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Feasibility study of a scalable laser communication terminal in NICT for next-generation space networks

Yasushi Munemasa*, Yoshihiko Saito, Alberto Carrasco-Casado, Phuc V. Trinh, Hideki Takenaka, Toshihiro Kubo-oka, Koichi Shiratama, and Morio Toyoshima
Space Communications Laboratory, Wireless Networks Research Center,
National Institute of Information and Communications Technology (NICT),
4-2-1, Nukui-kitamachi, Koganei, Tokyo, Japan, 184-8795

ABSTRACT

Recently, satellite broadband communication services using Ka-band are emerging all over the world, some requiring capacities in excess of 100 Gbps. With the radio bandwidth resources becoming exhausted, high-speed optical communications can be used instead to achieve ultra-broadband communications. The National Institute of Information and Communications Technology (NICT) in Japan has over 20 years of experience in R&D of space laser communications with missions such as the Engineering Test Satellite VI (ETS-VI), OICETS, and SOCRATES/SOTA. We are currently developing a laser communication terminal named "HICALI", aiming to achieve 10 Gbps-class space communications with a 1.5 μm-band laser beam between optical ground stations (OGSs) and the next generation high throughout satellite called ETS-IX with a hybrid communication system using radio and optical frequencies, which will be launched into the geostationary orbit in 2021. Moreover, we have studied laser communication terminals for terrestrial networks, as an alternative wireless system to radio frequency (RF) band. In 2014, we developed a terrestrial free-space optical communications network facility, named INNOVA (IN-orbit and Networked Optical ground stations experimental Verification Advanced testbed). Many demonstrations have been conducted to verify the feasibility of sophisticated optical communications equipment in orbit.

We have conducted a feasibility study of a laser communication terminal for next-generation space networks following the above R&D trends in space communication networks, which is a high-speed, secure, small, and scalable laser communication terminal for optical ground stations (OGSs) and satellites or airborne terminals. In this paper, we describe the plan of NICT to develop a scalable laser communication terminal for next-generation space networks.

Keywords: laser communications, satellite communications, RF-optical exchange on board

1. INTRODUCTION

Recently, the capabilities of remote-sensing satellites are becoming much more sophisticated, with an increasing number of sensors with more and more resolution. Therefore, the data gathered by these satellites is becoming larger and larger. To deal with the increasing bandwidth requirements, many satellite-communication operators around the world are developing broadband satellite-communication services based on the Ka-band. In December 2010, Eutelsat launched KA-SAT, an example of a high-throughput satellite (HTS). The KA-SAT satellite has 82 spot beams and a capacity in excess of 70 Gbps[1]. In October 2011, the ViaSat-1, known as HTS, was launched, with a capacity of 140 Gbps. Since January 2012, a satellite-based broadband Internet Protocol (IP) service has been deployed over North America. Sometime after 2019, ViaSat-3 should be providing global coverage with a capacity of 1 Tbps[2]. The Inmarsat-5 satellite network is currently providing the Global Xpress service, which is a Ka-band broadband satellite-communication service with 5/50 Mbps for uplink/downlink. Since August 2015, three operational Inmarsat-5 satellites have been launched to the Geostationary Earth Orbit (GEO), giving global coverage with 89 spot beams per satellite[3].

*munemasa@nict.go.jp; phone +81-42-327-5357; fax +81-42-327-6825;

In general, compared to laser communication systems, the RF-based satellite communication systems can simplify the mechanism of acquisition and tracking for communication beams, and also, the service area per beam is wider than that of laser communication systems. The RF systems are easy to use for portable or mobile communication systems on the ground. However, the above-mentioned HTS systemsare spread out by the worldwide mega constellation. On the ground segment, the 5th generation (5G) mobile communication system service will be provided in the beginning of 2020s, featuring the higher bandwidth, which is in the L-band, S-band and C-band, in order to meet the increasing demand of the high throughput wireless communications. In the near future, the available Ka band for RF satellite communications may be tight or depleted. Furthermore, downlink and uplink communication capacities between the satellites and ground stations using RF band are usually very limited due to the compromise of resources (power consumption, size capacity, mass, placement, etc.) within the satellite, and frequency regulation issues.

On the other hand, laser communication technologies are attracting a great deal of attention because of their large capacity in data transmission. In addition , the size and mass of optical terminals are smaller than their RF counterparts. Since the restriction of satellite resources is tighter for smaller satellites, the combination of optical communications and small satellites is regarded as suitable for applications generating large amounts of data. The beam of laser communications is extremely narrow, the usages of laser communication system are limited, such as single link systems for inter-satellite relay communication in the space. However, the systems offer many advantages for wireless communications, which are high capacity data link and highly secure communication such as a cryptographic key distribution system. Then, we are embarking on feasibility study of a scalable laser communication system and terminal for field application in the space and terrestrial communication scenarios .

In this paper, we describe the plan of NICT to develop a scalable laser communication terminal for next-generation space networks.

2. MOTIVATIONS OF THE STUDY

Several satellite systems are now being planned to provide optical data relays for Europe, the United States, and Japan. In September 2013, the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA) conducted 622-Mbps laser communication experiments between the Lunar Atmosphere Dust Environment Explorer (LADEE) and optical ground stations as part of the Lunar Laser Communications Demonstration (LLCD) program[4] . In April 2019, NASA plans to launch the Laser Communications Relay Demonstration (LCRD)[5] . The European Space Agency (ESA) runs the Copernicus program, which is a network of Sentinel Earth-observation satellites. In November 2011, the Sentinel-1A satellite successfully transmitted observation data using the Alphasat communication satellite via a 1.8-Gbps optical link[6] . In addition, ESA runs the European Data Relay System (EDRS). This has been operational since January 2016, when the EDRS-A satellite was positioned at 9° E; and since 2017, when the EDRS-C was positioned at 31° E. For Japan, the Japan Aerospace Exploration Agency (JAXA) is developing the Japanese Data Relay System (JDRS) for launch in 2019[7] .

In Japan, the National Institute of Information and Communications Technology (NICT) has a long history of the research and development (R&D) of space laser communications. The first important mission was the Engineering Test Satellite VI (ETS-VI) project, carried out between 1994 and 1996. The on-board equipment of 22-kg weight and 60-W power established 1-Mbps bi-directional optical links among ETS-VI and NICT's Koganei OGS (optical ground station) in Tokyo. From 2006 to 2009, we performed laser-communication experiments between OICETS satellite and the OGS, using a 0.8 µm wavelength with data rate of 50 Mbps for downlink and 2 Mbps for uplink. In addition to the space-OGS links, inter-satellite laser-communication experiments were successfully carried out between OICETS and ESA's ARTEMIS achieving 50Mbps. The microsatellite SOCRATES, which carried the laser-communication system SOTA (Small Optical Transponder) developed by NICT, was launched in 2014[8,9,10]. 10-Mbps communication links at 1.5-µm and 0.98-µm wavelengths were performed between SOTA and NICT's three OGSs (described later) for more than two years[10].

Figure 1 shows an overview of the R&D activities of the NICT's Space Communications Laboratory. Based on HTS satellites such as Inmarsat-5, Viasat-3, and O3b, higher-capacity Ka-band communication is required for satellites. Over the next 10–20 years, the trend in space communications is to replace radio frequency (RF) systems with ones based on laser. For this, it is necessary to utilize site diversity technique to mitigate the unavailability of individual laser links due to local weather conditions, which requires international collaboration. The target of the transmission speed should be around 100 Mbps for mobile users at Ka-band in the next generation HTS communication systems[11] .

We are currently developing a laser-communication terminal called "HICALI", with the goal is to achieve 10 Gbps-class space communications in the 1.5-μm band between Optical Ground Stations (OGSs) and the next generation high-throughput satellite (called ETS-IX) equipped with a hybrid communication system using radio and optical frequencies, which will be launched into the geostationary orbit in 2021. The development of the test and breadboard model for HICALI has been conducted for several years and we are now carrying out an engineering model as well as designing the OGSs segment.

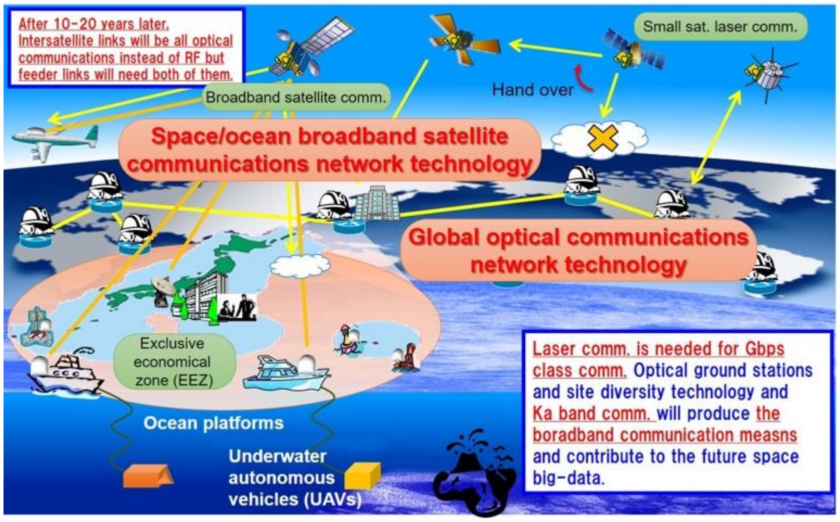

Figure. 1. Overview of the R&D activities of the NICT's Space Communications Laboratory.

3. SYSTEM CONFIGURATIONS OF NEXT-GENERATION HYBRID HTS COMMUNICATION SYSTEMS

3.1 Overview of Next-generation hybrid HTS in Japan

Regarding the R&D of the next generation of communication satellites, NICT has established a user consortium to identify the future needs of communication-satellite users, studied satellite-communication system concepts covering those needs, and settled on technical issues for increasing communication speeds. NICT has also come up with a conceptual design of a next-generation large-capacity satellite communication system, as shown in Fig. 2. A feasibility study has been conducted for a prototype system, and its development has begun. Our goal is to realize 100-Mbps-per-user, high-speed, large-capacity mobile communication using the Ka-band, and to implement flexible (variable-frequency bands and steerable beams) relay technology that can handle traffic fluctuations. According to projected increases in traffic and users, the feeder-link capacity in terms of frequency bands between satellites and terrestrial gateway stations will become exhausted sooner. In addition, the Radio Regulations tend to make it difficult for RF bands to be allocated. To solve these issues, the feeder links could be achieved optically instead. The objective is to realize 10-Gbps-class optical feeder-link technology for a geostationary Earth orbit. The next step is to verify this technology on orbit, which would contribute to the next-generation hybrid (RF and optical frequencies) HTS[12]. This will be the Engineering Test Satellite IX (ETS-IX), which is being developed by JAXA and planned for launch in 2021 by a H3 launch vehicle test flight No.2[13] as described in the Basic Plan on Space Policy in Japan[14] .

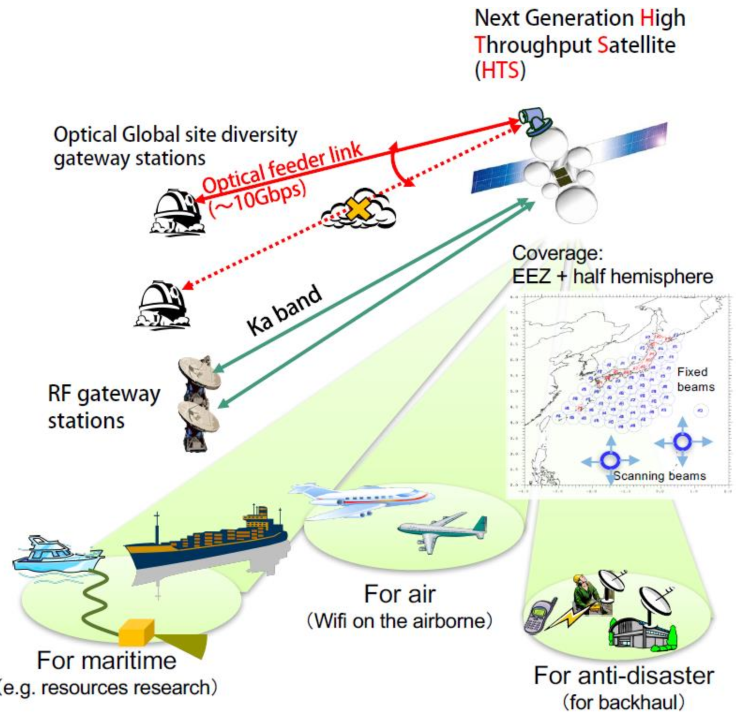

Figure. 2. Schematic drawing of the next generation High-Throughput Satellite (HTS).

3.2 Overview of HICALI Project

NICT has instituted a project called HICALI (HIgh speed Communication with Advanced Laser Instrument) to facilitate the next-generation space laser-communication research. The aim of the project is to achieve 10 Gbps-class space communications with a 1.5-µm-band laser beam from a geostationary satellite to ground. The terminal is going to be launched on a next-generation HTS on GEO in 2021. In Fig. 2, we display the schematic drawing of the HTS project, which will be equipped with not only the HICALI terminal but also RF terminals.

The main objectives of the HICALI project are as follows:

(1) in-orbit verifications of the first 10-Gbps-class laser communication from GEO to ground,

(2) in-orbit verifications of novel optical modulation/demodulation methods,

(3) in-orbit verifications of novel high-speed optical devices,

(4) acquisition of laser-beam propagation data and in-orbit experiences.

New approaches will be explored to find new usages such as:

- Acquisition of development knowledge in conjunction with manufacturers,
- Search for new users who have the potential to use laser communications.
- Demonstration of function for RF-optical (laser) communication exchange.

A feasibility study for the HICALI project was conducted in 2014, and to date a number of critical parts for the project have been identified. A breadboard model (BBM) was developed in 2015 as shown in Fig. 5 and the evaluation was done in 2016. Key devices such as optical delay line interferometers, tunable lasers, optical modulator, optical detector, clock data recovery circuit, and high-speed digital processing devices are based on Commercial Off-The-Shelf (COTS) parts.

In addition to the objectives, it is expected that NICT and Japanese manufacturers will be able to acquire knowledge of development of space laser-communication components and explore new users who have potential to use laser communications through the HICALI project.

3.3 Configuration of the HICALI system

Figure 3 shows the functional block diagram of the HICALI system [15]. To realize ultra high-speed optical communications, the HICALI space segment consists of mainly five components, OHA (Optical Head Assembly), OAMP (Optical AMPlifier), OTRX (Optical Transmitter and Receiver), HDU (HICALI Data Unit), and RFOX (RF-Optical eXchanger).

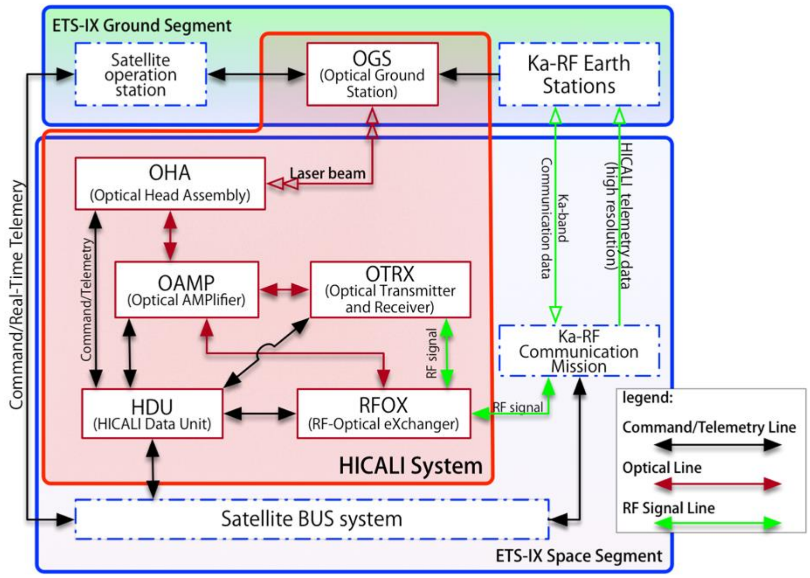

Figure 3. the functional block diagram of HICALI system.

OHA is in the optical section, which is mainly composed of optics and beam-steering mechanics for acquisition and tracking the OGS. The HICALI communication transmitting / receiving beams are collimated using the optics installed in the OHA, the beams (transmitting and receiving optical signals) travel to OTRX or RFOX via OAMP. OTRX consists of a MZ modulator and DBF-LDs for transmitting, a delay-line interferometer, a balanced receiver, and a clock data recovery circuit for receiving, and high-speed digital processing devices for high-speed code or decode processing. RFOX has interface functions for Ka-band communication sub-system, in order to demonstrate the next-generation hybrid (RF and optical frequencies) HTS system.

HDU has functions of control and storage the telemetry for OHA, OTRX, OAMP, and RFOX, receiving command and sending real-time telemetry for HICALI system via the satellite BUS system. Since the telemetry capacity is limited in HICALI, HDU can send detailed mission telemetry via Ka-band or laser, which are high-resolution monitoring data of HICALI components, receiving power at OHA and OAMP for analyzing the influence of atmospheric turbulence during uplink communication and measuring the BER (Bit Error Rate) at OTRX for system analyze.

3.4 Feasibility Study of RFOX System

RFOX has interface functions for Ka-band communication sub-system, in order to demonstrate the next-generation hybrid (RF and optical frequencies) HTS systems.

Generally, assuming that the end user of communication is connected to the Internet, the protocol of communication is packet-based exchange system, which is the most popular current mainstream communication infrastructure over the world. For the end user, the requirement evaluation index is high, which provides the quality of service (QoS) including the application, ultimately. On the premise that the satellite communication system is connected to the IP (Internet Protocol) network under design and physical restrictions on the satellite mounted components, there are many kinds of considered indicators, which are IP quality, Ethernet quality, etc. Considering the details of the viewpoint of IP quality, which constitutes the bandwidth, rate of transmitting data loss, and the jitter of delay time. In the satellite communication system, such as the transmission route, “end user” – “earth station” – “user link by RF” – “satellite” – “feeder link by RF or light” – “ground station” – “terrestrial network”, especially for GEO HTS, the delay time due to propagation can result in large quality degradation. Otherwise, for HTS with low orbital constellation, the delay time can be reduced, depending on configured en route of the transmission to the network. The jitter may be large depending on signal processing on board or routing configuration.

Furthermore, from the viewpoint of the environmental conditions (radiation, thermal control, power limitation on board) or reliability, it is quite difficult to mount devices and equipment having high-speed digital processing circuits. Then, it is very difficult to apply advanced network control and high-speed digital processing method designed for terrestrial wireless network system.

In optical communication, an original baseband data is directly modulated such as IM/DD (intensity modulation / direct detection), BPSK (binary phase shift keying) or other digital modulation and converted into a digital signal and transmitted. In the case of digital transmission, error correction, interleaver, etc. can be used and an encoding function effective for atmospheric fluctuation can be added. Then, HICALI subsystem adopts high-speed digital modulation with the function of playback to the baseband level on the board using a high-speed digital processing circuits.

However, in the ETS-IX communication mission, the RF subsystem adopts bent-pipe system (non-regenerative relay system on the board) for compatible versatile RF earth stations over a long term of the satellite life. Then, the difference of throughput is large (laser link: 10 Gbps, RF link: 100 Mbps). In order to simplify the interface design, the non-regenerative relay system, which is concatenated the HICALI (RFOX)-to-RF communication system with IF (intermediate frequency) signals, is adopted. As a similar communication system, RoF (Radio over Fiber (Fiber Optic Radio)) system or gap filler for the eliminating terrestrial TV reception fault, etc., which has already been put to practical use in terrestrial broadcast / communication network, etc., is available.

This system has the disadvantage that the effective bandwidth cannot be sufficiently utilized in the ultra-wideband,. However, for the HTS system adopting the non-regenerative relay system, since the interface design is simple, the compatibility is high, and the development risk is low, then it is easy to adopt it for commercial satellite communication system in the short term. It also has the merit that it does not depend on the modulation system of the RF earth station.

In the medium to long term, as satellite communication systems and progress in on-board technology, especially technology with an ultra-high-speed processing processor, become popular, regenerative relay system on the board will be the mainstream. Then, in the project, we will consider the proof of technology verification in consideration of the influence on QoS.

4. CONCLUSION

In this paper, we described the plan of NICT to develop a scalable laser communication terminal for next-generation space networks. The concept of a hybrid high-throughput satellite with an optical feeder link was introduced. The optical feeder link system called HICALI (HIgh speed Communication with Advanced Laser Instrument) project was also described. This type of hybrid satellite will create new opportunities in the next generation of high-throughput satellites. Especially, the feasibility study of RFOX system which is the interface function of HICALI and Ka-band communication subsystems, was introduced. We hope that this work will lead to technology demonstrations of laser communication networks with satellites and airborne, and contribute to enlarging the widely-accessible, scalable, and high-security laser communication networks not only in the space but also in the terrestrial scenarios.

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