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Research and Development of Key Technologies for Achieving Space Integrated Computing Network

Fumihiro YAMASHITA and Shigehiro HORI

abstract

Seeking to help realize a sustainable society that thrives with the use of outer space, NTT, in collaboration with Sky Perfect JSAT, advocates the concept of space integrated computing network. This is composed of three concepts : outer space sensing, outer space datacenter, and outer space RAN. This paper discusses the research and development of key technologies that we conduct in collaboration with related organizations in order to realize the concept of space integrated computing network.

Keywords : Space, satellite, communication, datacenter, sensing, RAN, NTN

1. Introduction

Since our announcement of the concept of the innovative optical and wireless network (IOWN) in 2019, which declared our commitment to building a telecommunication infrastructure of the future based on the active use of advanced optical technology and information processing technology, we at NTT have been conducting research and development seeking to cultivate value of various kinds, such as sustainable development, safety/security/reliability, and the optimizing of interactions between individuals and the whole, through seeking evolution under the two major themes of "Digital to Natural" and "Electronics to Photonics [1]". As the expanding of telecommunications in outer space is defined as one of the pillars supporting the development of wireless networks under the IOWN concept, we, in collaboration with related organizations, are currently conducting research and development toward the establishment of an infrastructure for outer space telecommunications with radio frequency (RF) and optical wireless communication [2]. Fig. 1 shows the concept of the space integrated computing network that NTT and Sky Perfect JSAT have released to the press. The concept presents the vision of a vertically extended outer space telecommunication and computing infrastructure based on the use of high-altitude platform stations (HAPS), which are unmanned airborne platforms held stationary in the stratosphere at an altitude of 20 kilometers from the ground and of low earth orbit (LEO) and geostationary orbit (GEO) satellites in outer space [3]. This integrated infrastructure will have the means for RF and optical wireless communication, and we aim to develop it eventually into an autonomously sustainable outer space infrastructure unaffected by incidents on earth like disasters as it should become able to process/analyze data generated in outer space in a self-contained manner using resources in outer space with the sharing of processing load through distributed

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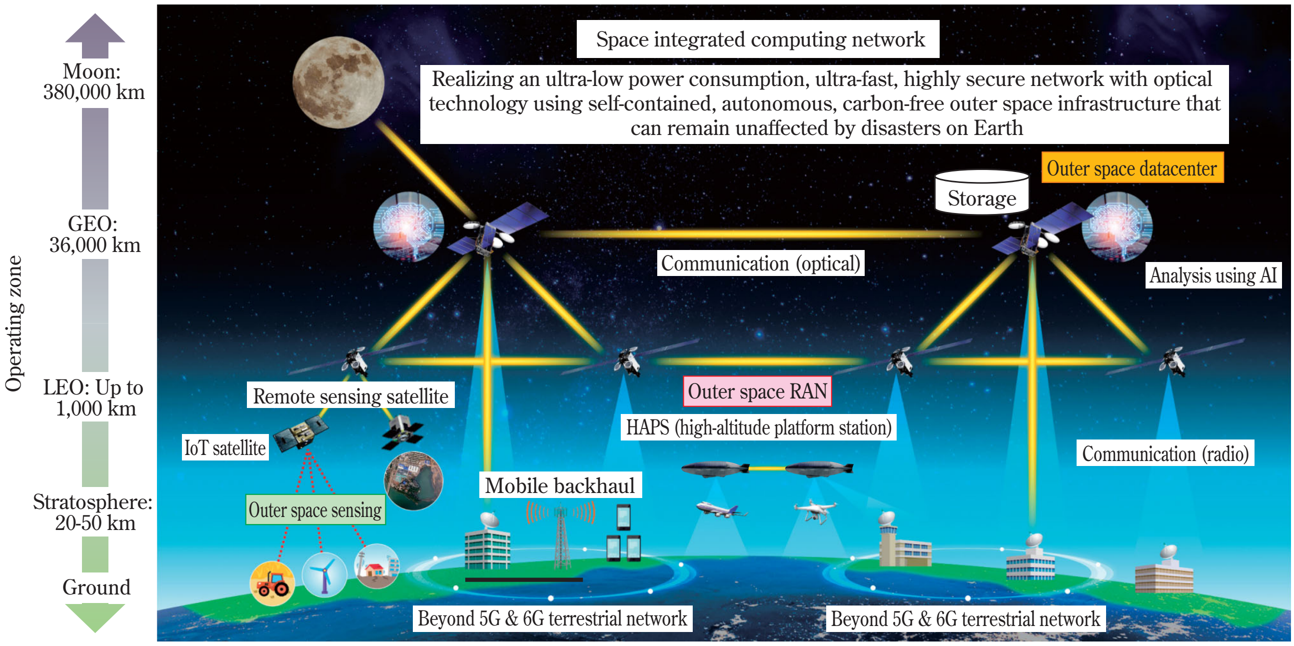

Fig. 1 Concept of space integrated computing network The concept presents the vision of a vertically extended telecommunication and computing infrastructure involving the use of HAPS, which are unmanned airborne platforms held stationary in the stratosphere at the altitude of 20 kilometers from the ground, and with low earth orbit and geostationary orbit satellites in outer space.

computing in a constellation type network configuration.

Space integrate computing network will have three capabilities. The first is outer space sensing with which we aim to enable the Internet of Things (IoT) communication in areas not served by terrestrial networks and to help realize global-scale comprehensive sensing by observation from satellites. The second is an outer space data center, which, taking advantage of the reduced power consumption of satellite mounted equipment realized through optoelectronic integration, we expect to furnish with an infrastructure for large-capacity optical communications and computing, enabling the development of various faster-response applications. The third is an outer space radio access network (RAN), which we shall develop for the era of Beyond 5G (B5G) and 6G by integrating the terrestrial network infrastructure with the outer space communication infrastructure, such as geostationary orbit (GEO) satellites, low earth orbit (LEO) satellites, and HAPS in pursuit of such advantages as ultra-wide coverage and ultra-high tolerance against disasters.

This paper presents an overview of the three components of a space integrated computing network, namely, outer space sensing, an outer space data center, and outer space RAN, with discussions on the key technologies supporting them.

2. Outer Space Sensing

2.1 Concept

As mentioned above, outer space sensing is applied for two different purposes : IoT communication and earth observation. First, we shall discuss the enabling of global-scale IoT communications. Fig. 2 shows the concept of an IoT platform that is under research and development at our company, which will realize global-scale coverage with IoT terminal devices.

Specifically, we seek to develop new markets by enabling data collection by ultra-wide coverage (over the ocean etc.), low-frequency sensing with low-cost 920 MHz band terminal devices, which will be able to access the network from anywhere on earth[4]. We expect to reduce the hardware procurement cost by making use of typical low power wide area (LPWA) terminal devices developed for terrestrial use. The satellite used will be a simple configuration : it will perform digital sampling on the received 920 MHz signal waveforms, temporarily store the results in satellite-mounted memory, and downlink the memory-stored data to the ground when it flies above the base station on the ground. Since the period of time in which the downlink is enabled is restricted by the movement of the LEO satellite, and moreover the frequency band available for use is limited, we will use MIMO

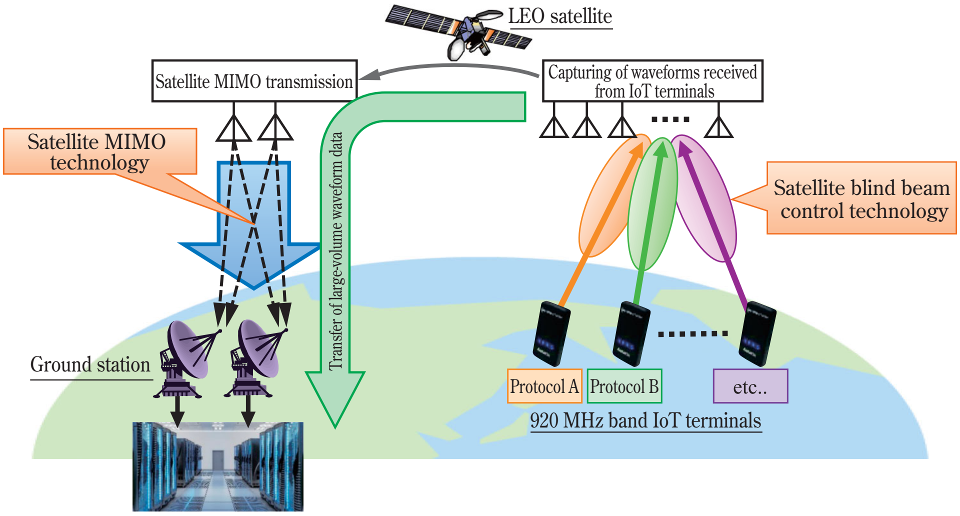

Fig. 2 Satellite IoT platform We seek to develop new markets by enabling data collection through ultra-wide coverage (over oceans etc.), low-frequency sensing with low-cost 920 MHz band terminal devices, which will be able to access the network from anywhere on Earth.

technology for the sending and receiving of different signals at the same frequency but with different antennas to increase the downlink capacity.

As to earth observation from remote sensing satellites, the application of microwave radar with image capture by high-definition camera (optical sensor) and the use of satellite-mounted synthetic aperture radar (SAR) is widely known. NTT, in collaboration with JAXA, is examining the idea of using terahertz remote sensing in the mission of comprehensively collecting data on various condensed particles in cloud/precipitation systems. Specifically, we are conducting research and development on an InP-HEMT/HBT-implemented 325 GHz band low-noise amplifier (for observation) for mounting on a satellite equipped with a 300 GHz terahertz-band wireless device featuring MMIC with InP-HEMT/HBT[5].

2.2 Key Technologies

(1) Satellite blind beam control technology

In recent years, the number of terrestrial IoT terminals using the 920 MHz band has increased rapidly in urban areas because of the use of smart meters and other factors. Therefore, we anticipate the problem of a 920 MHz band antenna mounted on a satellite catching interfering signals from urban areas together with the target signals. Therefore, we have the idea of equipping the satellite with multiple antennas to control beam directivity, that is to say, in the presence of major interfering signals from a particular direction, the null antenna gain direction should be turned in that direction to minimize impacts, while the highest antenna gain direction should be turned in the direction of the target signals[6]. Yet, since the satellite moves from time to time, changing the relative positional relationship between the satellite-linked sensor terminals and the interfering signal sources, real-time beam control is difficult. Therefore, we are examining the idea of first receiving signals from the satellite-linked sensor terminals using multiple antennas on the satellite, downlinking the received signals from the satellite to the ground, and then trying to maximize the receiving gain for the target signals through signal processing in which the signal from each single terminal should be processed to minimize interference from signals from other terminals. With such signal processing performed on the ground, we expect to improve the receiving signal interference noise ratio (SINR).

(2) Satellite MIMO technology

MIMO technology, which is used in mobile phones and wireless LANs, uses multiple antennas to increase transmission capacity over a limited frequency bandwidth. In a multipath environment, MIMO technology effectively increases transmission capacity when the correlations among MIMO channels are low. In a line-of-sight environment like satellite communication, the application of MIMO technology has been thought to be difficult because path-to-path correlations are high. In trying to meet this challenge, NTT, in collaboration with

JAXA, is proposing the idea of reducing channel-to-channel correlations by combining multiple antennas on the satellite with multiple antennas on the ground that are set up with large physical separation distances (7). Setting up the ground antennas with large physical separation distances reduces channel-to-channel correlations, but as a trade-off, has the drawback of producing relative asynchronicity among the receiving channels. Nevertheless, we contrived a method that will be able to perform MIMO interference compensation in such an asynchronous environment. In principle, as a major attraction of MIMO transmission, the capacity increases in a scalable manner with the number of antennas.

(3) Terahertz band wireless device technology

Typical silicon-based ICs, while allowing the achievement of high functionality through integration similar to CMOS, do not allow the achievement of higher speed and/or capacity beyond a certain extent. InP compound-based ICs, on the other hand, are not suitable for high-level integration but are more tolerant of higher speed and output than silicon-based ICs. For use in the comprehensive collection of data on condensed particles in cloud/precipitation systems, we are now evaluating the performance of an InP HEMT/HBT technology-implemented 300 GHz band wireless device for use in a satellite (with radiation tolerance evaluation etc.) (8).

3. Outer Space Datacenter

3.1 Concept

Existing services that rely on direct data transmission from an observation satellite to a ground station are restricted by limited timings at which the satellite can communicate with the ground station and by a transmission capacity limit due to limited frequency band availability. Optical data transmission via a GEO satellite, on the other hand, allows large-capacity, quasi-real-time data transmission. NTT and Sky Perfect JSAT jointly established the Space Compass Corporation with plans to apply on-orbit high-speed optical data relays and outer space edge computing to begin providing platforms that will solve the problem of transmission capacity shortages, which constitute the bottleneck in the use of earth observation satellites, and will also contribute to bringing the transmission speed closer to the real-time level (Fig. 3) (9). Our primary target is the startup of an optical data relay service for high-speed transmission to the ground via a GEO satellite with enormous data collected in outer space by observation satellites.

3.2 Key Technologies

(1) Optical wireless technology

In general, optical wireless has a larger transmission capacity than RF wireless and does not require a radio

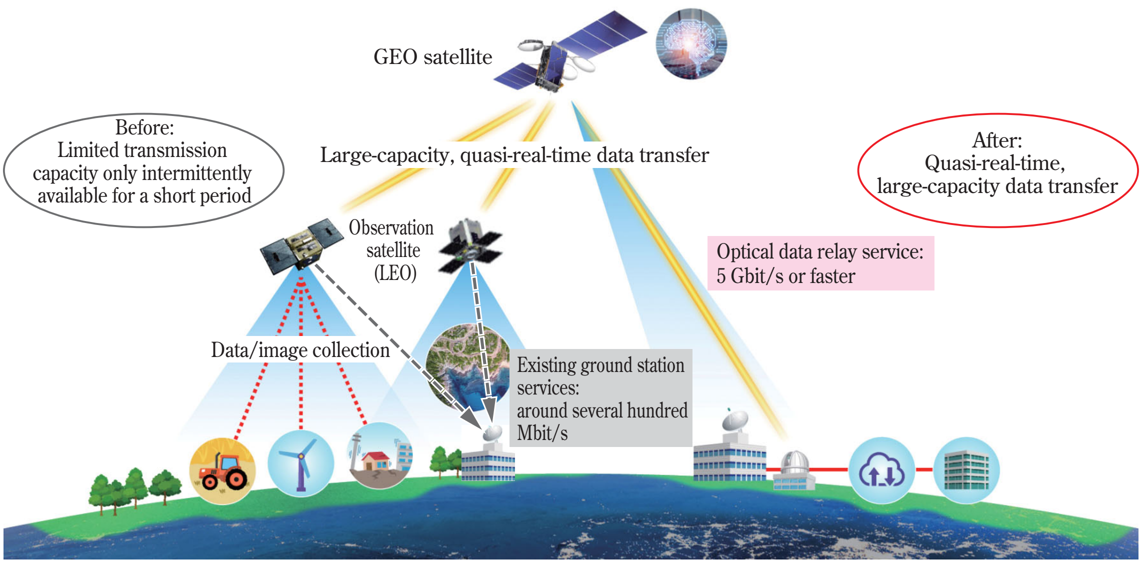

Fig. 3 Outer space datacenter concept We plan to apply on-orbit high-speed optical data relay and outer space edge computing to begin the providing of platforms that will solve the problem of transmission capacity shortage, which constitutes the bottleneck in the use of earth observation satellites, and will also contribute to the bringing of the transmission speed closer to the real-time level.

operator's license, so it is suitable for use in outer space, which is a line-of-sight environment. Optical wireless communication between the satellite and the ground requires the introduction of relevant technology for the assurance of quality because the communication quality is likely to deteriorate from such factors as obstruction by clouds and atmospheric fluctuations, but optical wireless communication between satellites is expected to be put to practical use earlier thanks to the absence of atmospheric influences [10]. In cooperation with JAXA, NTT is conducting research on phase sensitive amplifiers capable of lower noise amplification with a noise Fig. 3 dB less according to the theory compared with commonly used low-noise optical amplifiers and their application to optical communication in outer space [11].

（2） Optoelectronic integration technology

Power consumption will become an issue as complex computing processing across GEO satellites, LEO satellites, and HAPS will be realized, and the functions of on-board equipment will become more sophisticated in the future. Small satellites in particular have limited space for thermal discharge, requiring a reduction in the power consumed by the equipment, and NTT, while being engaged in the research and development of an all-photonics network in the framework of the IOWN concept, conducts research and development of optoelectronic integrated chips focusing on devices, such as optical modulators and optical transistors, and in the future, aims to reduce the weight and electric power consumption of onboard equipment by having it use such chips [12].

（3） Computing technology

The higher the resolution of the image data captured by the satellite, the larger is its volume and the longer the time required to transmit it to the ground. On the other hand, not all pieces of image data captured by the satellite are necessarily useful, so it is expected that the necessary pieces of data are selected on the satellite for transmission to the ground. NTT is conducting research and development on technologies that may help identify events as accurately as possible using limited computing resources available on the satellite [13].

4. Outer Space RAN

4.1 Concept

Today, as research and study toward the era of B5G/6G has started in different countries, and as study toward the realization of ultra-wide coverage by terrestrial mobile services is regarded as one of the pillars of that research, the utilization of satellite communication and HAPS is often discussed in this context [14]. The concept of ultra-wide coverage encompasses not only the coverage of rural areas on Earth, but also the expansion of non-terrestrial networks (NTNs) for the coverage of sky, sea, and outer space. NTNs are expected to make use of satellite communications for the delivery of mobile phone services for commonly used smartphones and for the delivery of automated/unmanned communication services for ships automobiles, and monitoring and control devices. Then, terrestrial networks and networks in the sky above will be combined in a hybrid configuration so that terrestrial networks may be used wherever they can be used, while satellites and HAPS may be used in places outside the coverage of terrestrial networks. In the past, satellite communication and mobile communication had their own communication protocols with different interface specifications; each of them formed a closed-ended network. To be able to support the realization of ultra-wide coverage in the era of B5G/6G, it is expected that seamless interconnection between satellite and terrestrial networks is enabled through the use of a general-purpose chip featuring a 5G communication interface with some of its specifications customized for compatibility with satellites by terminal devices and base stations. By realizing ultra-wide coverage services by means of an outer space RAN, integrating services for access to GEO satellites, LEO satellites, and HAPS, we will be able not only to improve our preparedness against disasters but also be able to improve the utility and deliver new added value by including remote islands/regions into service areas and by dramatically improving the communication environment for aircraft and ships.

By the way, as platforms for networks extended toward the sky above, GEO satellites, LEO satellites, and HAPS have their own advantages and disadvantages in terms of coverage, cost, latency, and technology maturity, so we do not have the idea of choosing any one of them for exclusive use. For example, coverage per single satellite is greatest with GEO satellites, but as a trade-off, they produce latency as large as 250 ms because they are used in satellite communications. On the other hand, latency in communication is as short as several milliseconds with LEO satellites, but as they move in the sky, many LEO satellites are needed to maintain the capability of real-time communication. The propagation distance is relatively short with HAPS, so they are likely to be able to allow direct access from smartphones and deliver broadband services in spot-like areas, but some time will be needed until the technologies for stable flight and communication while operating in the sky above Japan are established and low-priced communication devices become available for widespread use. Therefore, we anticipate the flexible connection of the ground with GEO satellites, LEO satellites, and HAPS looking for their best mix in consideration of country-specific regional characteristics and telecommunication environment.

4.2 Key Technologies

We conduct research and development on the following technologies toward the realization of NTNs that are capable of flexibly connecting the ground with GEO satellites, LEO satellites, and HAPS:

(1) NTN architecture

If traffic is to be accommodated by the combined use of GEO satellites, LEO satellites, HAPS, and terrestrial networks, network architecture design is of great importance. To establish technologies in this area, in the framework of the Project for Promoting R&D on Beyond 5G consigned to us from the National Institute of Information and Communications Technology (NICT), we are currently conducting the research and development of communication systems utilizing non-terrestrial networks for coverage extension (Fig. 4)[15]. The network architecture and traffic routing method differ depending on, for example, whether the GEO satellites, LEO satellites, and HAPS are equipped with gNB or not. It is important that we should establish a data transfer architecture that enables seamless end-to-end connections with multilayer networks. On the other hand, since the networks formed in the sky above with GEO satellites, LEO satellites, and HAPS are limited in transmission capacity compared with terrestrial 5G and optical fiber networks, operations must be performed in a manner that permits flexible responses to changes in the surrounding environment in the event of congestion, rainfall, or disasters. We are now developing an NTN simulator to establish the technology to accommodate traffic flexibly by taking account of the characteristics of the infrastructure of different kinds[16]. Moreover, since interference will occur if HAPS and terrestrial 5G use the same frequency, we are conducting research and development on techniques to evaluate interference using a simulator as well as techniques to avoid interference[17, 18].

(2) Technology for mounting equipment on HAPS

Currently, limitations about the maximum weight and power consumption of HAPS-mounted communication equipment makes it difficult to perform on a HAPS signal processing of a scale comparable to a terrestrial mobile

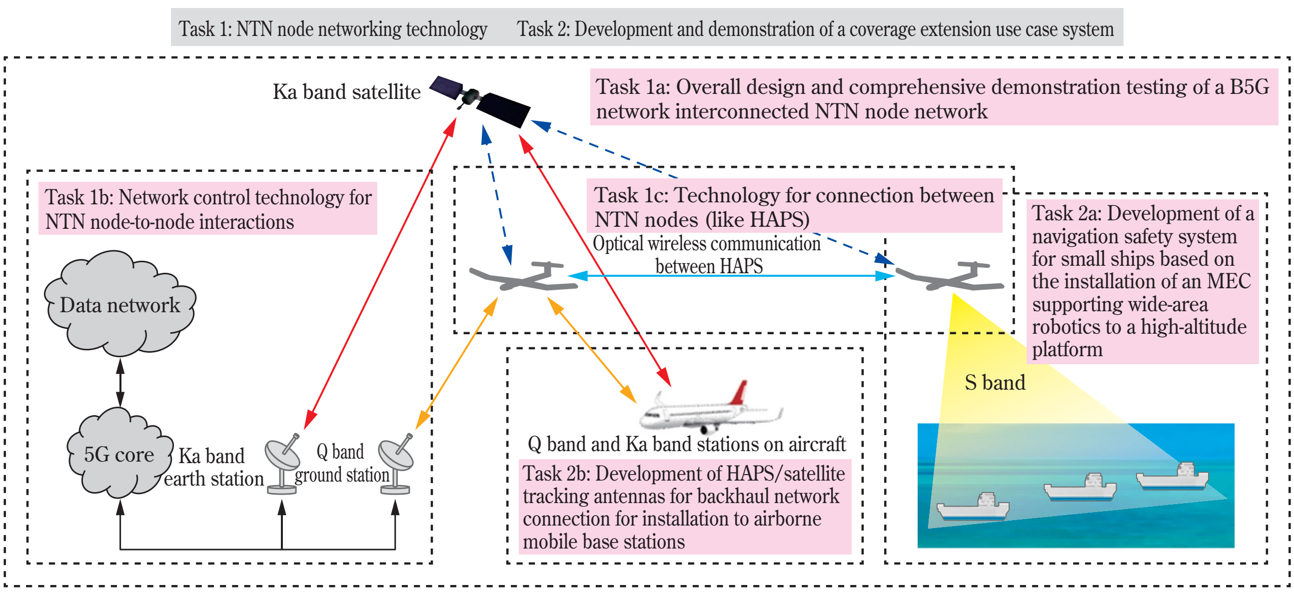

Fig. 4 Research and development of communication systems utilizing non-terrestrial networks for coverage extension Sky Perfect JSAT, NTT, NTT Docomo, and Panasonic are jointly involved in an NICT-consigned Beyond 5G R&D Promotion Project.

base station. Hopefully, the situation may improve with the further evolution of HAPS aircraft. As another issue, the delivery of services particularly on the sea requires the consideration of cases in which the distance between the HAPS and the ground station is so large that multi-hop connections, involving connections between neighboring HAPS or connection to a satellite, will be required. We are now conducting research and development toward the demonstration testing of HAPS-to-HAPS optical wireless connections, which are the key to the realization of multi-hop connections[19].

（3） Millimeter wave transmission technology

As the speed of service links for mobile users increases, NTN services require higher transmission capacity for service bundling feeder links between satellites/HAPS and base stations. Because of that, for feeder links, we consider the use of the Q band (30-40 GHz band) newly allocated by WRC-19. However, since rain attenuation is large in the Q band, its use in areas with heavy rainfall like Japan requires the introduction of rain attenuation compensation technologies. We are conducting research and development not only on the conventional diversity technology but also on the technology to proactively switch over base stations on the basis of rain forecasts and the technology for detour around rainfall using the above-mentioned optical wireless satellite/HAPS connections[20].

5. Conclusion

This paper presented outer space sensing, outer space datacenter, and outer space RAN as projects composing the space integrated computing network and discussed key technologies that support them. With each project, we are now conducting research and development toward the initiation of services. With attention to how we may exit from the development phase by the commencement of practical use and/or commercial service, we will continue to conduct research and development on core technologies in collaboration with related organizations.

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References

（1） IOWN 構想.
https://www.rd.ntt/iown/

（2） NTT/JAXA 報道発表，“NTT と JAXA 地上と宇宙をシームレスにつなぐ超高速大容量でセキュアな光・無線通信インフラの実現に向けた共同研究を開始，” Nov. 2019.
https://www.ntt.co.jp/news2019/1911/191105c.html

（3） NTT/スカパー JSAT 報道発表，“NTT とスカパー JSAT 持続可能な社会の実現に向けた新たな宇宙事業のための業務提携契約を締結，” May 2021.
https://group.ntt/jp/newsrelease/2021/05/20/210520a.html

（4） 糸川喜代彦，五藤大介，小島康義，坂元一光，藤野洋輔，山下史洋，加藤智隼，中台光洋，谷島正信，岩田隆敬，“低軌道衛星 MIMO 技術を活用した 920 MHz 帯衛星 IoT プラットフォームの軌道上実証と開発状況，” 第 65 回宇宙科学技術連合講演会，OS-16-5, 2021.

（5） N.T. Trung，田村亮介，西堀俊幸，堤　卓也，濱田裕史，徐　照男，I. Abdo，佐々木太郎，高橋宏行，中島史人，“300 GHz 帯直接検波型ラジオメータ研究開発とその宇宙実証ミッション検討状況について，” 第 66 回宇宙科学技術連合講演会，IAIZ, Nov. 2022.

（6） 坂元一光，景山知哉，吉澤健人，藤野洋輔，小島康義，糸川喜代彦，山下史洋，“920 MHz 帯衛星 IoT プラットフォームにおける各 LPWA 方式の端末収容台数評価，” 信学技報，SAT2020-35, pp. 35-40, Feb. 2021.

（7） D. Goto, K. Itokawa, F. Yamashita, C. Kato, and M. Nakadai, “Clock timing synchronization among distributed multiple antennas for LEO-MIMO communications system,” B1-4, ICETC 2020, Dec. 2020.

（8） 堤　卓也，濱田浩史，徐　照男，杉山弘樹，佐々木太郎，グェン タットトルン，西堀俊幸，高橋宏行，中島史人，“宇宙応用に向けたテラヘルツ帯 InP-HEMT-IC のデバイスプロセス技術，” 第 156 回結晶工学分科会研究会，April 2022.

（9） NTT/スカパー JSAT 報道発表，“NTT とスカパー JSAT，株式会社 Space Compass の設立で合意～持続可能な社会の実現に向けた新たな宇宙統合コンピューティング・ネットワーク事業をめざして～，” April 2022.
https://group.ntt/jp/newsrelease/2022/04/26/220426a.html

（10） 小竹秀明，阿部侑真，高橋靖宏，大倉拓也，布施哲治，佐藤洋平，板橋孝昌，山川史郎，辻　宏之，豊嶋守生，“光データ中継衛星搭載“LUCAS”を用いた地上─衛星間光通信の初期実験結果，” 信学技報，SAT2022-41, pp. 65-70, Aug. 2022.

（11） 橋本洋輔，風間拓志，荒木智宏，渡邉　啓，“位相感応増幅を用いた低雑音光増幅器とその宇宙光通信応用，” 2022 信学ソ大，no. BCS-1-7, Sept. 2022.

（12） 寒川哲臣，富澤将人，岡田　顕，後藤秀樹，“IOWN 構想特集─オールフォトニクス・ネットワーク実現に向けた光電融合技術─，” NTT 技術ジャーナル，vol. 32, no. 8, pp. 5-28, Aug. 2020.

（13） 江田毅晴，内藤一兵衛，山崎育生，田端啓一，史　旭，“宇宙コンピューティングに向けたイベント駆動型推論の検討，” NTT 技術ジャーナル，vol. 34, no. 10, pp. 14-16, Oct. 2022.

（14） NTT ドコモ，“6G White paper.”
https://www.nttdocomo.co.jp/corporate/technology/whitepaper_6g/

（15） 北之園　展，箕輪祐馬，鈴木　淳，山下史洋，浅井孝浩，外山隆行，“非地上系ネットワークによるカバレッジ拡張通信システムの開発─複数の NTN ノードの接続およびネットワーク制御技術とそのユースケース開発実証計画─，” 2022 信学総大，no. B-3-16, March 2022.

(16) 加納寿美，松井宗大，阿部順一，外園悠貴，小原日向，岸山祥久，山下史洋，“非地上系ネットワークによるカバレッジ拡張通信システムの開発～降雨時における UE の可用性評価～，”信学技報，SAT2022-37, pp. 48-53, Aug. 2022.
(17) 外園悠貴，小原日向，室城勇人，岸山祥久，浅井孝浩，加納寿美，松井宗大，阿部順一，“非地上系ネットワークによるカバレッジ拡張通信システムの開発―HAPS と地上ネットワークの周波数共用に向けた 3D セル制御技術による 2 GHz 帯の干渉回避評価―，”2022 信学ソ大，no. B-3-13, Sept. 2022.
(18) 外園悠貴，岸山祥久，浅井孝浩，“宇宙 RAN における HAPS 実用化に向けた取り組み，”NTT 技術ジャーナル，vol. 34, no. 10, pp. 17-22, Oct. 2022.
(19) 岸山祥久，浅井孝浩，阿部順一，山下史洋，箕輪祐馬，鈴木淳，北之園　展，大内幹博，外山隆行，“非地上系ネットワークによるカバレッジ拡張通信システムの開発―Beyond 5G に向けた NTN ノードのネットワーク化技術とカバレッジ拡張，”2022 信学総大，no. BI-3-7, March 2022.
(20) 北之園　展，鈴木　淳，外園悠貴，岸山祥久，浅井孝浩，“高高度プラットフォーム(HAPS)による 5G 網と連携した 38 GHz 帯の無線通信システム開発―フィーダリンクにおけるサイトダイバーシチの検討―，”2022 信学ソ大，no. B-3-15, Sept. 2022.

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