2-9 Wireless Communication Technology for Small Unmanned Aircraft Systems ~Towards the deployment of IoT in the Sky~

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The “aerial industrial revolution” is widely expected, in which the small unmanned aircrafts, or “drones”, are becoming popular in aerial photography and videography, survey, logistics, and disaster management. However, the safety of the drones is still not sufficient and it is said to be essential for future development of the industrial market. For safety control and telemetry, the reliable radio communication is indispensable. However, the most of the current drones use the radio technology used in radio control toys. We introduced small fixed-wing unmanned aircrafts four years ago aiming to develop “an aerial radio tower” for large-scale disaster situations, and have carried out field trials and radio propagation measurements and analysis. Moreover, based on those experience and its know-hows, we have also promoted R&D on wireless technologies for reliable operation of drones, including multi-rotors, which is necessary for their future growth of industrial applications. We will further extend and develop those technologies for contribution to aerial IoT and aerial industrial revolution.

1 Introduction

In a situation of a wide-area disaster caused by an earthquake, tsunami or flood, not only does traffic get shut-down due to damages to roads, but also, due to communication facility breakdowns or power outages, communication-networks, which we suppose are always available, fall into trouble. As a consequence, a large number of areas lose communication means and become so-called information-communication-isolated areas. In such information-communication cut-off situations, we have difficulties in confirming the safety of local residents or knowing what is going on in the disaster area. Consequently, we cannot start relief operations in a timely manner, or grasp what goods are in shortage.

For the purpose of preparing for such situation in disasters and promptly establishing emergency communication-links to isolated disaster-areas, we imported a drone system in 2012—in those days, terms or technologies like drone or unmanned aerial vehicle (UAV) were quite new in Japan. The aerial system we introduced was the world’s most advanced type of battery-power fixed-wing small unmanned aircraft having the following features: no runway required to take off; easy to handle and portable; promptly deployable at any time: long flight-time of two hours; and capable of flying in a beyond-line-of-sight environment if the wireless-connection is kept. By mounting a wireless relay equipment on the aircraft, we developed a wireless-link system working as a “flying radio-tower,” a wireless link system, conducting, in collaboration with local governments or other municipalities nation-widely, proof-of-concept experiments in simulated disaster situations from the point of disaster-prevention; and at the same time, we have collected and analyzed a variety of data relating to radio-propagation or communication quality in various environments.

Small unmanned aircrafts, in these days generally called drones—in particular multi-rotor-types—have become widely used—and at a rapid pace of growth—for hobby-use and business-use, particularly for aerial shooting, infrastructure management jobs, or disaster control operations—to the extent that the use of drones is called the “Industrial Revolution in the Air.,”—and reportedly the drone market size is expected to be 200 billion yen domestically and on the order of 10 trillion yen worldwide in 2022 (in five years from now).

The government's "Robot Revolution Realization Conference" released in January 2015 the "New Robot Strategies." In addition, from the standpoint of the legal system, enhancement was developed; in December 2015, the amended Civil Aviation Act, which has unmanned aerial vehicle-related articles, was effectuated. So, we have had a roadmap for the growth of industries, which covers the matters of technology development and the matters of environment improvement.

On the other hand, because a drone's essential feature is flying freely in 3D space, wireless means are indispensable for their control and status acquisition. So, another important issue, for the safety enhancement and the growth of acceptance of drones, is how to improve the reliability and user friendliness of the wireless systems. However, the wireless systems currently used in business operations are extension models of hobby-use systems (for radio-control planes)—although inexpensive and easy to handle—which have drawbacks in reliability as follows: the wireless range is short and it is susceptible to wave shielding by obstacles or electromagnetic interference; once the aircraft goes out of wireless range, we have no aircraft guidance means other than full automatic cruising mode (autopilot mode) where we are unable to override control of the aircraft. We have, through conducting drones operations, accumulated a variety of wireless technologies and knowhow on drone operation. By utilizing those experiences and knowhow, we successfully developed the following technologies and proved their validity through experiments: technologies for controlling drones—including the multi-rotor type—in places beyond line-of-sight, from where radio waves do not directly reach the drone; and technologies for securing safe simultaneous cruising of a number of drones belonging to different operators through having each drone share others' location information.

Along with the activities just mentioned, we have contributed to the efforts of standardization by international organizations including the International Civil Aviation Organization (ICAO) and the Asia Pacific Telecommunity Wireless Group (AWG). Also, we have assisted the Ministry of Internal Affairs and Communication in their activities for frequency allocation to robots (unmanned flying objects), which is the first business operation-oriented frequency allocation in licensed bands for drones in Japan.

In this article, we are presenting our activities starting with the first-in-Japan deployments and operations of drones to the recent achievements.

2 Developments and experiments of wireless link systems for avoiding communication blackout in disaster situations

2.1 Generals on systems

We developed a wireless link system[2] consisting of ground stations and small lightweight link units mounted on drones to work as a "flying radio tower" for the purpose of avoiding temporary and local area communication blackouts in the wake of a disaster (Fig. 1), based on the studies on the incidents that occurred in the Great East Japan Earthquake in March 2011 where communication infrastructures suffered extremely severe damages causing information-isolation of local communities or shelters. In 2012, we introduced three Puma AEs [1]—a type of unmanned small fixed wing aircraft—to mount our system on them.

The system wirelessly links two separated points on the ground, avoiding interference from mountains or buildings on the ground, using a drone circling around a fixed point in the air at an altitude of several hundred meters. Moreover, by applying a two-plane air relay via plane-to-plane wireless link, the system is able to link two points of far distance (Fig. 2).

The wireless link unit we developed has the configuration and characteristics as follows: the unit is mountable, with the batteries exclusively used by the unit, in an aircraft payload space of about 10cm wide;

the weight of the unit is around 500 grams including batteries;

the unit is operated in the 2 GHz band (with experiment radio station license);

its output power is 2 W;

it uses MSK modulation;

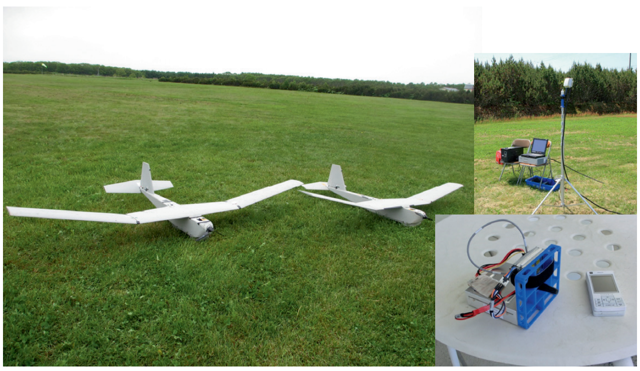

Fig. 1 Puma AE (introduced drone), drone mountable communication unit and ground station (developed)

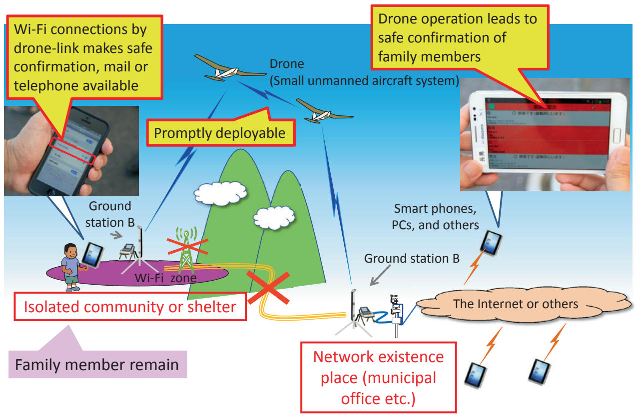

Fig. 2 Schematic diagram of 2-drone-relayed communication link

Fig. 3 Throwing launch of communication-link drone

it is continuously operable for about 1.5 hours.

The following are the details of transmission performance:

It uses, for multiplexing, TDMA / TDD;

the error correction code efficiency is 1/2, so its effective transmission speed is approximately 400 kbps—we confirmed communication between a drone and a ground station at a direct distance of longer than 15 km. On the other hand, because each of the two ground stations mutually linked via a drone has a LAN interface in it, by using the LAN port of one of the ground stations as the wireless LAN access point and connecting the other to the internet, we are able to easily establish a temporary wireless LAN (Wi-Fi) zone covering isolated areas, and use the internet connection for mail, IP telephone, and other applications for safety confirmation. In addition, although this will be discussed later, we successfully established a backhaul link by connecting our system, instead of to the internet, to a "femto cell," which is a micro hub station of a mobile phone network.

Puma AE is a battery-powered fixed wing unmanned aircraft with a wingspan of 2.8 m, a length of 1.4 m and a weight of 5.9 kg. It has several features as follows:

it is capable of autonomously performing a long flight at a low speed along a predetermined flight course and it can be in the air for two to three hours in a flight;

when taking off, it is thrown into the air from a sufficiently wide ground or open space (Fig. 3), or launched by a spring-powered launcher. Flying in rainy weather is not a problem because the aircraft and a ground station are waterproofed.

The wireless system works as follows:

the airframe control wireless system transmits, as well as control signals, command signals and telemetry signals, videos of VGA quality taken by an aircraft mounted camera at a rate of 30 FPS—the 2 GHz band has been used since it was first introduced;

the aircraft mounted wireless system (air station) and the ground stations are operated with an experiment radio station license permitting an output power up to 1 W, so the outreach distance of the wave transmitting command/video/telemetry signals is longer than 15 km under a line-of-sight condition. The system does not use the 2.4 GHz band—no license is required, and is the most widely used band for radio-controlled hobby craft or multi-rotor type drones;

on the hand controller used by an operator, the airframe telemetry information and the mounted camera videos are displayed in real time, so the operator can, if the wireless link is connected, navigate the aircraft in a situation where the operator cannot see the aircraft directly—such navigation is very similar to instrument flight rule (IFR) of a manned aircraft.

On the other hand, at the ITU World Radiocommunication Conference 2012 (WRC 12), the recommendation that the 5 GHz band (from 5030 to 5091 MHz) should be added to the frequency bands for unmanned aircraft control was agreed [3].

However, in order to make the frequency band applicable in actual situations, we need to study technological problems and finalize technical standards—we have to clarify the propagation characteristics in the frequency band, develop the technologies for avoiding interference in the band and to and from the adjacent bands, and develop the technologies for frequency sharing. For the purpose of contributing to such international activities, we acquired an experiment radio station license of the 5 GHz band (with the same output power as that of 2 GHz) to operate the wireless control link of two aircrafts of the three we introduced, having been conducting. During flight operations, measurements were taken. We have confirmed that, although the outreach distance was shorter than about 8 km, flights are as stable as those of 2 GHz.

Although almost all of the civil-use drones on the market these days are multi-rotor types, those multi-rotor type drones are operable for only 15 to 20 minutes. However, communication-link drones are required to stay in the air for longer hours. So, we believe that fixed-wing type drones, which can stay in the air for long hours, are more suitable to communication use.

2.2 Proof of concept experiments

We demonstrated the flight and operation of the systems we developed for the first time on March 25 and 26, 2013, as an open experiment held at the "Disaster Resilient ICT Research Symposium." We proved in the experiment that the exchange of safe confirmation information or mail to and from isolated areas at a long distance is secured even in a situation with no internet connection available, by our system using drones in the air—our system was connected to the testbed, independently installed at a campus of Tohoku University, of "Disaster Resilient Wireless mesh network." In the years since the first flight to March 2017, in many places in Japan, we have conducted more than 200 flight tests—for longer than 100 hours in total. Through those tests, we verified the performance, conducted measurements on wave propagation characteristics, carried out demonstrations to municipalities and participated in disaster prevention exercises. In addition, we have conducted measurements on high above the ground radio wave environments and radio propagation characteristics (Fig. 4). We are introducing below the experiments in Sendai and Kochi, out of the large number of our trials.

(a) Experiments on long-range communication (Sendai, Miyagi)

We set the experiment configuration as follows: we put a Puma AE circling at sea level of 750 m above the reclaimed land where Tohoku University's New Aobayama Campus is to build; we placed a number of ground stations in an area in the direction to the Pacific Coast across Sendai at the elementary/middle schools and hospitals—they are to be designated as shelters in a disaster situation. We conducted measurements of the propagation characteristics and throughput characteristics in the 2 GHz band at the various distances up to 14 km (Fig. 5). In the experiments, we observed diffraction effects caused by urban-area buildings leading to a degradation in communication quality compared to that of a simple free space propagation—we found up to a 30 percent drop in throughput at around a point 10 km away. However, we confirmed, in another experiment of long-distance communication conducted in Hokkaido—the ground was covered with woods or grass fields—that we suffered less diffraction effect and communication was good between the two points up to 20 km away.

(b) Experiments on mobile phone relay by the femto cell / satellite communication combination (Shimanto-cho, Kochi)

We conducted experiments on the temporary relief of mobile phone communications using a femto cell/satellite communication link—a femto-cell is a micro mobile phone hub station with a communication area of a 100 m radius or less—, on the assumption that ground mobile phone networks are shut down, where we used a femto cell, a drone communication link, and satellite links (Wideband Internetworking Engineering Test and Demonstration Satellite WINDS)[4] (Fig. 6).

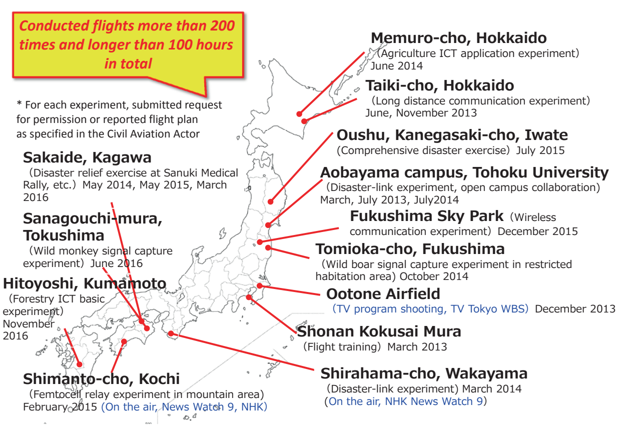

Fig. 4 Major experiments (conducted so far)

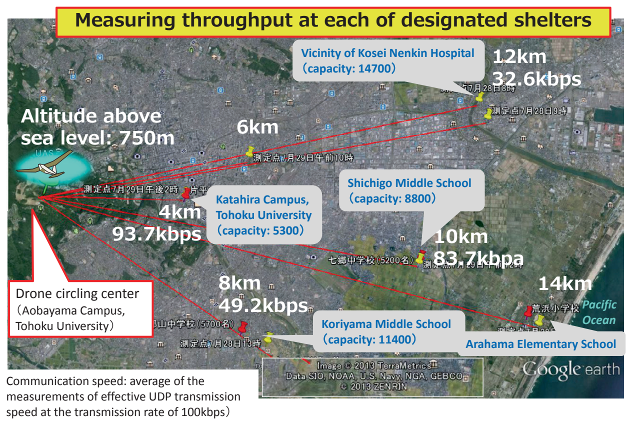

Fig. 5 Urban area long distance communication experiment (Sendai, Miyagi, July 2013)

Shikoku Bureau of Telecommunication hosted the experiment, Shimanto-cho, Kochi supported it, and NICT conducted it in cooperation with mobile phone business operators—NTT docomo, KDDI and SoftBank Mobile— in February 2015. The experiment site was a resident area in a so-called Hilly and Mountainous area in Shimanto-cho, Kochi. We set the experiment configuration and scenario as follows: we placed a mobile phone hub station, a drone link ground station, and a WINDS vehicle-mounted satellite earth station in an area where mobile phone services are unavailable; we launch the drone using a tiny space in a rice field—where harvest is completed; the drone went up along a valley, then the drone moved to a link point around where the drone was to create a wireless link—the point is about 2 km horizontal distance away from, and about 1,000 m high above, the place where the drone is to be launched—and circled around the link point. Note that the drone flew under beyond line-of-sight conditions, while the wireless link connection was maintained. The signals from the femto-cell hub station were connected to mobile phone networks via the drone link and the satellite link.

Although the link was in a slight unstable condition due to the limitation of communication capacity and the fluctuations in the drone's location or attitude, we successfully confirmed that bidirectional voice communications are available, proving, for the first time in the world, that aerial space relay technically enables mobile phone conversation.

Beside the proof-of-concept experiments described above, in collaboration with municipalities, we conducted experiments to use drones for capturing action traces of harmful animals from high places above the ground—we attempted chasing wild boars in Fukushima and monkeys in Tokushima in cooperation with Circuit Design, Inc. We

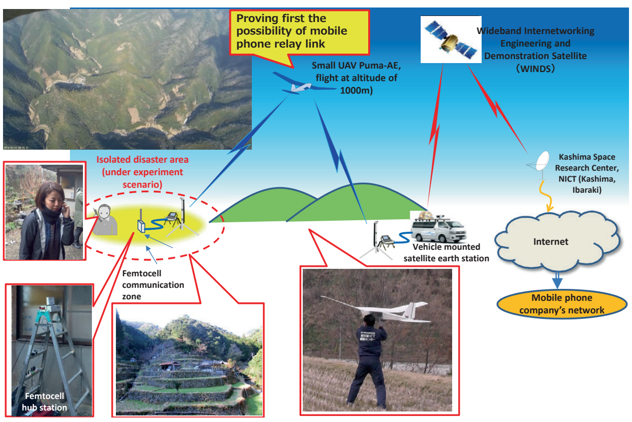

Fig. 6　Experiment of mobile phone link by air to space relay (Shimanto-cho, Kochi, February 2015)

mounted small transmitters the animals equipped with GPS devices to capture signals from those transmitters up in the air and transmit down to the ground for the extraction of animal action traces. We have found in such experiments several system problems to solve. So, we are preparing plans for conducting studies on those problems. In addition, we received an order from Hitachi High Tech Solutions Ltd for measurement of the radio environment in a coast area, where the total length of the flight course is about 13 km—Fukushima Prefecture has been developing, in Minami Soma, the "Fukushima Robot Test Field" for the performance evaluation of robots or drones to be used in a disaster situation and others. The area where we conducted the measurements includes the test field. So, in February 2017, we conducted radio wave measurements using a Puma AE, which is capable of performing long-duration beyond line-of-sight flight (with wireless connection maintained) [5]; the Puma AE, loaded with a small spectrum analyzer in its payload, cruised in each of three flight sections of about 4 km—the 13 km course was divided into such three sections—, made measurements of noise levels in the bands of 169 MHz, 920 MHz, 2.4 GHz, and 5.7 GHz, at two elevations from the ground of 100 m and 150 m; and the measurement results were publicized on Fukushima Prefecture's webpage [6]. Note that we conducted the flight under permission of "a flight without standard method specified" from the Ministry of Land, Infrastructure, Transportation and Tourism (in our case, we made beyond line-of-sight flight), and with regard to the contract research from the Ministry of Internal Affairs and Communication, which will be described later, the measurement conditions are similar to those in this case. So, because a Puma AE is suitable to wide-area aerial measurements of radio wave environments or wave propagation characteristics too, we will use the drone for such measurements.

3　Contract research from the Ministry of Internal Affairs and Communications

In 2012, while worldwide efforts for the utilization of drones had become active, the World Radiocommunication Conference (WRC- 12) agreed on the use of the 5 GHz band (5030 to 5091 MHz) frequencies for control-and-non-payload communication—CNPC link or C2 link—to control drones (transmitting commands) or monitor drones (receiving telemetry signals). Furthermore, in 2015, in WRC 15, they approved the conditional use of satellite-link frequencies in the Ku/Ka band to connect drones to satellites. However, because the 5 GHz band is already congested, we have to prepare interference avoidance measures or frequency sharing rules—ground wireless access systems use frequencies in the same band, and airport wireless access systems use frequencies in adjacent bands. Moreover, with regard to satellite links, we have to avoid interference with other satellite links. So, for the purpose of preparing such interference avoidance measures, the following have become the urgent matters: creating a quantitative wave propagation model; knowing the interference situations; developing interference reduction technologies; and in addition, highly reliable and efficient wave resources wireless communication technologies have been largely required.

In the abovementioned situations, the Ministry of Internal Affairs and Communications requested contract research proposals of "Research and Development of the Technologies for the Collaboration and Sharing of Wireless Link Systems using Unmanned Aerial Vehicle and Terrestrial Networks."

NICT, in response to the RFP, took a leading role in the establishment of a research consortium consisting of the five organizations—NICT, Tohoku University, Electronic Navigation Research Institute, KDDI Research, Inc., and NEC Corporation, acquiring contracts and conducting research and development in the three years from FY2013 to 2015. Figure 7 shows a schematic diagram of how an unmanned aerial vehicle works for keeping communications sustainable in a disaster situation—the diagram had been referred to during the research and development as the concept scenario. The research and development included a variety of items as shown below.

5 GHz band CNPC link sharing:

(1) Developing radio propagation models for evaluating frequency sharing (NICT),

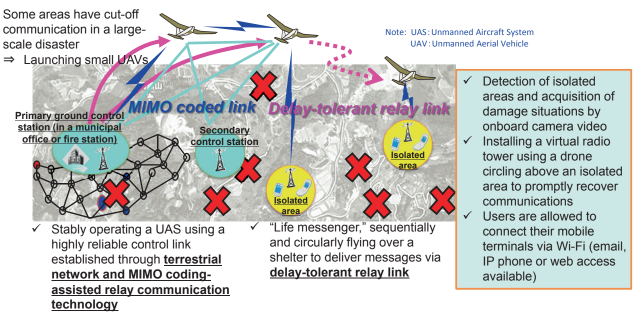

Fig. 7 Drone application scenario for keeping communications in a large disaster situation

(2) Technologies for frequency sharing with other ground wireless operations (Electronic Navigation Research Institute).

Sharing of via satellite CNPC link:

(3) Technologies for sharing frequencies in the Ku / Ka band between an UAV and satellite links for other uses (NICT).

Technologies of effective frequency utilization for communications by using drones in disaster situations, etc.:

(4) Technologies of advanced store-and-forward links by a drone-mounted small-sized server (KDDI Research Inc.),

(5) Research and development on delay-tolerant network configurations (Tohoku University),

(6) Link technologies for space-time coded signals in a massive MIMO system consisting of ground stations and drones (Tohoku University),

(7) Advanced frequency control technologies adaptable to the drone-use environment (NICT and Electronic Navigation Research Institute),

(8) Drone-assisted terrestrial network trouble diagnosis algorithm (NICT).

Effective frequency utilization in drone CNPC link:

(9) Technologies of ground-drone multi-link MIMO coding (NICT),

(10) Implementation and evaluation of ground stations-to-drone hand-over control algorithm (NEC Corporation).

Every above mentioned item, except for item (3), is related to wireless link in the 5 GHz band for drones to ground stations, or drones simultaneously in the air.

In the latter half of FY2015, we conducted actual flight tests jointly with the member organizations in the test fields in Fukushima and Kagawa to evaluate the performance of the test model we developed in a real flight environment, mounting the model on a fixed-wing type drone and multirotor type drone (Fig. 8). We will leave the details of the research and development results to another paper [7].

We used a part of those results in our international standardization activities; in FY2014, we participated in the 17th AWG meeting held in September (AWG 17), submitting a paper on "Technologies of Drone Control Ground Station-to-Station Handover," persuading other participating countries to finalize the APT Report; in addition, at the 18th AWG meeting (AWG 18) held in Japan in March 2015, we made a proposal from another report on the public use of drones, and at the meeting site, we had a demonstration booth to present a part of the results of our research and development; at the 19th meeting (AWG 19) held in February in 2015, we presented a working document for the preparation of the preliminary report on the drone services and applications for public business operations [8]; in addition, at the meetings of ICAO, we presented the results of the measurements we conducted on the radio wave propagation characteristics in the 5 GHz band and made a proposal on the frequency sharing technologies.

On the other hand, under the R&D administration committee of this project, an association was established, the "Liaison Council of the Organizations involved in Utilization Technology Development of Unmanned Aircraft Systems," participated in by 16 organizations as members from universities, national institutes, corporate laboratories and drone business associations, and six ministries and agencies as observers including MIC, MLIT, and METI. (the council is chaired by Prof. Shinji Suzuki, Tokyo University). In the years from FY2014 to 2015, six meetings were held in order to activate inter-organization collaborations—including ministries and agencies. The council conducted surveys worldwide and domestic trends in drone-related activities, what is required to communications in each drone utilization case, and what the challenges are with regard to the wireless systems; and the results were fed back to the R&D of this project.

While in these days drone-related associations and others frequently hold meetings or research sessions, in those days when the council was established, such an association was very rare in Japan. So, because the council represented proactive activity for the purpose of developing collaborations between ministries and agencies, it contributed to the cultivation of human networks, which have been inherited by a variety of cross-ministry committees or projects to function well.

Fig. 8 Scenes of MIC Contract Research Evaluation Experiment

In FY2016, the consortium of NICT (the representing organization), Tohoku University, Hitachi, Ltd., and NEC Corporation received from the MIC a new research contract, "Research and Development of Communication Network Technologies for Effective Frequency Utilization in Unmanned Aircraft Systems." We have established a 3-year plan for the improvement of frequency utilization efficiency and started our research and development activities focusing mainly on the 2.4 GHz and 5.7 GHz bands (refer to the next section) used in the "Image Transmission System for Unmanned Mobile Vehicles" developed by the ministry in FY2016.

4 Status of CNPC link for small UAV and radio wave allocation to robots

Almost of all the domestically used radio control operation terminals are generally called "Propo," independent of whether they are hobby use or business operation use. The 2.4 GHz band (so called ISM band) is used. As is well known, the band is widely used by wireless LAN (Wi-Fi) devices. So, drone radio control devices are less expensive and no license is required to use them. This means that the band is very convenient for both vendors and users. Furthermore, for those drones, a wireless method called frequency hopping—a number of carrier frequencies are used while being switched from one to another—is used. So, the method is resistant to wave interference, allowing a number of users to operate their drones simultaneously or even in an environment where Wi-Fi devices are working close to the drone-flying area. However, such drones widely used these days, while working sufficiently well for hobbies or some business operations where drones fly within a visible range, are operated with small power, having a narrower operation range—meaning they are unsuitable for long-range operations, having a larger risk of receiving wave interference when used in an environment like an urban area where many Wi-Fi devices are working. In addition, because the band is used not only for controlling drones but for telemetering or image transmission, drone system internal interferences cannot be ignored.

Except for the 2.4 GHz band or the 73 MHz band for industrial use drones (mainly used for crop spraying), the 920 MHz band, which is for small-power radio stations, is one of the bands requiring no license for controlling drones or telemetering. Some models of drones have been using that band. As for the 920 MHz band, because it is also used for ground sensor networks or RF tags, for the purpose of ensuring frequency sharing, the output power of a station is limited by a regulation to 20 mW—note, a registered ground station is permitted to transmit with a power of up to 250 mW—, and at the same time, the channel bandwidth is limited to 200 KHz—up to 5-channel-bundling is permitted—and the transmission rate (duty rate) is limited. So, the band is not suitable for high-precision video transmission, but not yet congested compared to 2.4 GHz although the device prices are low. In addition, because, in this band, the bandwidth and number of channels of a certain level is securable and the range is longer than that of 2.4 GHz, the band can be suitable mainly for business-use drone control or telemetry. Actually, the adjacent frequency bands are used for sensors or robots in many countries in the world, so such devices using the frequency band can have an opportunity to enter the international market. As will be mentioned later, we have already started the development of technologies using the frequency band.

On the one hand, the Information and Communications Council of the MIC made a recommendation on the technical conditions for advanced radio wave utilization in March 2016, stating that frequency bandwidth of over 130 MHz in total (including the 169 MHz band, a part of the 2.4 GHz band and the 5.7 GHz band) should be made available under a license for image transmission by unmanned vehicles like robots. The license system has been effective since August 2016 [9][10].

The opened frequency bands are for business operations; a radio operator license is required to operate in those frequency bands (the 3rd or upper land special radio engineer license); antenna power over 1W (unless otherwise permitted, limited to 10 mW for 169 MHz band when used above the ground) is permitted, so the use of the bands is suitable for operations where over-5-km communication range is required. Note that the frequency bands are supposed to be shared with other operations.

Although the main usage of those frequency bands is supposed to be flying object image transmission, they are usable for sending control signals. However, they are sharable bands and there is a risk of interference with other wireless systems. CSMA methods as used in wireless LAN systems might be applicable, but high efficiency is not expected in frequency utilization; particularly in some situations where a nearby station is transmitting with high power, the carrier sense mechanism is activated to halt transmission. So, in principle the use of these bands does not assume the CSMA method and the operators who are to share the frequency bands have to make operational arrangements.

Under the circumstances as described above, for the purpose of the realization of safe and efficient utilization of the three licensed frequency bands, under the recommendation of the Radio Engineering & Electronics Association, discussions were made on the introduction of a proper operation arrangement scheme and the realization of services for centrally controlling the following management items: robot operation management, including the management of robot ID and robot flight/operation area, location, and others; and radio wave management, including the management of frequency channels, bandwidths, antenna powers and others. Then, on July 11, 2016, the group "Japan Unmanned System Traffic and Radio Management Consortium" (JUTM) was established [11]. The group is chaired by Prof. Shinji Suzuki, Tokyo University, and participated in by communication business operators, universities, national institutes, private corporations, and others. Figure 9 shows a schematic diagram of the group's target system [12]. The group, at first, will limit their services to the provision of UAS pre-flight scheduling services on a public platform, and then they will enhance their system to provide real-time locations of unmanned and manned aircrafts in flight, weather reports, and wave propagation simulation 3D outputs. Furthermore, they have a plan for the future to introduce a system that enables alteration, in flight and real-time, of UAS's radio resources (transmission slot or frequency, antenna power, and others). Such a system will contribute to the safe navigation of robots, in particular business operation-use drones, and the efficient utilization of radio waves, which

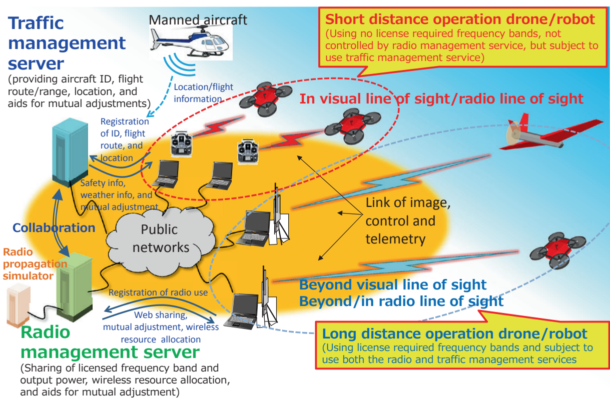

Fig. 9 Schematic diagram of operation and radio wave management system

will push forward the social acceptance of drones and the growth of their market.

5 Beyond line-of-sight drone control and between flying objects location information sharing

Before closing this article, we will introduce the following two technologies into which we, jointly with the National Institute of Advanced Industrial Science and Technology (AIST), have been putting efforts: 1. Latency-guaranteed multi-hop relay control communication technologies; and 2. Between-flying-objects location information-sharing technologies. Both of them were developed in the Tough Robotics Challenge [13](program managed by Prof. Satoshi Tadokoro, Tohoku University) of the ImPACT (Impulsing Paradigm Change through Disruptive Technologies) Program led by the Council for Science, Technology and Innovation, Cabinet Office.

1. Latency-guaranteed multi-hop relay control communication technologies

The technologies enable keeping control communication available in a situation where barriers such as a mountain or a building block direct radio waves—so called "beyond radio line-of-sight." Flights using such communication means are still strictly regulated by laws and acts. The "Roadmap for Small Unmanned Aircraft Utilization and Technology Development" [14] under study by the Government has set the general classification on drone flight into the following four levels: Level 1, manual flight within line-of-sight areas; Level 2, autonomous flight within line-of-sight areas; Level 3, beyond line-of-sight flight over unmanned areas; Level 4, beyond line-of-sight flight over manned areas. The roadmap recommends that beyond line-of-sight flight should be used for Level 3 flight in around 2018 and for Level 4 flight in the 2020s or later. There are two types of beyond line-of-sight flights: (a) the drone in flight is not in sight (beyond visual line-of-sight) but radio-wave connected; (b) the drone is not in sight and not radio-wave contacted (beyond radio line-of-sight). A drone in the case of (a), because it is radio connected, is able to fly safely, although not in sight—for instance, such a drone can be used for flights for drone mounted sensor or video camera operations; this type of flight operations has been realized by applying currently available technologies. The flights in the case of (b), although having much severer difficulties than in the case of (a), will become indispensable in the future for long-range goods delivery flight or low-altitude monitoring flight over an urban area or a mountainous area, where radio waves are often blocked. At present in most cases, we have no other means for accomplishing such flights than a 100-percent autonomous means depending on GPS and using preprogrammed route information, not depending on wireless communications. However, because the operator has no means to know the drone location or status, this type of flight can be very dangerous—note that generally used drones have a failsafe mechanism, returning automatically to the operator's position if it goes out of radio range.

Generally, three types of communication path establishment methods can be applicable to accomplish safe drone flights in such a "beyond radio line-of-sight" area, as follows: (Fig. 10): (1) connection through ground infrastructures—for example, mobile phone networks; (2) connection through satellites; and (3) connection through a relay station consisting of other drones or robots in collaboration.

Method (1) is the most easily applicable method for the realization of beyond line-of-sight flights, while the use of mobile phone frequencies by a drone has been prohibited so far by regulations. However, the MIC decided last year to give "practical test station licenses" to communication business operators and permit them to use mobile phone frequencies limited for tests [15]. Mobile phone companies have started tests by using the licenses. However, they have problems to solve such as interference with ground mobile phone networks or above-ground service area distributions. So, applications to practical situations are yet to be realized. In addition, their service might be limited to some extent by flight areas, and it is not clear whether their services would be available in a situation where ground facilities are

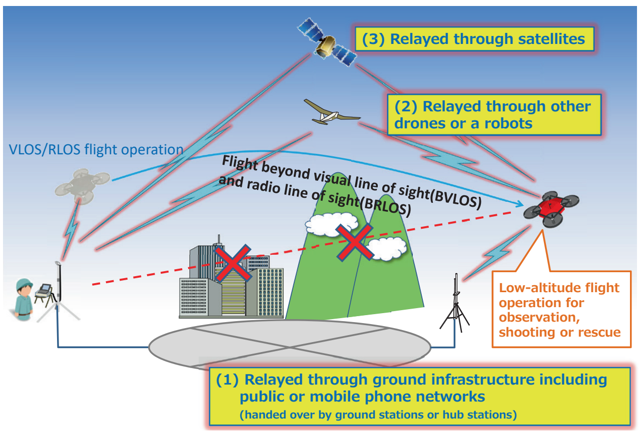

Fig. 10 Method for keeping wireless link connected in a situation of beyond radio line of sight

damaged. It also should be noted that such connections are not available free of communication charge.

With regard to method (2), systems using satellites such as IMMARSAT satellites have been available in the market; so, although limited to open air areas where satellite signal is available, we are able to conduct drone operations globally not constrained by locational conditions—on the sea surface or on a mountain. However, the method has major drawbacks: its operational cost will be a big matter to insufficiently funded users, and in addition, drones have to be large enough to have such satellite communication systems mounted.

Method (3) is expected to offer lower cost than methods (2) and (3). Although the conventional technologies for controlling robots by wireless relay are available, they are based on the wireless LAN technologies developed for the Internet; so, at each timing of relay path switching the control communication is interrupted for several 100 ms to over 1 second, which leads to the problem that the robot will be uncontrollable during such a period of communication cut-off. Another problem is that there exists a time delay fluctuation from command transmission to command reception (by a robot), and the control response delay time (latency) is not guaranteed. Consequently, such systems are not fully applicable to robot control.

We have promoted our research and development activities on the assumption that our system will be used in a situation as shown in Fig.11 where a robot beyond line-of-sight is to be controlled and monitored through other robots acting as relay stations. Our system should be dedicated to “robot control,” and our system uses “relayed communication,” to design and develop an advanced access

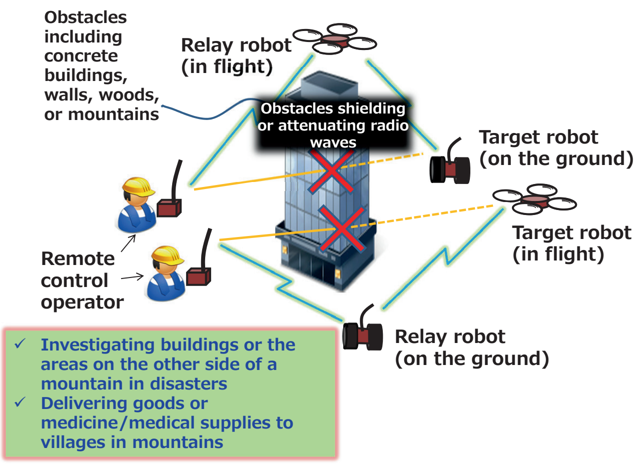

Fig. 11 Beyond line of sight operation through multi-hop relay by drones/robots

protocol that ensures keeping the latency under a certain value and avoiding communication interference [16].

We successfully guaranteed the latency by applying “Time Division Multiplex Access (TDMA)” to robot control, where to each of the communication paths—control station to relay station, relay station to relay station, and relay station to robot—a pre-defined timeslot is allocated. Furthermore, we applied the following scheme to robot control for the first time: instead of using the conventional procedures to find or determine communication paths prior to conduction of communications, every incoming signal to each slot is always received, and then sorted and accepted according to a rule where the strongest signal is accepted, or another rule where signal acceptance is determined by a predefined priority.

Through applying these technologies, we accomplished the following: suppressing the latency in a case of relaying though a relay station, which shows different values depending on operation conditions when a conventional method is used, within a control signal transmission period (about 60 ms), and enabling avoidance of instability in control; suppressing the duration of communication cut-off occurring when the relay path is altered as the robot moves, less than a tenth of the cut-off duration by the conventional method, which means that we enabled keeping the “freshness” of the control data received by the robot within a certain level even in a case where the control signal is relayed by a relay station on the control data path. We have been calling these technologies “tough wireless” because they are resistant to radio wave blocking and usable in a disaster situation.

The wireless devices we developed use frequencies or channels as follows: using a 920 MHz-band small power radio station (compliant to ARIB STD T108) for both control signals and telemetry signals bidirectionally; bundling up to five 200 KHz width channels within a width allowed by the standard and using the bands as a 1 MHz width band; improving the interference resistance by sequentially switching four frequencies one to another. In the proof-of-concept experiment field tests conducted in June, November 2016 and June 2017, we successfully conducted stable operations and telemetry signal reception of a small 4WD robot or a multi-rotor type drone existing in a location of beyond line-of-sight from an operator and at the same time beyond radio line-of-sight. During the experiment, another drone with a relay station mounted was hovering about 20 to 30 m above the ground. We confirmed that we were able to control the target drone, which had been lowered down until it moved behind trees or the landscape, to rise up again, or to get activated, take off and go up in the air (Fig.12). Note that, prior to the experiment, we had received flight permission required by the amended Civil Aviation Act, in the same way as in the case of the beyond line-of-sight tests of Puma AE.

At present, we have not improved our system to carry out image transmissions from a drone beyond line-of-sight. However, we have a plan to conduct trials of image transmission using the 920 MHz band. Because the band is not so suitable for image transmission, we will develop and evaluate test systems for low quality/low rate image transmission.

Currently, our wireless module is equipped with, in addition to a 920 MHz band wireless device, a 169 MHz band wireless device—a type of "unmanned vehicle image transmission system" newly approved by the MIC. We received a radio station license for the 169 MHz band device on June 14, 2017, soon mounting the device on a multi-rotor type drone. Then, on June 17, 2017, although it was a short range such as dozens of meters, we successfully conducted the following trials using 169 MHz frequencies: the first command transmission and telemetry reception between a drone and a ground station by direct communications (1 hop); conduction of a drone flight by control signal linking by relayed communications (2 hop) via a relay drone. We will leave the details to other articles, and we are going to show our conclusions as follows: as expected, the 169 MHz band is not so promising for a high transmission speed, and moreover, the number of available channels is around four maximum. However, with regard to transmission distances, we will be able to have a long free-space propagation distance from ground to high positions in the air, which is far longer than in the 920 MHz or 2.4 GHz bands. So, the band could be used for backup links in the case where the radio wave in operation is interrupted or becomes unstable, and be effective for reliability improvement in drone operations in a visual beyond line-of-sight or radio beyond line-of-sight environment.

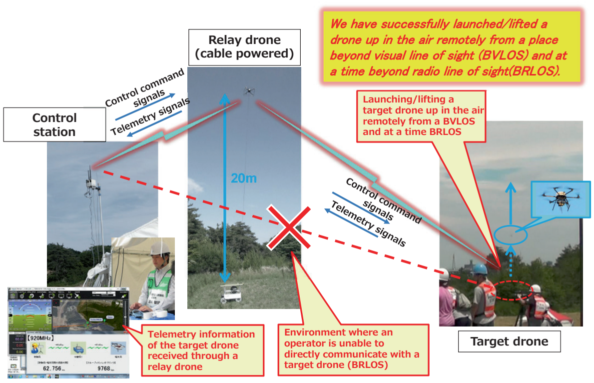

Fig. 12 Field test of beyond line of sight relayed control using "Tough Wireless" (June and November 2016, June 2017, at New Aobayama Campus, Tohoku University, Sendai, Miyagi)

2. Between-Flying-Objects Location Sharing Technologies

Near-miss incidents of a drone with a manned helicopter have been reported recently. Such an incident could lead to a life-threatening accident to a helicopter pilot or passengers—even if no human damages would occur on the drone side. Moreover, in the future situation of the air expected to be congested with a large number of drones flying for goods delivery or disaster missions, there would be a high risk of human or ground facility damages caused by drone collisions or crashes to the ground.

For preparing for such risks, we developed a system that is useful for the avoidance of drone-to-drone or drone-to-manned aircraft collisions, where drones or aircrafts share mutually location information using broadcast-type transmission protocols. We have been conducting proof-of-concept experiments using, similarly to the previously mentioned system, a 920 MHz band special small power radio station. We have named the system "Drone Mapper" [17] (Fig.13). Similarly to the previous system, this system has a multi-hop function and we can describe how it works, taking, as an example, the situation shown in Fig.13, as follows: Operator A does not have, in his line of sight, Drone B' operated by Operator B. If Drone A' operated by Operator A is in the line of sight of Drone B, Operator A is able to know the location of Drone B' via Drone A (relayed by Drone A).

Speaking from the technical point of view, the system is based on a ground-based "device-to-device communication network technology" (Section **2-7**), which has been

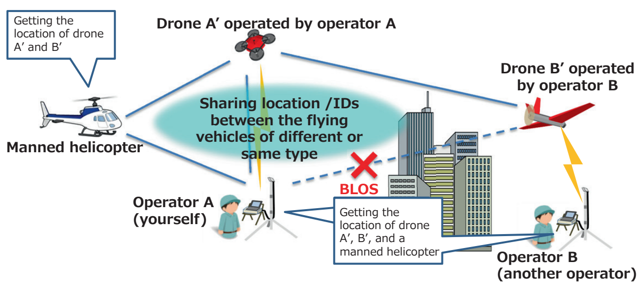

Fig. 13 Drone mapper: flying objects' location sharing system

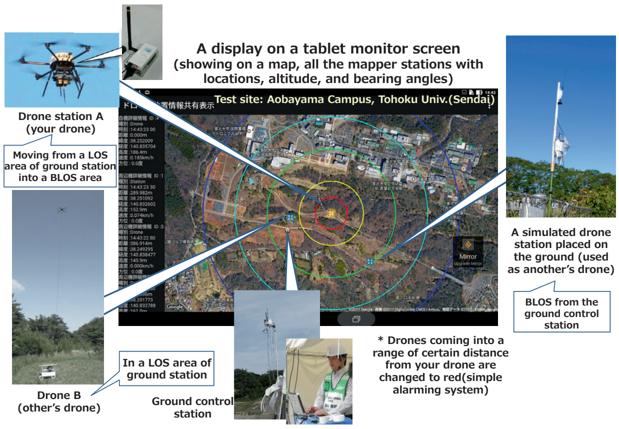

Fig. 14 Mounted done mapper on a drone, and locations of nearby drones displayed on a tablet screen

developed and evaluated as a simple system consisting of communication terminals and using no communication infrastructure facilities such as a central control equipment in a hub station. The MAC layer (media access control layer) protocol used is under international standardization as IEEE802.15.8.

A helicopter pilot or a drone operator, with a drone mapper mounted on their craft, is able to know other drone mapper-mounted drones or helicopters as follows: on their tablet terminal screen, relative locations of other flying objects, if they are equipped with drone mappers, are displayed at a refresh rate of 2 to 4 times per second with their own craft centered on the map just like a radar chart (Fig.14). When a drone or helicopter comes close in a certain horizontal or vertical distance, its icon turns red—working as an alert system, although being a simple system. We have a plan to enhance the graphical user interface (GUI) mentioned above through discussions with drone users and manned aircraft users.

Note that we have confirmed in a ground test that the longest wave range of a drone mapper is over 9 km at shortest, because it uses a wave with a narrower bandwidth compared to the previously mentioned Tough Wireless and also uses a broadcast-type protocol.

6 Conclusions

For a long time before the recent drone boom, we have noticed how promising unmanned aerial vehicles are, and how essential the wireless technologies are for them. So, we have accumulated field experiences one by one through operating a proven small unmanned vehicle made in America. It had been used widely in the world, as we acquired knowhow on wireless technologies for drones, and we have been analyzing a variety of problems and studying the solutions. While we had been putting efforts into fixed-wing unmanned aircraft operations, many media companies paid attention, having interviews with us—five TV programs were broadcast from stations including NHK and TV Tokyo, and 11 articles were published in newspapers including general papers.

Furthermore, based on the abovementioned field experiences, we have developed technologies for beyond visual line-of-sight/beyond radio line-of-sight flight and technologies for sharing drone information, applicable to such beyond line-of sight-situations, where we targeted multi-rotor type drones as well.

On the other hand, for social contributions by using our technologies, we started joint studies with a research institute who aims to develop drone-based radioactivity monitoring systems usable in the vicinity of a nuclear power plant. In addition, we have started joint research and development projects with an electric power plant company who wants to apply our technologies to their power infrastructure inspection jobs in mountainous areas where it is difficult to have line-of-sight conditions, and moreover a venture company aiming for the expansion of their drone business.

Furthermore, jointly with research institutes and companies, we received a collective research contract (staring in 2017) order from the New Energy and Industrial Technology Development Organization (NEDO). So, we have already started activities for further advancing the technologies we described in this article and developing systems working with better performances in practical situations. We hope, through our activities mentioned so far, to secure our competitiveness in drone operation technologies which are expected to grow, and to contribute to society.

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