Extreme Coverage Extension in 6G: Cooperative Non-terrestrial Network Architecture Integrating Terrestrial Networks

Yuki Hokazono, Hinata Kohara, Yoshihisa Kishiyama, and Takahiro Asai
6G–IOWN Promotion Department, NTT DOCOMO, INC., 3–6, Hikari–no–oka, Yokosuka–shi, Kanagawa 239–8536 Japan
Email: yuki.hokazono.cx@nttdocomo.com

2022 IEEE Wireless Communications and Networking Conference (WCNC) | 978-1-6654-4266-4/22/$31.00 ©2022 IEEE | DOI: 10.1109/WCNC51071.2022.9771820

***Abstract*—Because communications in the future will be as commonplace as the air around us and as important a lifeline as power and water or even more so, the Fifth Generation (5G) Evolution and Sixth Generation (6G) mobile communications systems aim ultimately to expand coverage so that mobile services are available ubiquitously. Towards that goal, we present a new architecture for 5G Evolution and 6G that integrates non-terrestrial networks (NTNs) with terrestrial networks (TNs). The proposed cooperative NTN and TN architecture is promising as a means for expanding coverage in the future because it enables improved cost efficiency by sharing equipment and conservation of frequency resources through shared frequencies. In addition, by making full use of wireless technologies such as handover, carrier aggregation, and dual connectivity between NTNs and TNs, users can connect to 5G Evolution and 6G networks anywhere without being aware of the connection destination. In this paper, we propose a cooperative architecture that focuses on the link between NTNs and TNs, and a cooperative configuration with a particular focus on high-altitude platform stations (HAPSs). Furthermore, we present a HAPS performance evaluation using a 6G system-level simulator developed as a stepping stone for actualizing HAPS technology.**

***Index Terms*—Non-terrestrial network (NTN), high-altitude platform station (HAPS), 5G Evolution, 6G, extreme coverage extension**

I. Introduction

While the 5th generation (5G) mobile communications system is an important technology for regional development and solving regional issues, a key issue in the 5G Evolution and 6th generation (6G) eras is expected to be ubiquitously expanding the communications area where its benefits can be enjoyed [1]. As shown in Fig. 1, we are conducting research and development aimed at actualizing extreme coverage extension whereby mobile communications can be made available in all locations that are not adequately covered by conventional mobile communications networks including the air, sea, and space. Coverage extension is to be implemented through drones, flying cars, ships, and even space stations.

To achieve this extreme coverage extension, we propose a non-terrestrial network (NTN) architecture that cooperates with a terrestrial network (TN). NTN technologies that use geostationary (GEO) satellites, low Earth orbit (LEO) satellites, and a high-altitude platform station (HAPS) are promising tools for providing high-quality communications services to areas that cannot be covered by conventional

Fig. 1. Extreme coverage extension.

mobile communications networks. In addition, utilizing the characteristics of GEO, LEO, and HAPS, a multi-layer NTN cooperative system in which satellites and HAPS are connected to the TN can form a larger three-dimensional heterogeneous network than previously achieved. Since GEO, LEO, and HAPS differ in terms of performance and cost, it is desirable to find a proper mix that satisfies the requirements. The proposed architecture represents a promising approach that enables cooperation between the NTN and TN as a means for expanding coverage in the future because it can improve cost efficiency by sharing equipment and conserve frequency resources through the sharing of frequencies. By fully utilizing wireless technologies such as handover, carrier aggregation (CA), and dual connectivity (DC) between the NTN and TN, users can connect to the 5G Evolution and 6G networks anywhere without being aware of the connection destination.

To date, there have been some studies on a scenario in which NTN nodes are connected in multiple layers, but no consideration has been given to the examination of architectures linked to the TN. A previous study comparing the Shannon capacity of LEO-ground and LEO-HAPS-ground [2] did not consider redundant network configurations with relays among multiple NTN nodes. Another study presented multilayered hierarchical NTNs for 6G [3], but it did not consider a detailed cooperative architecture between the NTN and TN.

This article proposes a cooperative NTN architecture with TN, which is a key architecture for actualizing 5G Evolution

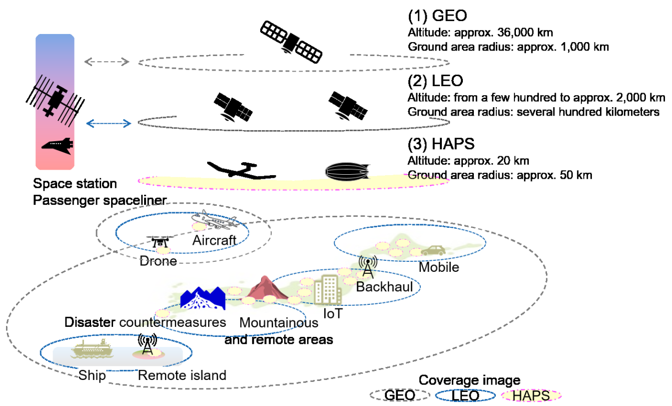


Fig. 2. How satellites and HAPS extend coverage to the sky, sea, and space.

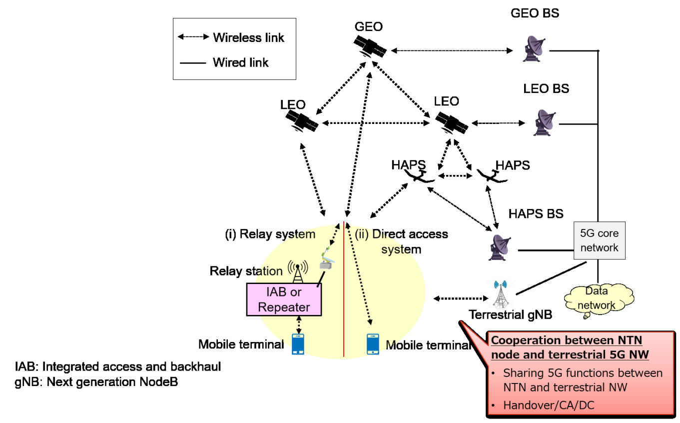


Fig. 3. Cooperation between multi-layered NTN system and terrestrial 5G network.

and 6G. Specifically, we describe the concept behind NTN technology, which has attracted attention as a promising approach, the use cases, and technical issues of wireless system technology using HAPS and TN. Furthermore, we present a HAPS performance evaluation using a 6G system-level simulator developed as a stepping stone for actualizing HAPS technology.

II. Extreme Coverage Extension and NTN Technology for 5G Evolution and 6G

Extreme coverage extension supports use cases in any location including air, sea, and space. It will extend coverage to users that cannot be covered by conventional mobile communications networks by using, for example, drones, flying cars, ships, and space stations. To achieve extreme coverage extension, it will be necessary to develop technologies that facilitate highly efficient long-range wireless transmission over at least several tens of kilometers.

As shown in Fig 2, by considering the use of (i) GEO satellites, (ii) LEO satellites, and (iii) HAPS, we will be able to provide communications services to mountainous and remote areas, the sea, sky, and even outer space [4].

A GEO satellite typically orbits the Earth at an altitude of approximately 36,000 km. Although the one-way radio wave propagation time between a GEO satellite and a ground station antenna is relatively long (approximately 120 ms), only three or four GEO satellites are needed to provide the entire planet with constant coverage. Even today, GEO satellites are used to complement TNs by providing a mobile backhaul. Since additional network capacity will be required in the 6G era, very high throughput satellites are being studied with the aim of increasing system capacity by optimizing the allocation of power and frequency across multiple beams [5].

An LEO satellite orbits the Earth at an altitude ranging from a few hundred kilometers to approximately 2,000 km. Unlike a GEO satellite, it has a much lower orbit and a much shorter propagation delay, *i.e.,* only a few milliseconds for a one-way trip. LEO satellites are currently used for satellite mobile phone systems and satellite sensing. They are expected to be used to expand the communications capacity through the reduction of satellite fabrication costs and the use of MIMO technology, and as high-capacity low-latency backhauls in satellite constellations that form networks through cooperation among multiple satellites [6].

HAPSs have recently attracted renewed attention due to their ability to park at an altitude of approximately 20 km in a fixed location. This allows them to provide services across terrestrial cells with a radius of approximately 50 km or more [7]. Since their altitude is lower than that of LEO satellites, it is possible to achieve a one-way radio wave propagation time of approximately 0.1 ms, depending on the cell radius. In addition, the 38.0-GHz to 39.5-GHz frequency band was specified for the HAPS system at the 2019 World Radiocommunication Conference (WRC-19) [8]. By using radio waves in the broadband millimeter-wave band, a high-speed high-capacity fixed communications system that supports backhaul links at base stations (BSs) on 5G networks can be achieved [9]. As a result, HAPSs are considered to be an effective way of deploying services in regions that have suffered natural disasters and in many industrial use cases envisioned for 5G Evolution and 6G.

The 3GPP has initiated research into how satellites and HAPSs can be used to extend New Radio to NTNs [10]. As shown in Fig 3, the multi-layered NTN system, in which satellites and HAPS are connected to the terrestrial 5G (or future 6G) core network, is a larger scale three-dimensional heterogeneity network than previously achieved. It is expected that TNs, satellites, and HAPS will cooperate and provide seamless communications according to the location (including air, sea, and space) to offer service and the required communications speed and latency.

Two systems are being considered for access to mobile terminals in NTNs: (i) a relay system that accesses the mobile terminal from a satellite and HAPS through the relay station, and (ii) a direct access system that directly accesses the mobile terminal from a satellite and HAPS. As a derivative of system (i), a cellular backhaul (CBH) system in which satellites and HAPS support a backhaul between the core network and the BS as an independent tunnel line is conceivable. In the 5G Evolution and 6G eras, mobile devices can be accessed everywhere in various ways depending on use cases and optimization of the entire network.

The following are problems facing NTNs: expansion of the radio interface that is suitable for long-distance communications, an efficient frequency effective utilization method for the ground network, and a network design to actualize high-efficiency cooperation with the ground network. In addition, further investigation into wireless technologies such as handover, CA, and DC between the NTNs and TNs would be beneficial. On the other hand, since each NTN platform has different features such as capacity and propagation delay, it is necessary to examine routing and network construction considering the features of each platform. NTNs are also promising as a means to advance cost effectively future expansion of 5G network coverage already introduced, and they yield the possibility to optimize network development from the beginning in the 6G era. Perhaps 6G will start from the sky.

III. HAPS Use Cases and Network Configuration/Control Techniques

We are conducting research and development on communications methods and network architectures that can flexibly link 5G networks and other TNs with stratospheric HAPS networks. In addition to providing flexible support for a wide range of future use cases as envisioned in 5G Evolution and 6G, this project is conducting studies aimed at the implementation of communications systems that use realistic HAPS in terms of development and operation costs.

A. HAPS Use Cases

As shown in Fig. 4, for the 5G Evolution and 6G eras, it is expected that various use cases will involve using HAPS to relay radio waves or emit radio waves as a BS. These use cases include fixed systems that provide services for backhaul applications, and mobile systems that provide services to terminals either directly or via repeaters and relays. In particular, the use of broadband millimeter wave radio signals is expected to enable the timely provisioning of high-speed high-capacity low-latency lines that are required for various applications including industry and public events, regardless of whether or not optical fibers or other wired networks are available ubiquitously.

The requirements of HAPS systems can vary widely from one use case to the next. As shown in Fig. 5, different use cases require different communications speeds and different bandwidths. There is a need for flexible communications methods and systems that can support all use cases of fixed and mobile systems.

For example, it is considered that the communications speed for backhaul applications to 5G BSs will have to be at least 1 Gbps per service link. Furthermore, to provide multiple simultaneous service links, the feeder link must be capable of even faster communications speeds (several gigabits per

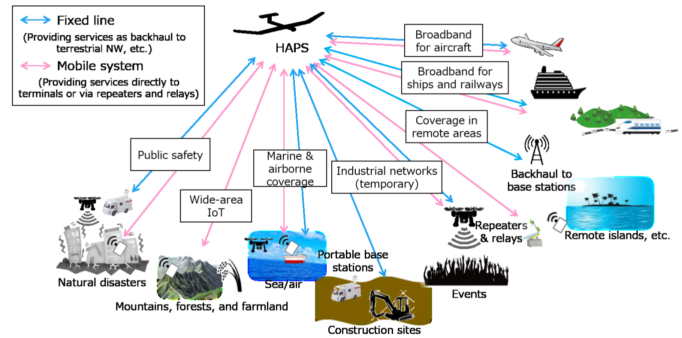


Fig. 4. Various expected use cases for HAPS.

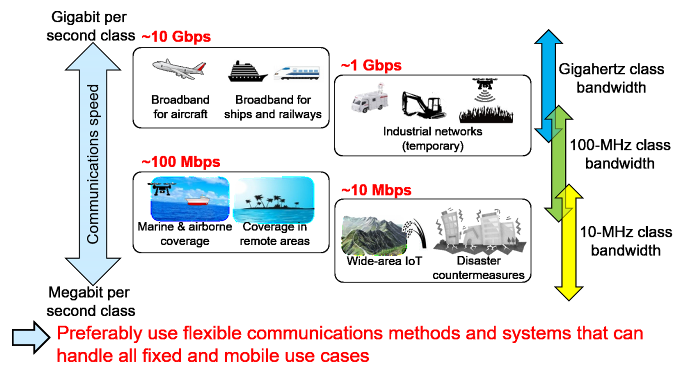


Fig. 5. Requirements for each HAPS use case.

second to several tens of gigabits per second) and must operate as stably as possible regardless of weather-related effects.

It is also necessary to control lines flexibly so that they can be adapted from normal business applications to public safety applications in the event of a disaster. Current disaster countermeasures are geared towards providing basic communications services such as voice calls and SMS. However, in the future, it may be necessary to consider use cases that require faster communications speeds such as remote control of equipment at disaster sites, video transmission, and communication via drones. For disaster countermeasures, it will also be necessary to study network configurations and control techniques that assume the ability of a system to operate even if some devices become unavailable.

B. Technology for Network Configuration and Control in Conjunction with 5G Networks

1) Classification of HAPS-Mounted Stations: In the network configuration and control technology used when implementing backhauls to 5G BSs via HAPS, we focus on the categorization of HAPS-mounted stations. They can be roughly divided into two types: (i) relay stations that receive signals from ground stations and relay them back to other ground stations after performing necessary processes such as frequency conversion, and (ii) BSs that are formed by installing 5G network BS equipment (or at least part of it) in a HAPS [11].

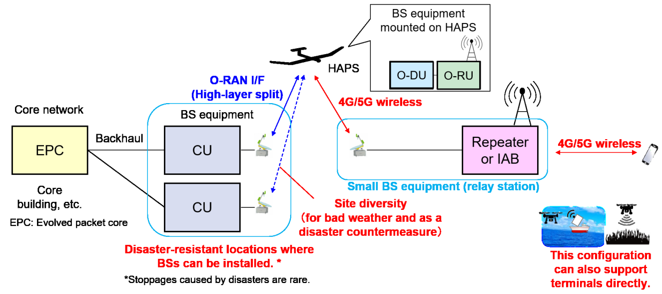


Fig. 6. Example of cooperative configuration when HAPS is used for backhaul.

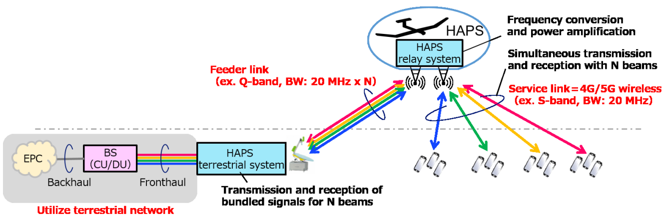


Fig. 7. Example of cooperative configuration when HAPS is used for direct access.

(i) The relay type is effective when the number of on-board devices is relatively small and the size, weight, and power consumption of the HAPS-mounted station are strictly limited.

(ii) The BS type is formed by equipping a HAPS with an antenna device together with many BS functions. The more of these functions it includes, the greater the degree of control enabled within the HAPS, making it possible to reduce the amount of feeder link information. On the other hand, installing more functions results in a station that is larger, heavier, and consumes more power.

In general, implementing more of the BS functions on the ground network side has the advantages of lower development costs and ease of operation, but implementing these functions on the HAPS results in greater resilience to natural disasters. In terms of performance, a HAPS-mounted station should at least implement some functions such as beam control when using millimeter waves. It is also necessary to study comprehensively a wide range of requirements to be considered when incorporating HAPS systems into a 5G network. These include the size, weight, and power consumption of HAPS-equipped stations; their development and operating costs; the ability of these HAPS platforms to be shared by fixed-line and mobile communications systems; and their ability to cooperate with GEO/LEO satellites.

2) Examples of Network Configuration in Conjunction with 5G Network: An example of a HAPS BS in a network configuration linked to the 5G network is shown in Fig. 6. Here, the distributed unit (DU) and radio unit (RU) of the 5G BS are mounted on the HAPS in accordance with Open RAN (O-RAN) Alliance specifications [12]. In this configuration, availability is ensured by installing a centralized unit (CU) at

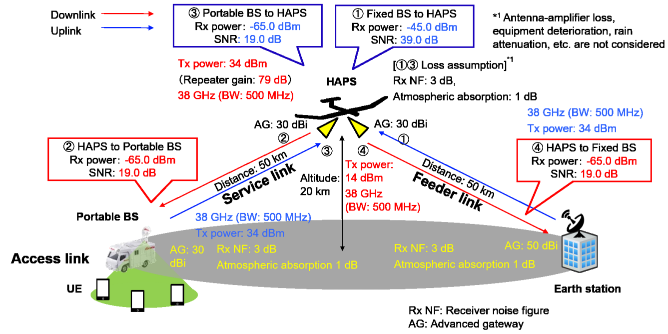


Fig. 8. Example of link budget between HAPS and radio station.

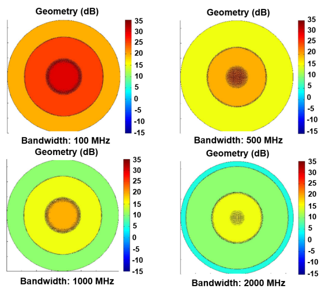
a disaster-resistant point on the ground. Information received by the HAPS from the CU in the feeder link is transmitted via 5G radio to a small terrestrial BS device (relay station) in the service link, thereby enabling the use of portable 5G BSs without having to use a wired backhaul. In this configuration, it is also possible to provide direct communications from the HAPS to 5G terminals without the need for intervening relay stations. As a further extension, site diversity can be implemented by using multiple CUs on the ground side to reduce the impact of bad weather and natural disasters. Mobility support can be implemented by switching the communications target to a different HAPS when the terminal moves from one communications area to another.

Another promising configuration employing a relay-type configuration where a 5G radio repeater is installed in a HAPS is shown in Fig. 7. In this configuration, the TN is utilized from the core network to the fronthaul, and the HAPS terrestrial system equipped with the RU function bundles and communicates signals for multiple beams. A broadband frequency such as the Q-band is used in the feeder link, and the HAPS relay system performs frequency conversion and power control. Then, HAPS can establish service link communications using multiple beams at the same time. As the service link, certain frequency bands below 2.7 GHz already identified for IMT should be used according to the specifications in WRC-19 [8] and the agenda in WRC-23 [13].

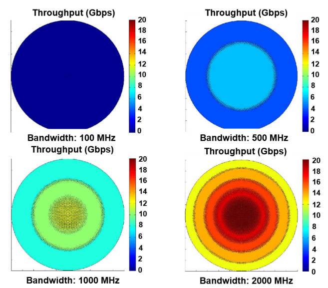
In addition to the configurations shown in Fig. 6 and Fig. 7, we consider other promising configurations in which a HAPS is used to carry a standalone 5G BS. For each configuration, it is necessary to conduct a comprehensive study that takes into account various attributes such as mobility support, site diversity technology, frequency sharing technology, and HAPS installation requirements such as links with GEO/LEO satellites, the equipment weight, and power consumption.

IV. Feasibility Evaluation of Ultra-coverage with HAPS Using 6G System-Level Simulator

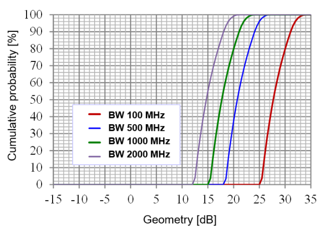
We developed a 6G system-level simulator to demonstrate the feasibility of ultra-coverage expansion with HAPS. In this simulator, the system capacity is calculated according to various communications environments on the ground by



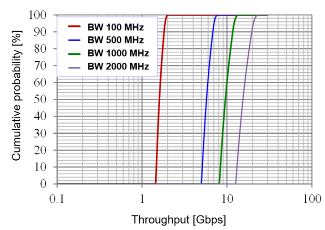
(a) Color map of geometry



(b) Color map of throughput

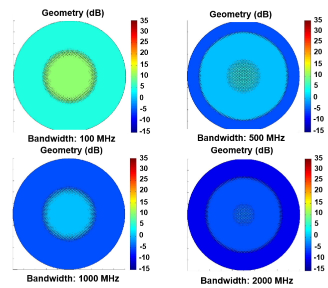


(c) Cumulative distribution of geometry

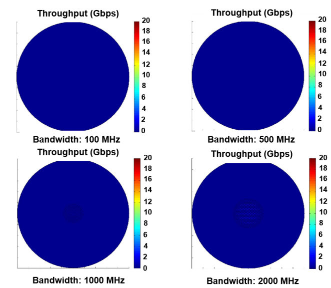


(d) Cumulative distribution of throughput

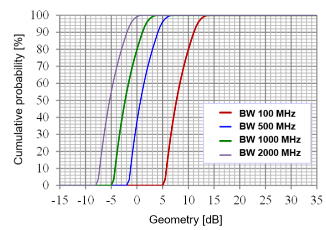
Fig. 9. Basic characteristic evaluation of service link for evaluation area radius of 50 km.



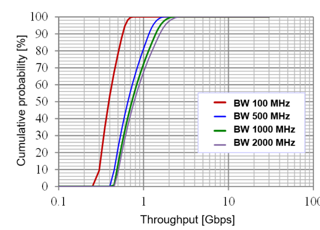
(a) Color map of geometry



(b) Color map of throughput



(c) Cumulative distribution of geometry



(d) Cumulative distribution of throughput

Fig. 10. Simple evaluation of rainfall attenuation effect on service link for evaluation area radius of 50 km.

setting the wireless communications parameters of the HAPS system.

To verify the practicality of HAPS as a CBH system, it is important to evaluate the line when high frequencies such as millimeter waves are used for the feeder link and service link. In this section, we show the initial evaluation using this simulator in which the HAPS communications characteristics, *e.g.*, geometry and throughput, are evaluated.

A. Simulation Evaluation Scenario

In this section, we evaluate the feasibility of communications between HAPS placed in the sky and a radio station, *e.g.*, a terrestrial station and a portable BS, existing on the ground as an environment assuming the 6G service era. To evaluate the feasibility of HAPS, it is necessary to evaluate the reception performance of the uplink feeder link, *i.e.*, from the terrestrial station to the HAPS, and that of the downlink service link, *i.e.*, from the HAPS to the portable BS, as shown in Fig. 8. For this scenario, we consider two types of evaluation: (i) basic characteristic evaluation when the transmission power is 34 dBm for both the terrestrial station and HAPS, and (ii) a simple evaluation of the rainfall attenuation effect by reducing the transmission power of HAPS by 20 dB.

In evaluation (i), the terrestrial station is located at either the center of the evaluation area or at the edge of the evaluation area. In addition, since the purpose of evaluation (ii) is to evaluate the tendency of the effect of rainfall attenuation, the evaluation is performed under ideal terrestrial station placement conditions, *i.e.*, placed at the center of the evaluation area.

As the CBH system target value for ensuring coverage in this evaluation, we set a throughput level of 1 Gbps or more at a cumulative distribution of 5 %, which is equivalent to the throughput of users at the edge of the coverage area.

B. Evaluation Conditions

Table I gives the simulation parameters. The bandwidth is the same for the feeder and service links, and the evaluation is performed under ideal conditions without considering the interference between the feeder and service links and the interference between the HAPS beams. Therefore, geometry represents the signal-to-noise ratio (SNR). The throughput is calculated without considering the bandwidth overhead required to reduce interference.

C. Evaluation Results

First, we describe the evaluation results of the feeder link. The geometry in the evaluation area with the radius of 50 km and bandwidth of 500 MHz is 48.07 dB when the terrestrial station is placed at the center of the area and 39.46 dB when the terrestrial station is placed at the edge. The throughput under the same conditions is 14.55 Gbps when the terrestrial station is placed at the center of the area and 11.77 Gbps when the terrestrial station is placed at the edge.

Next, we describe the evaluation results of the service link. In the service link evaluation, there is no difference in the communications characteristics of the service link at any of the terrestrial station locations, so the examination is conducted only when the terrestrial station is located at the center of the evaluation area. The basic characteristic evaluation of geometry and throughput in the evaluation area with the radius of 50 km is shown in Fig. 9. A simple evaluation of the rainfall attenuation effect of geometry and throughput in the evaluation area with the radius of 50 km is shown in Fig. 10. In the basic characteristic evaluation, the throughput at the cumulative distribution of 5 % is 1 Gbps or more, which is the target value for ensuring coverage; however, it is only 0.43 Gbps in the simple evaluation of the rainfall attenuation effect. Compared to evaluations with different area radii values, the results show that it is necessary to set the area radius to as narrow as approximately 25 km and widen the bandwidth to 1000 MHz or more to obtain the target value of 1 Gbps during periods of rainfall.

Since the influence of rainfall attenuation on service links using millimeter waves such as 38 GHz is large as in these evaluations, it is necessary to study countermeasures for rainfall attenuation such as adaptive modulation, power control, and site diversity. In addition, to evaluate the performance in a more realistic environment, we plan to perform an evaluation considering the interference between beams and the position of clouds.

Currently, we are planning to expand this simulator so that we can evaluate frequency sharing technology and handover between HAPS networks and TNs.

V. Conclusion

In this paper, as part of our efforts towards implementing extreme coverage extension, which is an important issue facing 5G Evolution and 6G, we presented a new architecture that integrates NTNs with TNs. Specifically, we proposed a cooperative architecture that focuses on the link between NTNs and TNs, and a cooperative configuration with a particular focus on HAPSs. It is expected that the TN, satellite, and HAPS will cooperate and provide seamless communications according to the location that the service is provided and the required communications speed and latency. We also presented a HAPS performance evaluation using a 6G system-level simulator developed as a stepping stone for actualizing HAPS technology. Based on the evaluation results of the simulator, we confirmed the validity of the HAPS link budget. We will continue developing NTN technology aimed at achieving extreme coverage extension and technology for actualizing HAPS networks.

TABLE I
Parameters

Center frequency	38 GHz
Bandwidth	100, 500, 1000, 2000 MHz
Evaluation area radius	25, 50, 75, 100 km
Path loss model	$FSPL(d, f_c) = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d)$ (TR38.811 6.6.2) (Does not consider curvature of the Earth)
Maximum rank	2 (for both feeder link and service link)
Tx power	34 dBm (for all earth stations, HAPS stations, and remote base stations) (Replace only HAPS station with 14 dBm when it rains)
Tx antenna gain of earth station	50 dBi (peak value)
Tx antenna gain pattern of earth station	$4\left\lvert\frac{J_1(ka\sin\theta)}{ka\sin\theta}\right\rvert^2$ J_1: Bessel function of the first kind k: $2\pi f/c$ (f: carrier frequency [Hz], c: light speed [m/sec]) a: Radius of the parabolic dish [m] $= 0.6$ [m] θ: Angle off boresight [rad]
Tx antenna gain of HAPS station	30 dBi (peak value)
Tx antenna gain pattern of HAPS station	$4\left\lvert\frac{J_1(ka\sin\theta)}{ka\sin\theta}\right\rvert^2$ $a = 0.06$ [m]
Rx antenna gain of HAPS station and remote base station	30 dBi (peak value)
Rx antenna gain pattern of HAPS station and remote base station	Ideal (always set the peak value of the Rx antenna gain)

Acknowledgement

This work was supported by funding from the Ministry of Internal Affairs and Communications (Research and Development for Expansion of Radio Resources; JPJ000254).

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