasks. In optical satellite networks, the appropriate blocking threshold can reduce blocking probability and get a reasonable average queuing delay time of network tasks.

Previous works have studied the effect of improved RWA algorithm that can reduce the probability of network congestion^[9,10]. However, these studies assumed laser network operating in the call-loss system. They fail to interpret the impact of blocking threshold on network performance in LEO satellite optical networks from the perspectives of network operation

mechanisms and the time distribution of network tasks. Actually, as for the communication networks served for tasks, there are usually three basic network operation mechanisms: call-waiting system, call-loss system and composite queuing system, as they are shown in Fig.4.

Figure 4 Description of three different network operation mechanisms: (a) Network of call-waiting system; (b) Network of call-loss system; (c) Network of mix queuing system

Call-waiting system is defined as follows: if network communication tasks cannot be executed immediately, the task will be added to the waiting queue, until the execution condition is satisfied. Call-loss system illustrates that if network communication tasks cannot be executed immediately the task will be blocked and removed immediately from the task list, which generally lead to a greater blocking probability. The composite queuing system is a compromise between two systems described above. Namely, if network communication tasks cannot be executed immedi-

ately, they will wait for a moment in the networks or in a fixed length queue. During the waiting period, once the conditions are fulfilled, the tasks will be executed immediately. Otherwise, when the waiting time in the queue is up to the limit or the new added task exceeds allowable length of the queue, the task is blocked and then deleted from the task list. The blocking threshold in optical satellite networks can be regarded as a limit of the task in the composite system.

5 The integration between waves and microwaves in space network

We can also integrate the laser and microwave Network into a composite network system, which not only possess the advantages of the high transmission rate and low probability of intercept for laser links, but also the advantages of wide coverage and strong penetration for microwave links in aspects of user access and information distribution. The feasibility of laser/microwave composite network can be verified to provide technical supports for the construction of the network. The operating modes of laser/microwave composite network are as follows (Fig.5).

Figure 5 Integration between waves and microwaves

1) Input laser and output laser mode: if the rates are matching with each other, routing switching can be completed without any other treatment. However, the rates cannot be matched with each other, there are mainly two cases: if the input rate is less than that of

the output, the output rate is in accordance with the input rate, which can also send data together combined with that of the same output port; if the input rate is larger than that of output, we can consider storage of the received data quickly and then send the data slowly. Or we can compress the input data to match the output rate, and then transmit the input data.

2) Input microwave and output laser mode: generally, the information rate of microwave is less than that of laser. We can use the integrated microwave technologies to combine multiple microwave into one high-speed information, and then output the data laser.

3) Input laser and output microwave mode: as discussed above, the information rate of laser is usually greater than that of microwave. In this case, we can consider storage of the received data quickly, and then send the data slowly. Or we can compress the input data to match the output rate, and then transmit the input data.

6 The prospects of the space optical information network

6.1 Applications in the military field

Increased demand for information transmission is forcing military to establish high-speed/real-time information transmission networks in space, and the satellite laser communication technology is the highly effective strategy.

With the development of satellite technology, satellite surveillance and detection technology has made a considerable progress, which includes a variety of categories and undertakes various investigative and surveying missions. Besides, these remote sensing, telemetry systems are developing in the co-existence direction of multi-resolution and multiple remote sensing platforms. Furthermore, space resolution, time resolution and spectral resolution have been

improved, with the demand for huge information transmission. Therefore, new requirements should be called for as follows.

1) Remote sensing data contains a large amount of information.

2) Improve the quality and timeliness of acquired information.

3) Stronger ability of security and privacy of data transmission.

The existing satellite data transmission capacity can not meet demands. It is essential to build global coverage of satellite laser communication networks, and explore the user satellite laser communication terminals, which provides new communication technologies of high-capacity fidelity. High-speed laser communication link based on relay satellite nodes, can be established among various spacecrafts. Meanwhile, the various space laser optical communication systems are connected to flexible ground optical communication networks, forming space-earth integrated high-speed communication system, which is an effective way to solve problems of the current space communication.

6.2 Mobile internet and big capacity data transmission

Generally, as for the mobile communication services, voice communication is usually a basic function. Mobile internet has become the major development direction of the next generation mobile communication technology. At the same time, multimedia communication, mobile computing, cloud computing, networking and social networking are the core network technologies. These new-emerging information industries are much greater than the existing internet industries. So increased demands are forcing us to improve the capacity of the communication system.

In addition, lots of the remote rural areas, such as mining, water bodies, forests and deserts, cannot

be covered. Mobile satellite communication systems have been proposed, in which the most typical systems are satellite constellation communication systems, including Iridium system and Globalstar system. But these are narrow-band communication systems, which are mainly based on voice and low-speed data services.

Along with the development trend in the mobile communication technology, global broadband satellite communication systems have come into play. According to incomplete statistics, up to 85 broadband satellite communication systems are proposed in the world. For example, the United States has developed LEO satellite communication system Teledesic, GEO satellite communication system CyberStar and MEO satellite communication system Spaceway, which can provide voice, video, multimedia, data transmission services for users, including high-speed internet access, intranets and virtual private networks. Europe has also put forward the concept of highway in the sky. Euro-Sky-Way, which provides mobile users with a broadband GEO system. The mobile satellite broadband technology has become a hot topic in the field of satellite communication.

6.3 Internet and big capacity of data transmission

The space-earth integrated high-speed information network can provide integrated services, including:

1) Mobile communication information can access high speed optical communication network. As it is shown in Fig.6, once the information of the ground mobile terminals access relay stations channel via microwave, relay stations can send the information to satellite laser communication system via laser channel. This technique can establish high-speed direct connection in any two relay stations, Considering that the system bandwidth is

effectively improved, the system can provide more mobile terminals with high-speed communication services.

Figure 6 Laser communication system provides high-speed information transmission services for the mobile terminals

2) Provide high-speed communication services for special areas such as the remote rural areas, like mining, water bodies, forests, deserts, etc., the establishment of independent stations can easily provide access satellite laser communication system. This technology can keep costs of construction down, as it is shown in Fig.7.

Figure 7 High-speed satellite laser communication system provides communication services for special areas

3) Provide high-speed communication services for long-distance transports. Currently, high-speed broadband communication services can not be reached on trains, planes, ships and other large vehicles. The local area network can access satellite laser communication system by installing the laser communication

terminals in these vehicles, and then it can connect with the other high-speed network, making the high-speed mobile internet easily (Fig.8).

Figure 8 Satellite laser communication system provides high-speed communication services for long-distance transports

4) Temporary emergency services. As for the emergencies, such as disaster relief, scientific exploration and environmental protection, and so on, satellite-to-ground laser communication links can be quickly established between satellites and portable moving communication terminals in a region. And then information can access satellite laser communication system. However, the current satellite communication system is based on microwaves. The communication capacity is limited. The large size, high weight, more power consumption, and high cost of manufacturing and launching of satellite, makes it impracticable to develop broadband communications satellites. Novel space satellite optical information networks are expected to widen the internet services and improve the capacity of data transmission.

7 Conclusions

Free-space optical communication and space optical information network potentially offer many more advantages, such as higher data transfer rates, smaller platforms to launch, and lower costs. The novel in-

formation network can be used in a number of fields, ranging from traditional territory and the surrounding areas to the outside regions, forming global coverage. Integrated with space-earth networks, space-earth integrated information networks provide a powerful guarantee for real-time high-resolution tasks, such as geographical observation, deep space exploration, manned space flight, space experiments and so on. In the future, space optical communication technology will play an important role in space high-speed information networks.

References

- [1] LESH J. Free space laser communications in lasers and electro-optics[C]//Summaries of Papers Presented at the Conference, Baltimore, MD, USA, c1999: 1-5.
- [2] YU S Y, MA Z T, MA J, et al. Far-field correlation of bidirectional tracking beams due to wave-front deformation in intersatellite optical communication links[J]. Optics express, 2015, 23(6): 7263-7272.
- [3] TANZILLO N, DUNBAR B, LEE S. Development of a lasercom testbed for the pointing, acquisition, and tracking subsystem of satellite-to-satellite laser communications link[C]//Proceedings of SPIE6877, c2008: 04-06.
- [4] YU S Y, MA J, TAN L Y. Methods of improving acquisition probability of scanning in intersatellite optical communication[J]. Journal optoelectronics laser, 2004, 16(12): 57-62.
- [5] KIM I I, RILEY B, WONG N M. Lessons learned from the STRV-2 satellite-to-ground lasercom experiment[C]//Proceedings of SPIE4272, c2001: 1-15.
- [6] TOLKER-NIELSEN T, OPPENHAEUSER G. In Orbit test result of an Operational Optical Intersatellite Link between ARTEMIS and SPOT4, SILEX[C]//Proceedings of SPIE4635, c2002: 1-15.
- [7] PANAHI A, KAZEMI A A. High speed laser communication network for satellite systems[C]//Proceedings of SPIE8026, Photonic Applications for Aerospace, Transportation, and Harsh Environment II, Pasadena, CA, c2011: 80260L.
- [8] CHAN V W S. Optical space communications: key building blocks for wide area space networks[C]//Proceedings of SPIE8026, San Francisco, CA, USA, c1999: 80260L-12.
- [9] PRIBIL K, KUDIELKA K. Analog optical intersatellite links[C]//Proceedings of SPIE Vol, c2002, 4635: 215.
- [10] TOYOSHIMA M. Free-Space Laser Communications: The Japanese Experience[Z]. National Institute of Information and Communications Technology, 2009.

About the authors

MA Jing [corresponding author] was born in 1956. He received the Ph.D. degree in Optics from Harbin Institute Technology. He is now is the famous professor in Harbin Institute of Technology School of Astronautics, the director of the Space Optical Communication Technology Research Center, Director National Key Laboratory of Science and Technology on Tunable Laser, and Director of National Defence Key Laboratory on Satellite Laser Communication Technology. His research interests include Satellite Optical Communication, Laser interferometry, Optical Information Processing and Laser Holography. (Email: majing@hit.edu.cn)

TAN Liying was born in 1957. She received B.S. degree in Physics from North East Heavy Machinery Institute, Qiqihar, China in 1982, the M.S. degree in physics from Harbin Institute of Technology, Harbin, China in 1995, and the Ph.D. degree in electronic science and technology from Harbin Institute of Technology, Harbin,

China in 2003. She is currently a Professor in School of Astronautics, Harbin Institute of Technology. Her research interests include free-space optical communications, wavelet optics and optical information processing. (Email: tanly@hit.edu.cn)

YU Siyuan was born in 1974. He received the Ph.D. degree in Space Optical Communication from Harbin Institute of Technology, China. He is now a Professor in School of Astronautics, Harbin Institute of Technology, Associate director of National Defense Key Laboratory on Satellite Laser Communication Technology of Harbin Institute of Technology in China. His research interest include Highly-Integrated Space/Ground Information Network Technique, Bi-beam pointing, acquisition and tracking technique, and the optical signal of atmospheric transmission compensation technology, and so on. (Email: yusiyuan@hit.edu.cn)