Technology Reports (Special Articles) NTN HAPS Extreme Coverage Extension

Special Articles on 5G evolution & 6G (1)

Research on NTN Technology for 5G evolution & 6G

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In 5G evolution & 6G, extreme coverage extension is being studied for use cases in all places including air, sea, and space. NTNs using GEO satellites, LEO satellites, and HAPS are promising tools for providing high quality communication services in areas that cannot be covered by the conventional mobile communication network. In this article, we describe these technologies and the details of a 39 GHz band airborne propagation measurement experiment performed using a small airplane at an altitude of about 3 km.

1. Introduction

While the 5th Generation mobile communication system (5G) is expected to be an important technology for regional development and solving regional issues, a key issue for the 5G evolution and 6G era is expected to be expanding the communication area to any place where its benefits can be enjoyed [1]. As shown in **Figure 1**, NTT DOCOMO is conducting research and development aimed at realizing extreme coverage extension[*1] whereby mobile communication can be made available in all locations, including the air, sea and space, that are not adequately covered by conventional mobile communications networks, thereby extending coverage to drones, flying cars, ships, and even space stations.

To achieve this extreme coverage extension, we are focusing on Non-Terrestrial Network (NTN)[*2] technology using satellites and High-Altitude Platform Stations (HAPS)[*3]. This technology is able to provide communication coverage in mountainous and remote areas, at sea, and even in outer space by employing satellites and HAPS systems that are

Figure 1 Extreme coverage extension

free of geographical restrictions.

This article describes extreme coverage extension, which is one of the key issues for the realization of 5G evolution & 6G. Specifically, we describe the concept of NTN technology, which has been attracting attention as a promising approach, the use cases and technical issues of wireless system technology using HAPS, and our work on measuring the propagation of radio waves using a small aircraft.

2. Extreme Coverage Extension and NTN Technology for 5G evolution & 6G

Extreme coverage extension supports use cases in any location, including air, sea and space. This will extend coverage to users that cannot be covered by conventional mobile communication networks, including 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 **Figure 2**, by considering the use of (1) GEOstationary (GEO) satellites, (2) Low Earth Orbit (LEO) satellites, and (3) HAPS, we will be able to cover mountainous and remote areas, the sea, the sky, and even outer space, and to provide communication services to these areas [2].

(1) A GEO satellite that orbits the Earth at an altitude of about 36,000 km. Although the one-way radio wave propagation time between a GEO satellite and a ground station antenna is relatively long (about 120 ms), just three or four GEO satellites can provide the entire planet with constant coverage. Even today, GEO satellites are used to complement terrestrial networks by providing a mobile backhaul[*4]. Since additional network capacity will be required in the 6G era, Very High Throughput Satellites (VHTS) are being

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*1 Extreme coverage extension: Extending the area in which base stations can communicate with mobile terminals to any location, including the air, sea and space, that is not covered by the current mobile communication system.

*2 NTN: Any network in which the communication area is not limited to the ground but extended to other places such as the air, sea and space through the use of non-terrestrial equipment such as satellites and HAPS.

*3 HAPS: An airborne platform that is designed to operate in the stratosphere on board a vehicle such as a solar-powered aircraft or airship.

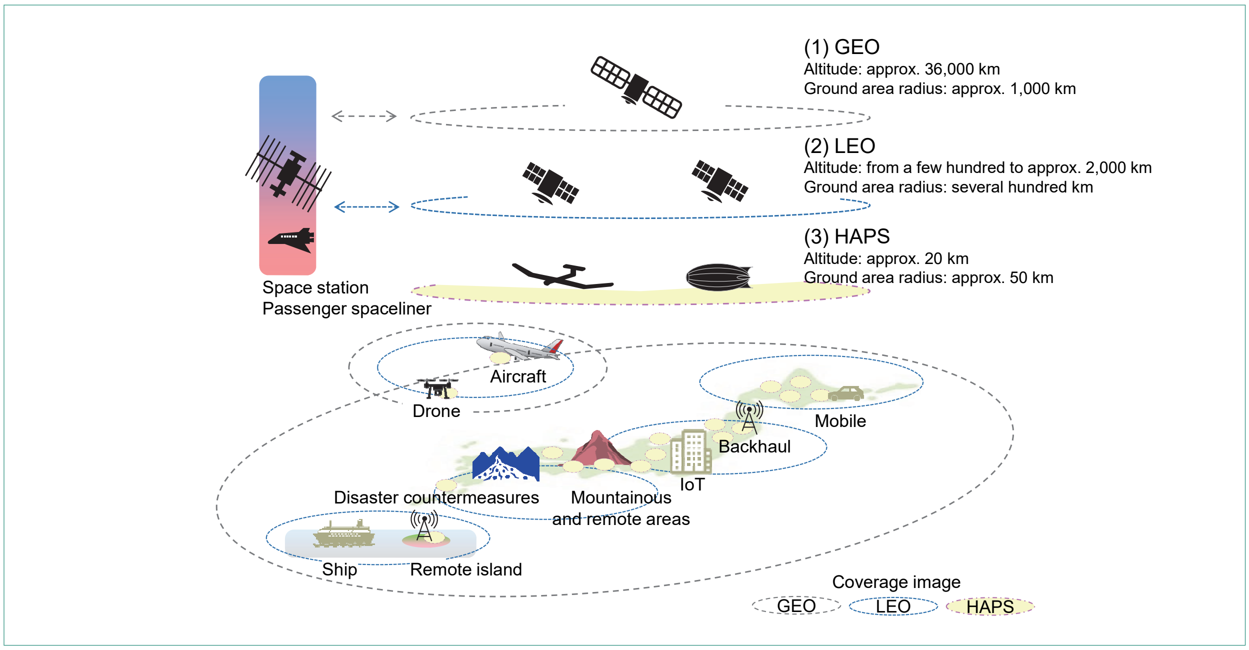

Figure 2 Illustration of how satellites and HAPS can be used to extend coverage to the sky, sea, and space

studied with the aim of improving system capacity by optimizing the allocation of power and frequency across multiple beams [3].

(2) An LEO satellite orbits the Earth at an altitude ranging from a few hundred km to about 2,000 km. Unlike a GEO satellite, it has a much lower orbit and a much smaller propagation delay (just a few ms for a one-way trip). LEO satellites are currently used for satellite mobile phone systems and satellite sensing*5. They are also expected to be used for the expansion of communication capacity through the reduction of satellite fabrication costs and the use of Multiple Input, Multiple Output (MIMO)*6 technology, and for high-capacity, low-latency backhauls in satellite constellations that form networks through cooperation between multiple satellites [4].

(3) HAPS have recently attracted renewed attention due to their ability to parked at an altitude of about 20 km in fixed locations, allowing them to provide services across terrestrial cells*7 with a radius of approximately 50 km or more [5]. Since their altitude is lower than that of LEO satellites, it is possible to achieve a one-way radio wave propagation time of about 0.1 ms, depending on the cell radius. As a result, they are considered to be an effective way of deploying services not only in regions that have been hit by natural disasters but also in many of the industrial use cases envisioned for 5G evolution & 6G.

The 3rd Generation Partnership Project (3GPP) has begun studying how satellites and HAPS can be used to extend New Radio (NR)*8 to NTNs [6].

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*4 Backhaul: In a mobile communication network, a backhaul is a fixed line that supports high-speed, high-capacity transmission of information between a large number of wireless base stations and the core network.

*5 Satellite sensing: Observing the state of the atmosphere and earth's surface from space by means of instruments carried on board satellites.

*6 MIMO: A signaling technique whereby multiple transmit and receive antennas are used to transmit signals simultaneously and at the same frequency to improve communication quality and the efficiency of frequency utilization.

3. HAPS Use Cases and Network Configuration/control Techniques

NTT DOCOMO is working on the research and development of communication methods and network architectures that can flexibly link 5G networks and other terrestrial networks with stratospheric HAPS networks [7] [8]. In addition to providing flexible support for a wide range of future use cases as envisioned in 5G evolution & 6G, this project is conducting studies aimed at the implementation of communication systems that use realistic HAPS in terms of development and operation costs.

3.1 HAPS Use Cases

As shown in **Figure 3**, for the 5G evolution & 6G era, it is expected that various use cases will involve using HAPS to relay radio waves or emit radio waves as a base station. These use cases include fixed systems that provide services for backhaul applications, and mobile systems that provide services to terminals either directly or by via repeaters and relays. In particular, the use of broadband millimeter wave*9 radio signals is expected to enable the timely provision of high-speed, large-capacity, low-latency lines required for various applications including industry and public events, regardless of whether or not optical fibers or other wired networks are available, and in any location, including at sea, in the air, or in remote areas.

The requirements of HAPS systems can vary widely from one use case to the next. As shown in **Figure 4**, different use cases require different communication speeds and different bandwidths. There is a need for flexible communication methods and systems that can support all use cases of fixed and

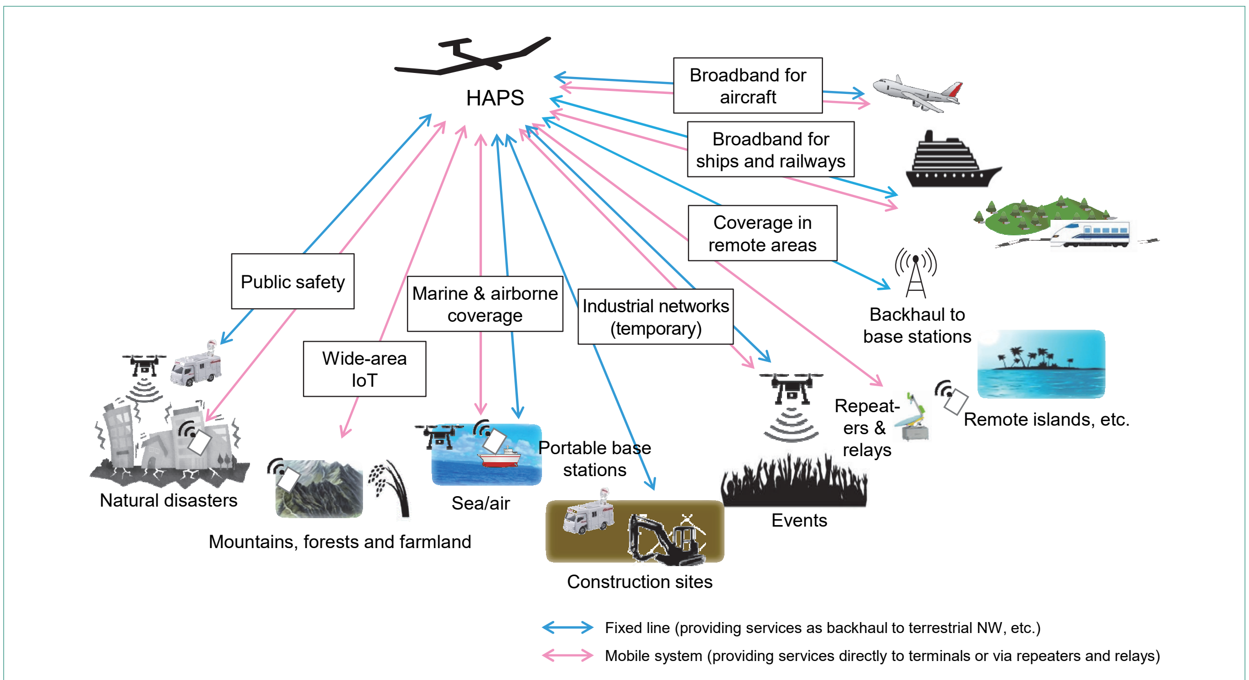


Figure 3 Various use cases expected for HAPS

*7 Cell: The unit of area division that makes up the service area of a mobile communications network.

*8 NR: A radio system standard formulated for 5G. Compared with 4G, it enables faster communication by utilizing high frequency bands (e.g., 3.7 GHz and 28 GHz bands), and low latency and highly reliable communication for achieving advanced IoT.

*9 Millimeter waves: Radio signals in the frequency band from 30 GHz to 300 GHz as well as the 28 GHz band targeted by 5G all of which are customarily called "millimeter waves."

mobile systems.

For example, it is considered that the communication speed for backhaul applications to 5G base stations will have to be at least 1 Gbps per service link[*10]. Furthermore, to provide multiple simultaneous service links, the feeder link[*11] will have to be capable of even faster communications speeds (several Gbps to several tens of Gbps) and must operate as stably as possible regardless of weather-related effects.

It is also necessary to flexibly control lines so that they can be adapted from normal business applications to public safety[*12] applications in the event of a disaster. Current disaster countermeasures are geared towards providing basic communication services such as voice calls and SMS, but in the future, it may also be necessary to consider use cases that require faster communication 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.

3.2 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 base stations via HAPS, we are focusing on the categorization of HAPS-mounted stations. They can be roughly divided into two types: (1) relay stations, which receive signals from ground stations and relay them back to other ground stations after performing necessary processes such as frequency conversion, and (2) base stations, which are made by installing 5G network base station equipment

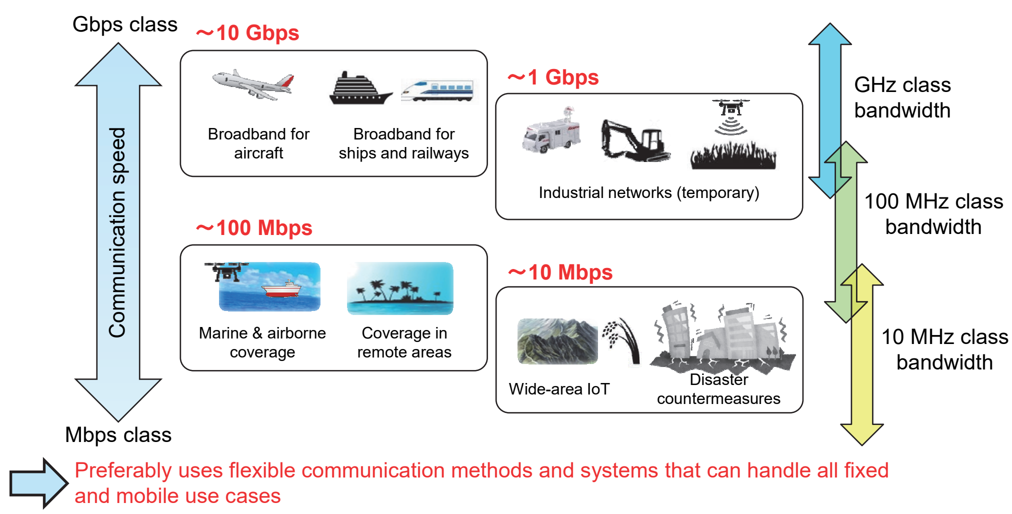


Figure 4 Requirements for each HAPS use case

*10 Service link: A communication path between a satellite or HAPS and a terminal in an NTN communication system.

*11 Feeder Link: A communication path between a satellite or HAPS and a terrestrial base station (gateway) in an NTN communication system.

*12 Public safety: A generic term for services that ensure the safety of the public, including disaster prevention, police, fire, and first-aid services.

(or at least part of it) in a HAPS.

(1) 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.

(2) The base station type is formed by equipping a HAPS with an antenna device, together with many base station functions. The more of these functions it includes, the greater the amount of control that can be performed 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.

Table 1 shows a comparison of possible HAPS-

Table 1 Comparison of HAPS-mounted stations

	On-board station type	Wireless standard (FL/SL)	Applications of HAPS communication	Features (advantages)	Issues
#1	Repeater	Fixed/ fixed*1	Fixed	Reduced weight and energy requirements of on-board stations*2	Support for simultaneous connections with multiple beams
#2	Repeater	Mobile/ mobile*1	Fixed & mobile	Reduced weight and energy requirements of on-board stations*2	Support for simultaneous connections with multiple beams Increased PAPR due to use of OFDM signals*3
#3	Base station type (Full BBU)	Fixed/ fixed	Fixed	Flexible support for both FL and SL standards with a single communication system	Increased power consumption and weight of on-board stations due to higher performance (increased communication speed and number of simultaneous connections)
#4	Base station type (Full BBU)	Mobile/ mobile	Fixed & mobile	Flexible support for both FL and SL standards with a single communication system	Increased power consumption and weight of on-board stations due to higher performance (increased communication speed and number of simultaneous connections) Increased PAPR due to use of OFDM signals*3
#5	Base station type (DU/RU only)	Fixed/ mobile	Fixed & mobile	May be possible to reduce power consumption and weight of on-board stations while providing the same performance as #6	Two communication systems need to be installed, resulting in increased station power consumption and weight Increased PAPR due to use of OFDM signals (SL only)*3
#6	Base station type (Full BBU)	Fixed/ mobile	Fixed & mobile	Achieving ultra-high capacity services by independently optimizing for FL/SL frequencies and radio standards	Two communication systems need to be installed, resulting in increased station power consumption and weight Increased PAPR due to use of OFDM signals (SL only)*3

BBU: Base Band Unit PAPR: Peak to Average Power Ratio
FL: Feeder Link SL: Service Link

*1 Repeater types (#1, #2) may be able to operate regardless of the wireless standard (with multiple wireless standards).
*2 It is expected that the higher the required communication speed, the greater the relative merits of the relay type compared with the base station type.
*3 Single-carrier waveforms may be adopted by NTNs in the future, such as for 6G.

mounted station configurations. In general, implementing more of the base station 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 comprehensively study 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 operation costs, the ability of these HAPS platforms can 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 the 5G Network

An example of a HAPS base station in a network configuration linked to the 5G network is shown in **Figure 5**. Here, the Distributed Unit (DU)*13 and Radio Unit (RU)*14 of the 5G base station are mounted on the HAPS in accordance with Open RAN (O-RAN)*15 Alliance specifications [9]. In this configuration, availability is ensured by installing a Centralized Unit (CU)*16 at 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 base station device (relay station) in the service link, thereby enabling the use of portable 5G base stations without having to use a wired backhaul. In this configuration, it is also possible to provide direct communication from the HAPS to 5G terminals

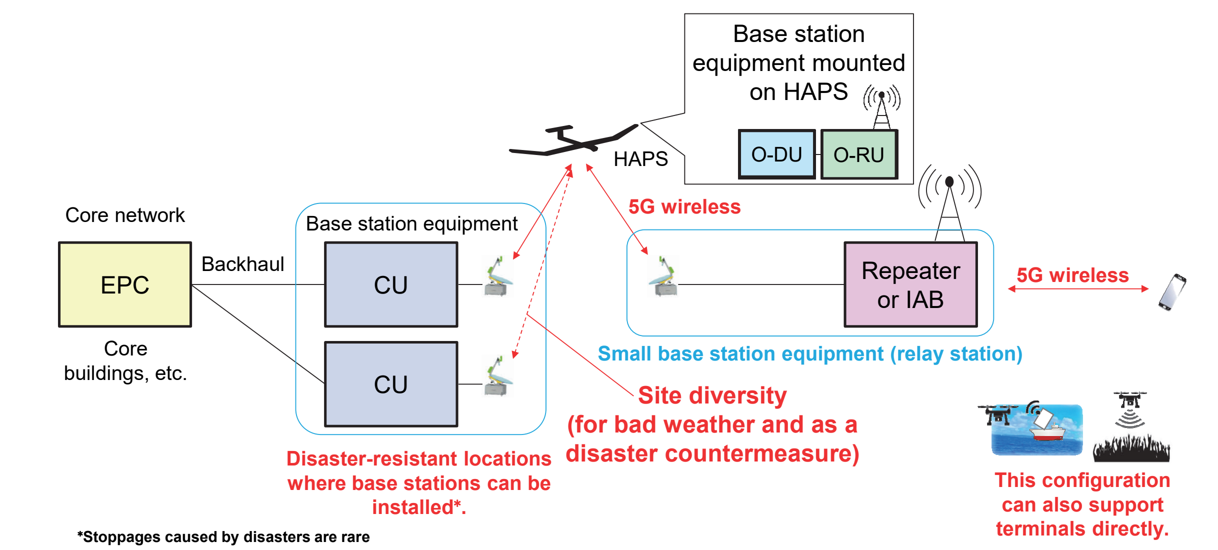


Figure 5 Example of cooperative configuration when HAPS is used for backhaul

*13 DU: A functional unit of a wireless base station that performs real-time data link layer control and other functions.

*14 RU: The radio unit of a wireless base station.

*15 O-RAN: An open, intelligent radio access network aimed at efficiently providing a variety of services in the 5G era.

*16 CU: An aggregating node that implements functions such as non-real-time L2 (Layer 2) functions and RRC (radio resource control) functions in a radio base station.

without the need for intervening relay stations. As a further extension, site diversity*17 can be implemented by using multiple CUs on the ground side to reduce the impact of bad weather and natural disasters, and mobility support*18 can be implemented by switching the communication target to a different HAPS when the terminal moves from one communication area to another.

In addition to the configuration shown in Fig. 5, we are also considering other promising configurations: one in which a HAPS is used to carry a standalone*19 5G base station, and another with a relay-type configuration where a 5G radio repeater is installed in a HAPS. For each configuration, it is necessary to conduct a comprehensive study that takes account of various attributes such as mobility support, site diversity technology and frequency sharing technology*20, as well as HAPS installation requirements such as links with GEO/LEO satellites, the equipment weight and power consumption.

4. Experimental 39 GHz Band Propagation Measurements Using a Small Aircraft

To implement a communication area from an airborne station in 5G evolution & 6G, we conducted an experimental demonstration of radio wave propagation measurements in an urban area (Odawara City, Kanagawa Prefecture), a mountain forest (Tanzawa), and a remote island (Izu Oshima) using a small aircraft (February 15–26, 2021) [10]. Before using the actual HAPS system, we performed an initial experiment to compare the propagation of millimeter wave (39 GHz band) radio signals, which are suitable for 5G high-speed communication, and signals at a lower frequency (2 GHz band), which propagate more easily than millimeter wave signals. These signals were sent from the ground to a receiver mounted on a small aircraft about 3 km above ground level. In the urban environment, we measured the effects of obstacles such as buildings and reflected waves. In the forest, we measured the effects of terrain and trees. And in the remote island, we measured the effects of clouds and low elevation angles above the sea. Our results show that radio wave propagation in the 39 GHz and 2 GHz bands depends on various environmental factors, and changes when the airplane turns.

4.1 Measurement Environment and Measured Items

Figure 6 shows an illustration of the airborne propagation measurement test. The radio wave transmission points were located in an urban area (Odawara City in Kanagawa Prefecture), a forest (Tanzawa), and a remote island (Izu Oshima), and the reception point was a small aircraft circling with a radius of 1 to 2 km. The elevation angle of the small aircraft (receiving point) from the transmitting point was determined to be equivalent to the use case of a HAPS circling at an altitude of 20 km. Specifically, we assumed a coverage radius of 50 km for an altitude of 20 km in the urban and forest use cases (elevation angle: 21.8°), and a coverage radius of 200 km for an altitude of 20 km in the remote island use case (elevation angle: 5.7–11.5°). In addition to the line-of-sight environment, we also measured the received power with intervening obstacles such as buildings and trees in each use case, as shown in **Figure 7**.

*17 Site diversity: A technique for improving communication quality by switching between multiple ground stations when radio waves are highly attenuated due to rain or obstacles.

*18 Mobility support: Technology that allows communication to continue when a terminal moves across a communication area by switching it to a different base station before communication is interrupted.

*19 Standalone: A deployment scenario using only NR, in contrast with non-standalone operation which uses LTE-NR DC to coordinate existing LTE/LTE-Advanced and NR.

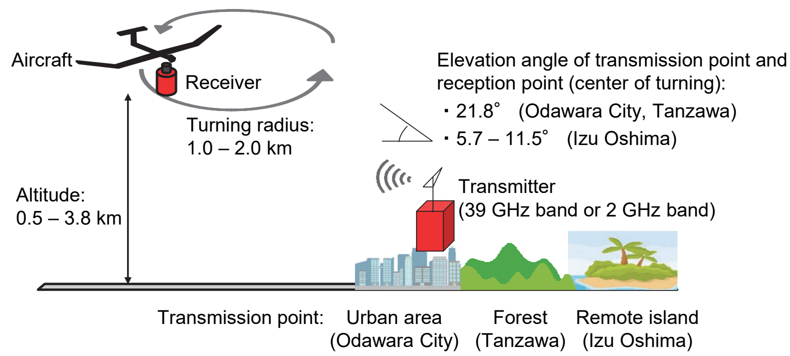
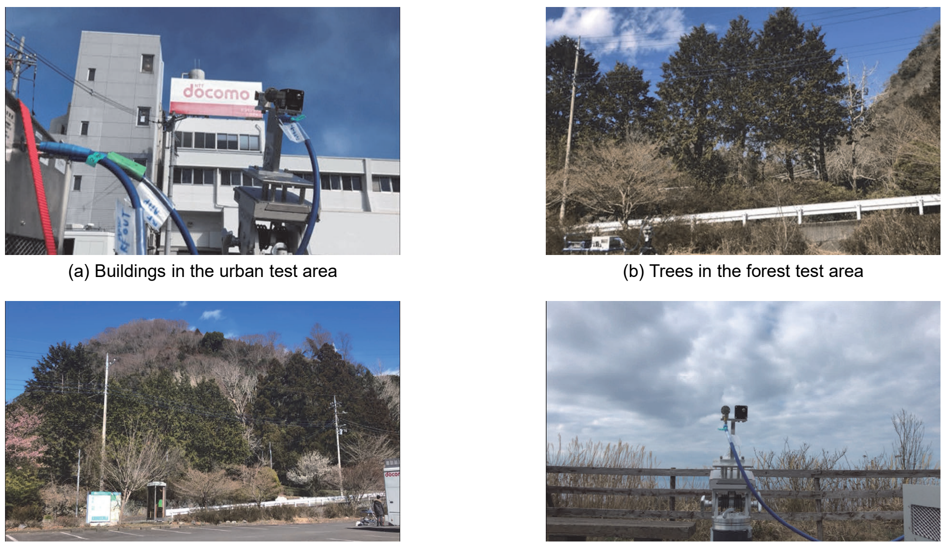


Figure 6 Illustration of the airborne propagation measurement test



(a) Buildings in the urban test area

(b) Trees in the forest test area

(c) Mountains in the forest test area

(d) Clouds in the remote island test area

Figure 7 Test environments with various obstacles

Table 2 lists the main specifications of the experimental equipment. For the transmitting antenna, we selected a product that was able to cover the turning range of the aircraft within the beam width*21, and we fixed the direction of this antenna toward the aircraft's turning center. The receiving antenna was housed in a mounting frame, and a 3-mm-thick polycarbonate radome*22 designed to cause almost no propagation loss*23 was secured to its base. We also performed an initial experiment in which neither of the transmitting or receiving antennas were provided with tracking functions, and the receiving antenna was fixed directly to the underside of the aircraft.

4.2 Evaluation

1) Overview

Table 3 shows the results of measuring the

*20 Frequency sharing technology: Technology that makes it possible to share frequencies by suppressing the interference effects that occur when two systems use the same frequency at the same location. In this article, we are mostly concerned with frequency sharing between HAPS systems and terrestrial mobile communication systems.

*21 Beam width: The antenna radiation angle at which the beam is radiated with gain of -3dB or less from the maximum antenna gain.

*22 Radome: An enclosure to protect an antenna. These are made of materials that are transparent to radio waves.

Table 2　Main specifications of the airborne propagation test apparatus

	Frequency band	Main specifications of the test apparatus and equipment
Transmitter	39.75 GHz band	· Maximum transmitter output: 37 dBm · Transmitted wave type: unmodulated · Antenna type: horn · Maximum transmitting antenna gain: 14.6 dBi · Radio wave emission direction: towards the aircraft's turning center · Polarization: vertical
	2.2001 GHz band	· Maximum transmitter output: 42 dBm · Transmitted wave type: unmodulated · Antenna type: sleeve · Maximum transmitting antenna gain: 2.2 dBi · Radio wave emission direction: horizontal · Polarization: vertical
Receiver	39.75 GHz band	· Antenna type: omni · Maximum receiving antenna gain: 3.0 dBi
	2.2001 GHz band	· Antenna type: omni · Maximum receiving antenna gain: 0.0 dBi

Table 3　Summary of the airborne radio wave propagation measurement results

39 GHz band measurement environment	39 GHz band measurement results
Everywhere	· The maximum line-of-sight reception sensitivity roughly matches the results of desktop calculations in all environments (within 5 dB of error). · The predicted average/median was about 14–24 dB less than the maximum. ➢Fluctuations in the directivity pattern of the transmitting and receiving antennas due to turning, polarization losses, and occlusion by the aircraft itself have a large effect. ➢For the practical application of HAPS, it will be important to develop control technology that can suppress this sort of turning-related effect and maintain a constant received power. · The difference between the mean and median was within 2.5 dB except for Tanzawa (mountain), where there was a lot of data buried in the noise floor, and the difference was about 3.8 dB. · In the 2 GHz band, which was tested by way of comparison, the signals also tended to be attenuated due to obstacles and the effects of turning.
Odawara (buildings)	· Compared with the forecast, the average value was approximately 17 dB lower, and the median value was approximately 19 dB lower.
Tanzawa (trees)	· Compared with the forecast, the average value was approximately 18 dB lower, and the median value was approximately 19 dB lower.
Tanzawa (mountains)	· Compared with the forecast, the average value was approximately 30 dB lower, and the median value was approximately 36 dB lower.
Izu Oshima (white clouds)	· Compared with the forecast, the average value was approximately 2 dB higher, and the median value was approximately 4 dB higher. ➢Hardly any cloud attenuation was observed, and it is inferred that flight trajectory errors have a dominant effect.

airborne propagation of radio waves. From this experiment, we found that the maximum reception sensitivity in the unobstructed line-of-sight environments was almost identical to the value obtained by desktop calculations, while the loss of received power in the 39 GHz band was relatively

*23　Propagation loss: The amount of attenuation in the power of a signal emitted from a transmitting station until it arrives at a reception point.

large when there were intervening buildings and trees. To reduce the influence of obstacles of this sort, it will be necessary to consider adopting measures such as site diversity. We also confirmed that the influence of clouds was relatively small in the absence of rainfall.

Furthermore, since signals were transmitted and received in this experiment by means of antennas with the same directivity pattern regardless of the aircraft's position and flight attitude, it also became clear that the received power varies greatly with changes in the angle of the antenna caused by turning of the aircraft. For the practical use of HAPS in the future, these results confirm the importance of using control technology to suppress the effects of turning the aircraft and maintain a constant received power.

2) Experimental Results in Odawara

As a concrete example of the measurement results, this section describes an experiment that models an urban use case. For the line-of-sight environment in Odawara City, Kanagawa Prefecture with the aircraft circling with a turning diameter of 2 km, **Figure 8** shows the time series data of losses in the 39 GHz band, and the cumulative distribution*24 of propagation losses in the 39 GHz and 2 GHz bands are shown in **Figure 9** (a) and (b), respectively. When the maximum receiver sensitivity in the 39 GHz band is calculated from the free space loss shown in Fig. 8, the results generally match the figures obtained in desktop calculations with an error of only about 1.2 dB. On the other hand, the time-series data fluctuated greatly when the aircraft turned, with the average received power decreasing by about 17 dB from the maximum value and the median*25 decreasing by about 14 dB. It is thought that these reductions were mainly caused by fluctuations in the directive gain of the transmitting and receiving antennas, polarization losses*26, and the obstruction of radio waves by the aircraft itself when the underside of the aircraft was facing away from the transmission point.

Next, using the data obtained while flying with a turning diameter of 2 km in an environment with buildings as obstacles, Fig. 9 (c) shows the cumulative distribution of 39 GHz band propagation losses,

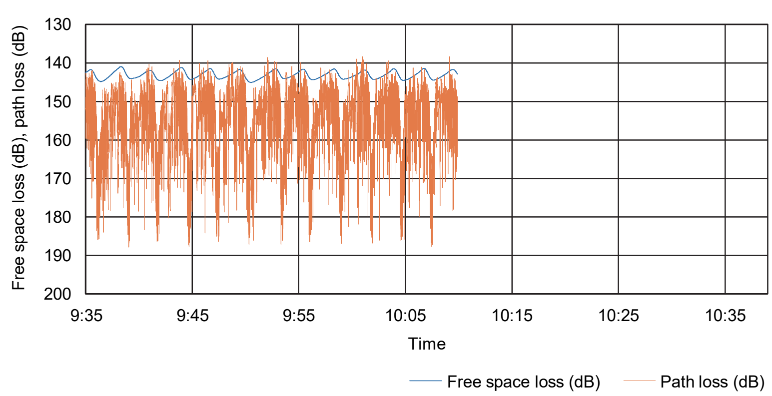


Figure 8 Propagation loss time series data in the 39 GHz band at Odawara City (line of sight)/2 km turning diameter

*24 Cumulative distribution: A function that represents the probability that a random variable will take on a value less than or equal to a certain value.

*25 Median: The value in the middle when countable data is ordered in increasing (or decreasing) size.

*26 Polarization loss: A loss of power received by a receiving antenna that occurs due to the vibration direction (polarization) of the electric field when radio waves propagate in space.

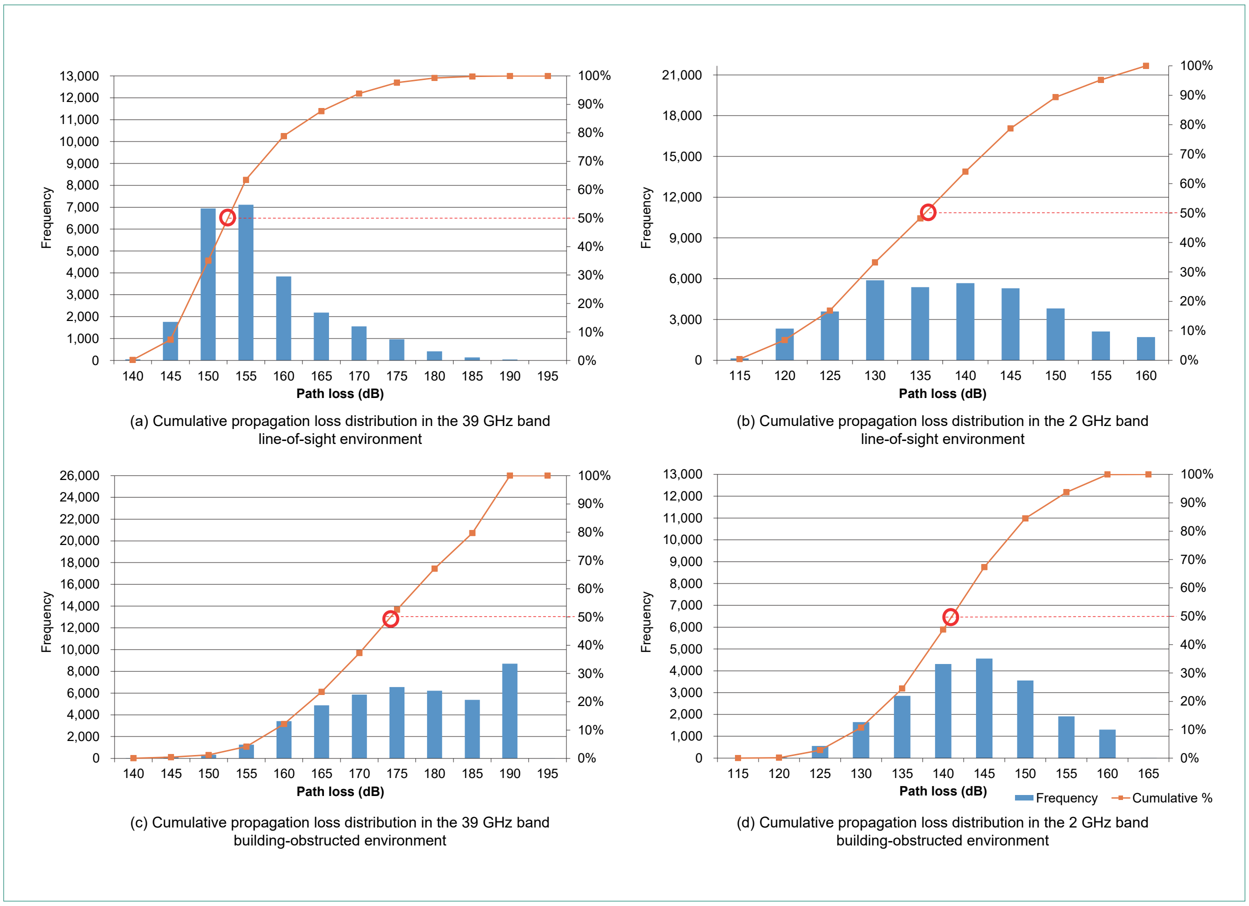


Figure 9　Cumulative distribution of propagation loss in Odawara City with a 2 km turning diameter

Fig. 9 (d) shows the cumulative distribution of 2 GHz band propagation losses, and **Figure 10** shows a map of propagation losses in the 39 GHz band. Comparing the mean and median values of Fig. 9 (a) and (c), the 39 GHz propagation loss has a mean value about 17 dB larger and a median value about 19 dB larger in the building-occluded environment compared with the line-of-sight environment. By comparing the average and median values of Fig. 9 (b) and (d), it can be seen that although obstruction by buildings also affects the 2 GHz band, the losses are relatively small – about 8 dB in the average value and about 9 dB in the median value – compared with the line-of-sight environment. Furthermore, from Fig. 10, it can be seen that when the underside of the aircraft is tilted towards the transmitting point, the received power is at least 40 dB greater than when the aircraft is tilted in the other direction.

5. Conclusion

In this article, as part of our efforts towards implementing extreme coverage extension, which is one of the important issues for 5G evolution & 6G, we have described NTN technology, especially

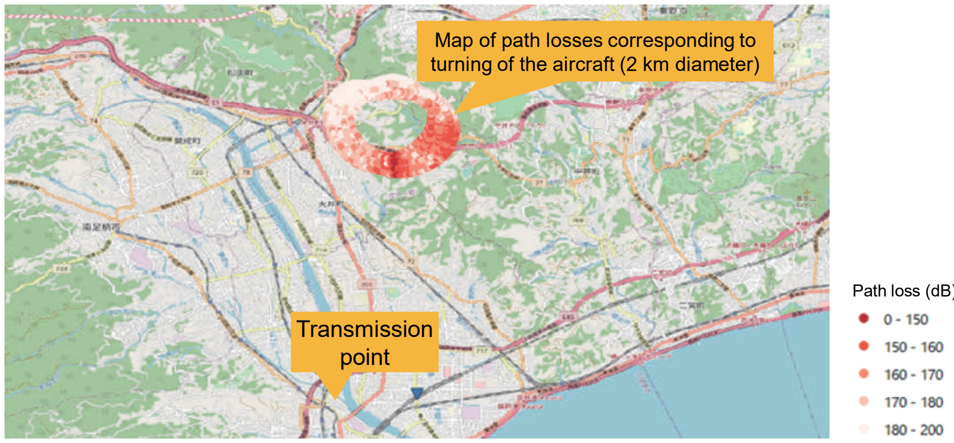


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Figure 10　Map of propagation losses in the 39 GHz band at Odawara City (buildings)/2 km turning diameter

HAPS use cases and network configuration/control technology, and we have shown the results of airborne radio propagation tests performed using a small aircraft assuming HAPS use cases. NTT DOCOMO will continue developing NTN technology aimed at achieving extreme coverage extension and technology for realizing HAPS networks, and promoting demonstration experiments and standardization activities.

Finally, part of this research and development is carried out by the Ministry of Internal Affairs and Communications (Research and Development for Expansion of Radio Resources; JPJ000254).

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