2-4 Development of Communication Technology for Search and Rescue Robots

HADA Yasushi and TAKIZAWA Osamu

Conventional wireless ad-hoc network has many restrictions such as low rate, low reliability, delay of transmission, and restriction on node positions. In order to solve these problems, we propose new concept network; wired-wireless hybrid ad-hoc network. Efficiency of the new concept network has been evaluated by simulation. We adopted the network to long-distance remote control of rescue robots. Field experiments using prototype system have been frequently performed, and we achieved long-distance (700m) remote control of rescue robots. Thereby, the long-distance search activities of danger area were attained.

Keywords
Robot, Wireless Ad-hoc Network, Rescue

1 Introduction

In large-scale disasters, a large number of people need to be rescued. In the event of a disaster, only members of the rescue team come to the rescue. However, prior to the rescue work, search and rescue robots can be put to effective use in determining the conditions of the disaster site that cannot be accessed by members of the rescue team due to confinement or contamination. Although there is a term for a so-called "rescue robot," such robots have never been put to practical use in securing the safety of disaster victims. Instead, the rescue has been conducted by members of the rescue team. A rescue robot is referred to as a search and rescue robot equipped with cameras and various sensors to determine the situation in the disaster area. Figure 1 shows the concept of a search and rescue robot.

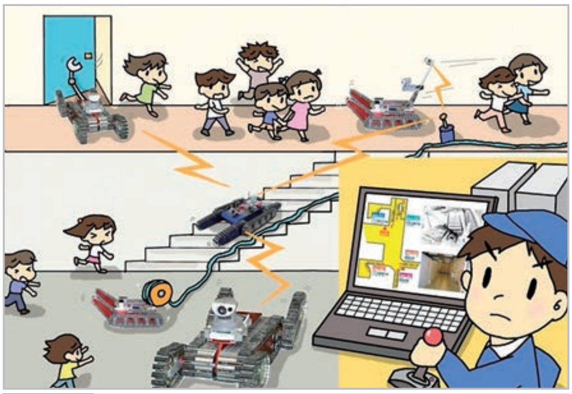

Fig.1 *Concept of a search and rescue robot*

NICT has been engaged in the research and development of information and communications technology for controlling search and rescue robots. NICT is a contributing research institution engaged in research under contract to two government agencies. The first is the Ministry of Education, Culture, Sports, Science and Technology and its Special Project for Earthquake disaster Mitigation in Urban Areas, namely, The Development of Advanced Robots and Information Systems for Disaster Response. NICT has been engaged in this research since FY2002. The second is the Ministry of Internal Affairs and Communications Strategic Information-Communication Research and Development Promotion Institution (SCOPE) and its Development of a Robotic System for Multimedia Investigation in Disaster Areas. NICT has been engaged in this research since FY2003.

In the light of this experience, the Disaster Management and Mitigation Group participated in a group researching the High-speed Search Robots for Confined Space (hereinafter referred to as the NEDO project) (Fig. 2). This project has been adopted as one of the research and development projects of NEDO's research under contract, namely, the Project for Strategic Development of Advanced Robotics Elemental Technologies/ RT system to travel within disaster-affected buildings (the Special Environment Robots). The group has participated in this project since FY2006 and has been engaged in the research and development of parts of the communication.

The NEDO project started, conducted by Professor Satoshi Tadokoro of Tohoku University as the representative researcher, together with eight accredited organizations as consignee institutions.

These institutions are: International Rescue System Institute (hereinafter referred to as IRS), Tohoku University, the National Institute of Advanced Industrial Science and Technology, NICT, Thinktube Inc., BL Autotec, Ltd., Bando Chemical Industries, Ltd., and Hyperweb Co., Ltd. as a consignee institution. Furthermore, robot researchers from other universities, such as Professor Eiji Koyanagi of Chiba Institute of Technology and Lecturer Sho-ichi Maeyama of Okayama University also took part in the project as IRS members. The NEDO project is under the auspices of the Ministry of Economy, Trade and Industry, which, from the outset, has been strongly aware of the practical applications and commercialization of the research. The Ministry has promoted the research and development with an emphasis on the stability and robustness of the development system. The Ministry has also strived for practical application by

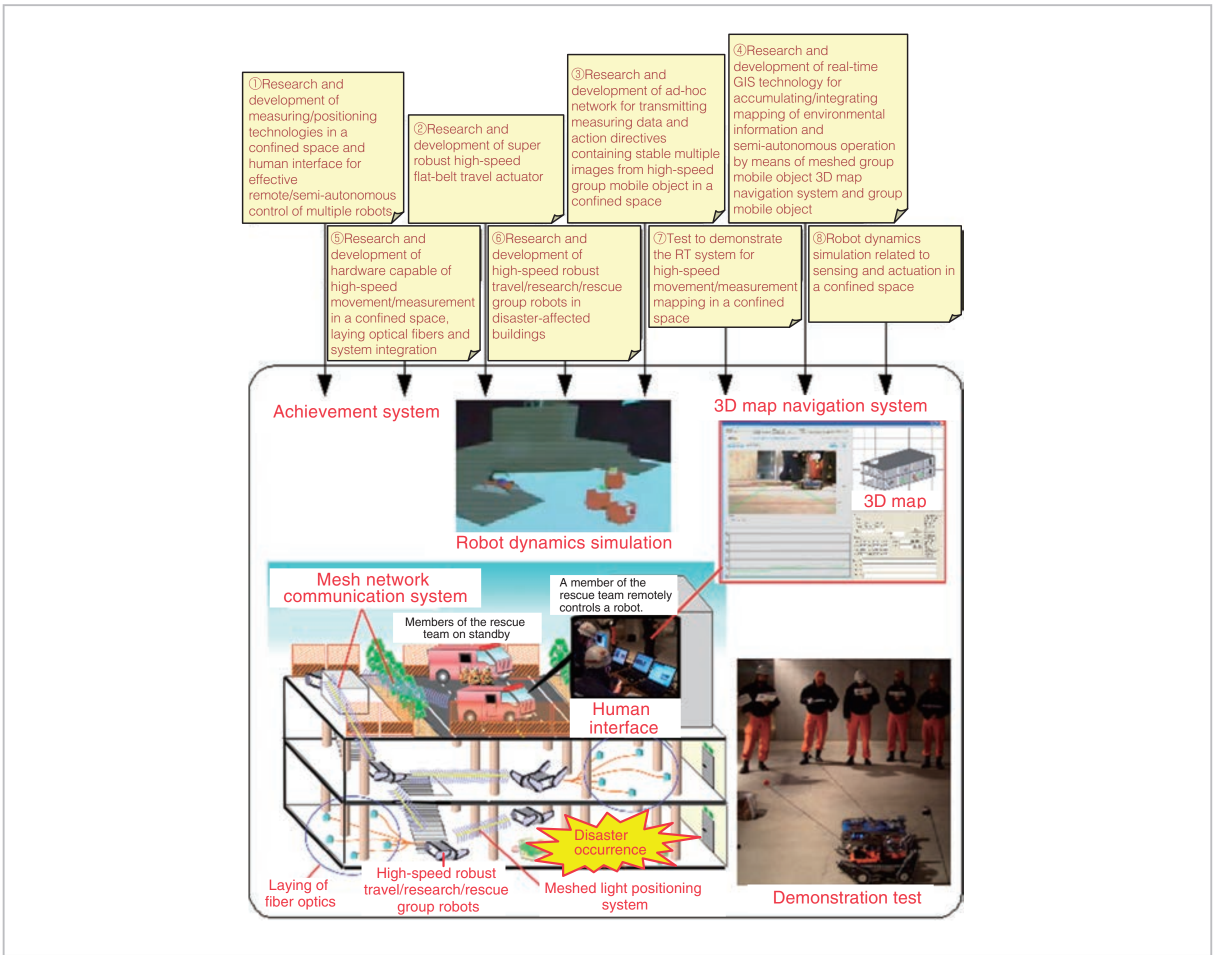

Fig.2 *Overall description of the NEDO project, the High-speed Search Robots for Confined Space*

forming a rescue team made up of volunteer fire fighters, rescue workers and ambulance attendants known as IRS-U (international rescue system unit). The Ministry has repeated evaluation of the development system and shown ingenuity in improving operability. For the progress of activities of the NEDO project, refer to **1** Introduction, Chapter **3**, of this special issue, which discusses—The Aim and Strategy of the Disaster Management and Mitigation Group—[1].

This paper describes the results of five years of research and development centred on the communication part, for which The Disaster Management and Mitigation Group is partially responsible in the NEDO project.

2 Target of the project

The target of the NEDO project is to develop communication technology for transmitting sensing information, including multiple remote control images, reliably and in real time to a control console. The console is to be located at least 700 meters from multiple search and rescue robots operating in disaster-affected buildings. This objective presents significant challenges in simultaneously satisfying a range of requirements. The robots operate in a difficult, confined environment and communicate over an extended distance of 700 meters. The objective also involves broadband communication of multiple real-time images. Accordingly, the NEDO project has identified the following technical problems and strives to create a communication system that resolves these problems:

- **Technical problem 1: Search area (distance) …** A wide area, including an underground mall of 700 meter should be covered.
- **Technical problem 2: Scale (extendibility) …** Ten or more robots distributed in the above-mentioned area should be able to operate simultaneously.
- **Technical problem 3: Reliability of communication service …** There should be minimal delay without communication disruption.
- **Technical problem 4: Fault tolerance of the system …** The system should have redundancy so that applications can continue to operate if a part of a system goes down.
- **Technical problem 5: Convenience …** The network should automatically be established simply by turning on the power.

3 Wired-wireless hybrid ad-hoc network

3.1 Problems of existing communication methods

Table 1 shows the results of comparing alternative communication methods for remotely operating a group of robots. The methods include wired communication, communication that uses the infrastructure and wireless communication. Wired communica-

Table 1 Comparison of communication methods for remote-control robots

	Baud rate	Communication distance	Communication delay	Equipment weight	Reliability at the time of disaster	Mobility	Flexibility	Redundancy
Wired LAN	◎	◎	◎	×	◎	×	×	×
Cell phone network (3G)	△	◎	×	○	×	◎	○	×
Wireless LAN	○	×	△	○	○	○	○	×
Wireless multihop communication	×	○	×	△	△	△	△	○
Wired-wireless hybrid network	○	◎	◎	△	○	○	○	◎

tion has physical constraints, such as the cable becoming twisted or caught on obstacles, the weight of the cable, and so forth. Communication that uses the infrastructure is also considered to be impractical due to the damage that the base station would sustain in the event of a disaster. Wireless communication using a regular wireless LAN and specified low power radio is subject to legal restrictions on electric power and can communicate a comparatively short distance of 50 to 100 meters due to attenuation. This attenuation is particularly strong in an underground mall.

At the same time, active research has been underway into wireless ad-hoc networks by relaying communications between terminals and robots. However, the following problems were encountered when applying the network to the remote control of a mobile robot group:

- **Reduction in the baud rate …** The transfer rate is decreased because communication of multiple terminals is performed according to time-sharing in the same communication area. Furthermore, since the communication capability is put under stress due to the presence of other relays, the number of terminals is limited to two to three (8 to 10 Mbps) even when using multiple wireless bands (Fig. 3, left).
- **Reduction in reliability …** Reliability is reduced by repeating the wireless relay operations.
- **Transportation of relay terminals …** The weight of the robots increases when conveying terminals, and thus mobility is reduced.
- **Influence of the batteries in relay terminals …** When the power for the relay terminals is turned off, the robots stop communicating.
- **Restrictions on the positional relationship …** Due to communication being relayed, a relationship of positional dependency occurs between the terminals and the robots (Fig. 3, right).

Although a general wireless ad-hoc network consists only of wireless communication, disaster-affected sites cannot be assumed to be completely flat. It is not easy to establish a stable wireless link in an environment where it is difficult to fit polarization planes, such as stairs, and where the influence of phasing interference is large due to the number of walls. Although a wired network is apparently superior to the wireless system in terms of transmission capacity and communication stability, a wired network is beset by the need to lay cables at the disaster site. However, once the cables have been laid, the wired network can communicate at several hundred Mbps. At present, the communication capability is merely several tens of Mbps even in a wireless LAN system, which has the largest transmission capacity of the generally utilizable wireless networks. It should be considered that neither wired communication nor wireless communication is superior in absolute terms. The superiority of either method depends on the circumstances at the disaster site and the time given for missions to be accomplished.

For these reasons, we propose a new meth-

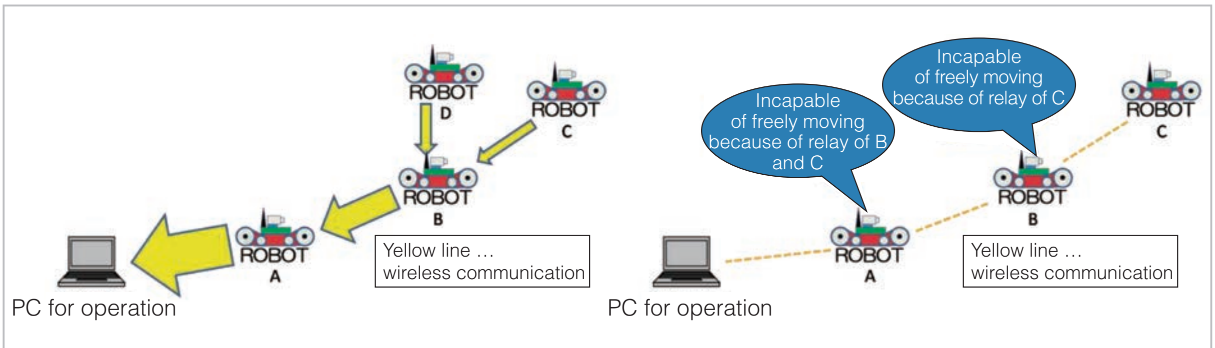

Fig.3 *Problems of wireless ad-hoc network (left: Increase in relay capacity, right: Restrictions on movement)*

od, namely the wired-wireless hybrid ad-hoc network shown at the bottom of Table 1. This method combines wired communication and wireless communication, with the appropriate communication method used in the appropriate place. Wired communication is used where it is easy to lay wires and placing the wireless ad-hoc network at the periphery of the area for wired communication[2][3].

3.2 The proposed method

The proposed method involves dividing the subject group of mobile robots into two types: Trailer Robot (TR) and Search Robot (SR).

The Trailer Robot is engaged in creating the infrastructure, and moves around the environment while laying cables (referred to as an ad-hoc cable) to connect the relay terminals (ad-hoc nodes) at certain intervals. The objective of this robot is to lay cables. It does not engage in in-depth search activities. The robot carries the ad-hoc cables internally and lays the cables by running them out in order while traveling. The robot is controlled via the wired LAN from the control console using the cables that it has laid.

The free search robot is a search-and-rescue robot that operates freely in the environment while engaging in ad-hoc wireless communication via the nodes on the cables. Communication between the free search robot and the operation PC is achieved by using the wireless ad-hoc network only for the part connected to the nearest ad-hoc network, and by using the high-speed wired LAN from the nodes to the operation PC. Consequently, the free search robot is not physically hindered by the cables and is able to communicate with fewer wireless hops. Furthermore, the free search robot itself has a wireless ad-hoc node function, and it is also possible to search places remote from the ad-hoc cables through wireless multi-hop communication for relaying multiple robots. It is possible to extend the search area on demand simultaneously and concurrently while conducting the search. Moreover, in the unlikely event that the robot moves to an area where wireless communication from the cable does not reach the robot and it is not possible to operate the robot, other free search robots relay the communication to re-establish communication with the robot (Fig. 4).

The proposed method is superior to the existing methods of communication as follows:

- **Reduced burden of communication traffic …** Wireless communications for each

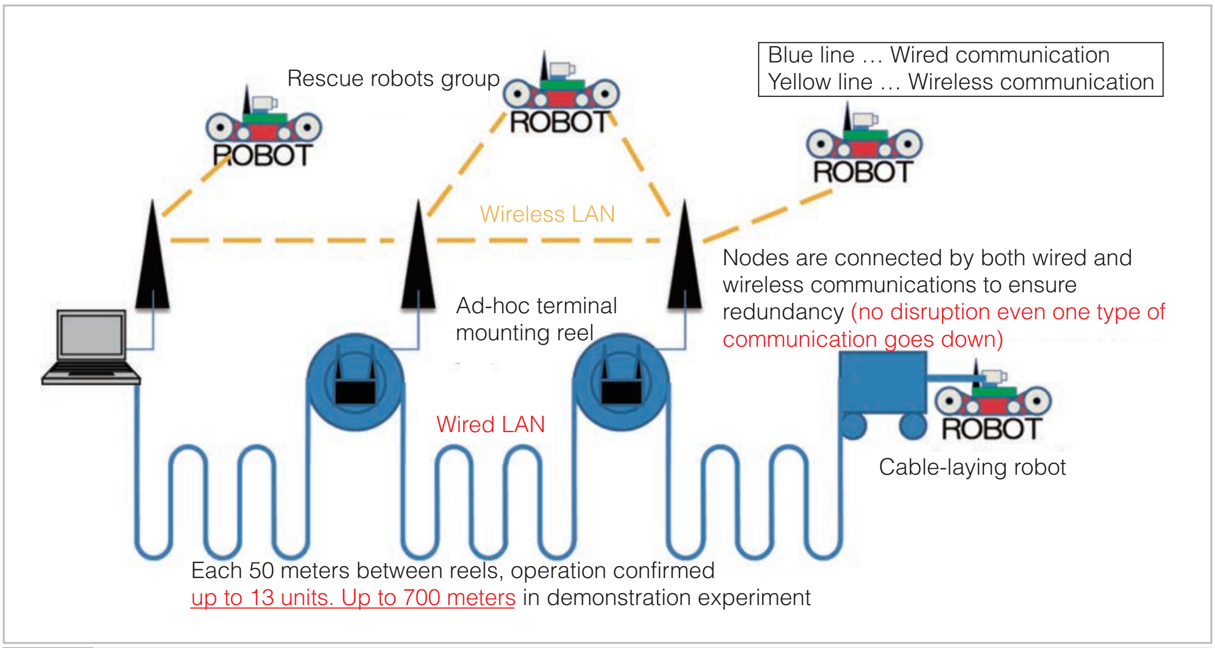

Fig.4 *Wired-wireless hybrid ad-hoc network*

free search robot is sufficient to the nearest ad-hoc node. Therefore, unlike the network that uses only the wireless LAN, it does not place a load on the wireless band.

- **Improved reliability …** It is possible to use wired communications having a large, high-speed capacity and superior reliability from the ad-hoc node to the control console.
- **Improved degree of freedom of action …** Fewer robots relay other robots' communication. Therefore, it is possible to engage in relatively free action.
- **High redundancy …** Since the ad-hoc nodes at both ends of the cables are also connected wirelessly, communication does not fail if the cables are disconnected on the way. Since this method also has the ad-hoc network function, it is possible to enhance redundancy by multi-hopping between the free Search Robots.

By using the basic wired network created by Trailer Robot as a communication backbone, and by using the free Search Robots with the wireless ad-hoc function at the periphery of the backbone, the system provides the features shown in Fig. 5, namely, the requirements of scale and extendibility, making it possible to flexibly extend the search area as the occasion demands.

In the wired-wireless hybrid ad-hoc network, there is a feature that enables other robots to act freely on the periphery of the cables laid by the Trailer Robot. However, there is a problem that the mechanism becomes complicated because it is necessary to place relay nodes at certain intervals along the cables.

3.3 Evaluation

Experiments to demonstrate the capabilities of the proposed system were conducted at the Sendai Subway Station in December, 2007, and at the Kobe/Sannomiya Underground Mall and elsewhere in June, August, September and November, 2008. Five robots were simultaneously remote-controlled, two of which were able to be controlled over a distance of 683 meters (Fig. 6). However, in this experiment, the operation of laying cables was carried out manually.

Communication failure during roaming is a serious problem for the person who controls the robot and the result may be loss of robot control. Therefore, comparative verification related to roaming performance was conducted at the Tachikawa training range of the Tokyo Fire Department on September in 2010.

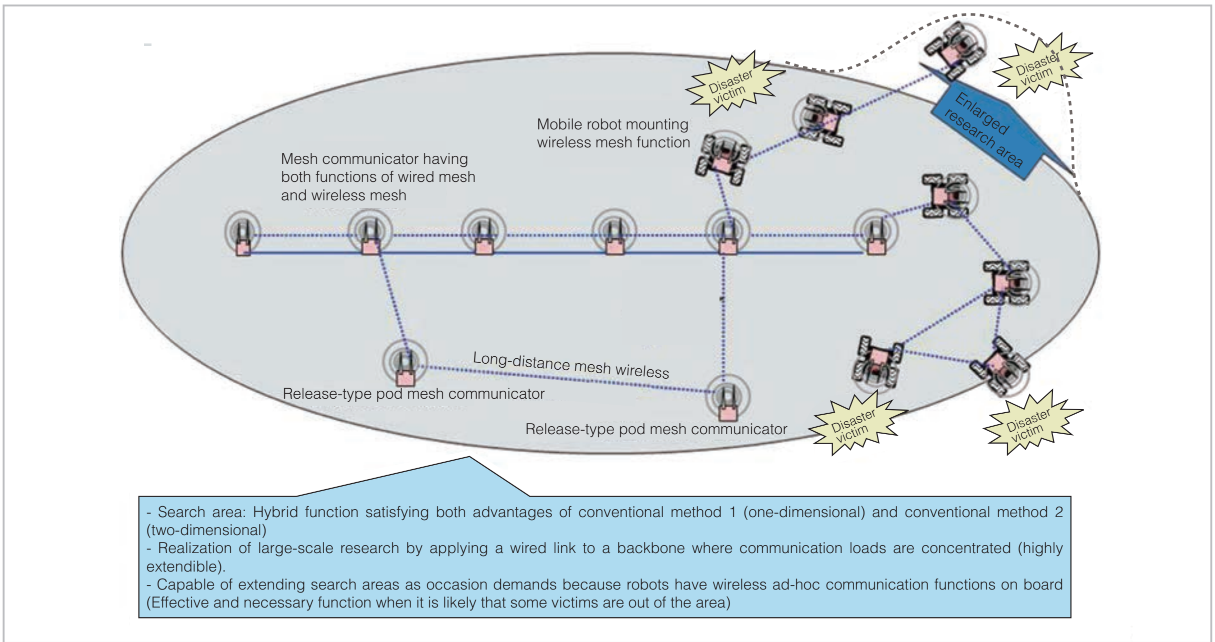

Fig.5 *Features of wired-wireless hybrid ad-hoc network*

The comparison was between the case where a general wireless LAN access point (hereinafter referred to as an AP) was used and the case where the system proposed here is used.

An experiment was conducted using the configuration shown in Fig. 7, in which general AP equipment (NEC Aterm) was connected by the wired LAN and a wireless LAN client machine mounted on a robot. Under this configuration, communication failed for several tens of seconds, and the robot stopped for an extended period as shown in Fig. 8. Performance depends greatly on the specification of the client equipment. Because the L2 bridge function was used, it took time for the route to be updated in the case associated with a topology change.

However, when ad-hoc communication equipment is used under the same configuration in Fig. 7, instead of the wireless LAN AP equipment and the wireless LAN client equipment, there was a communication delay slightly in excess of 500 ms during roaming, but communication failures rarely occurred, as shown in Fig. 9.

4 Network middleware

4.1 Summary

Ad-hoc middleware has achieved considerable success in large construction sites and outdoor spaces (Thinktube Inc., one of the agencies contributing to the NEDO project research, has engaged in R&D and expanded its business since 2001). We developed the following extendable functions and verified

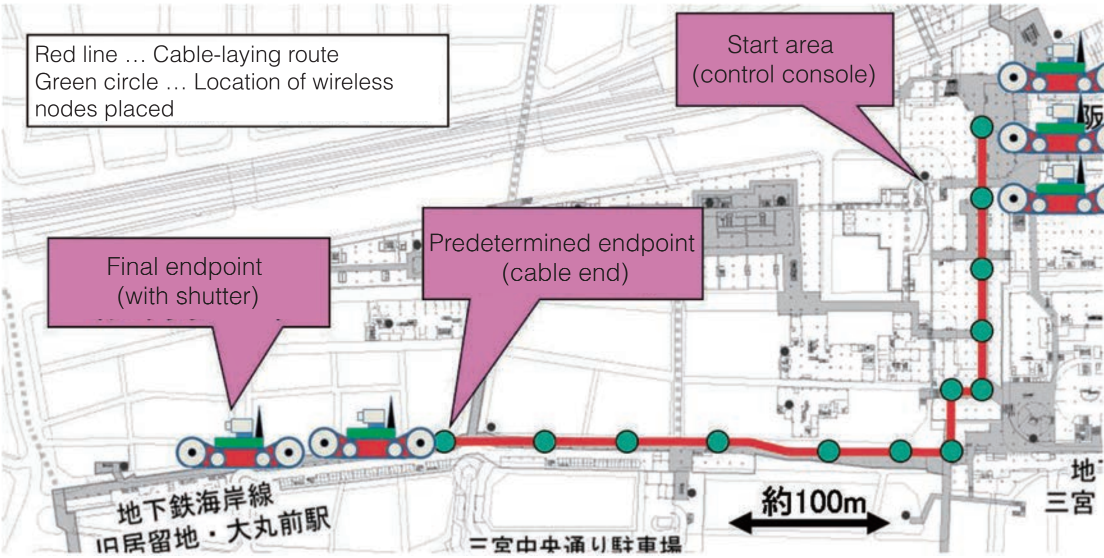

Fig.6 Result of long-distance search experiment using five robots in Sannomiya Underground Mall

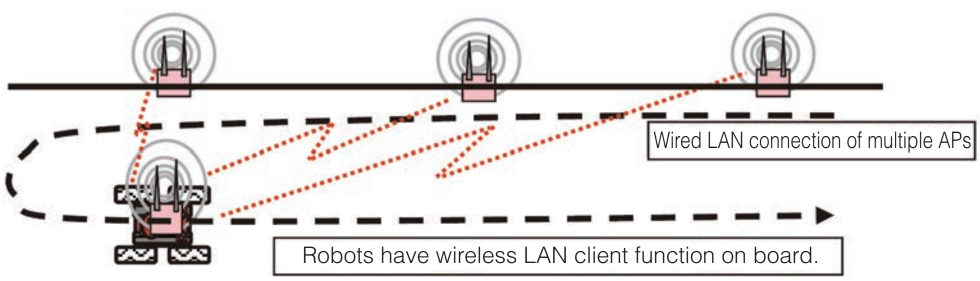

Fig.7 Configuration of roaming performance verification experiment

their performance in an effort to achieve multiple camera image transmissions on the wired-wireless hybrid ad-hoc network.

Technical problem 1: Improvement in image quality for control while the robots are moving

Technical problem 2: Effort related to reducing the image delay to support the person controlling the robot

Technical problem 3: Dealing with 5 GHz (increase in wireless transmission capacity)

4.2 Technical aspects

The middleware (MeshCruzer) is used for this research and development, which makes it possible to have a virtual single ad-hoc network, in which multiple wireless areas and wired areas are arbitrarily combined by handling the link of a wired LAN part as a highly reliable and virtual wireless link. To suppress the wireless radio interference and to maximize the gross transmission capacity of the network, a mechanism for preferentially adopting the wired link is implemented whenever there is a transmission route via a wireless link and a transmission route via a wired link. Based on this design, communication can continue almost seamlessly when the cables are broken by instantaneously searching for an interchangeable wireless link and changing to an alternative route within seconds. These functions have been confirmed in the experiment to demonstrate the functionality.

4.2.1 Technical problem 1: Improvement in image quality for control while the robots are moving

According to a report on image delay when switching over routes from a person controlling the robot (a firefighter) in an experiment conducted in November in 2008, a method for switching over routes for robots moving along a wired ad-hoc network was analyzed, considered, improved and developed. As a result, we confirmed the improvement shown in Fig. 10.

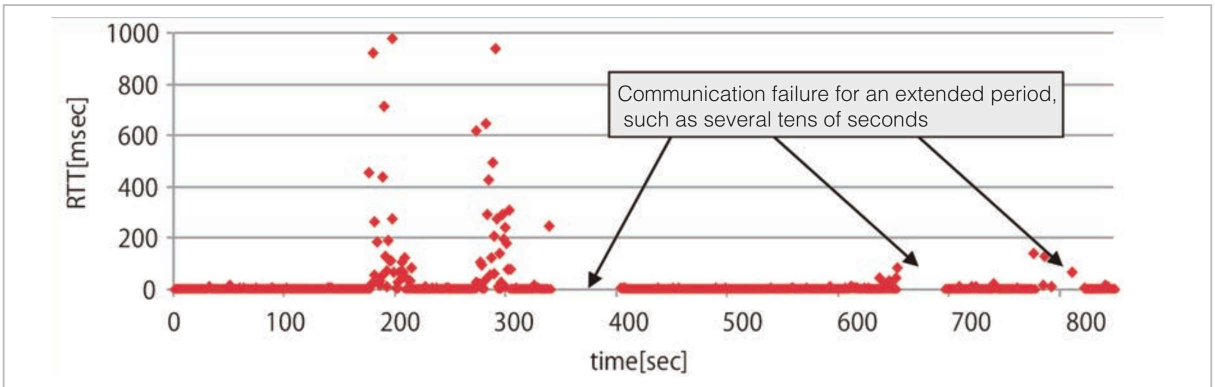

Fig.8 *Result of roaming performance verification when using general WLAN AP*

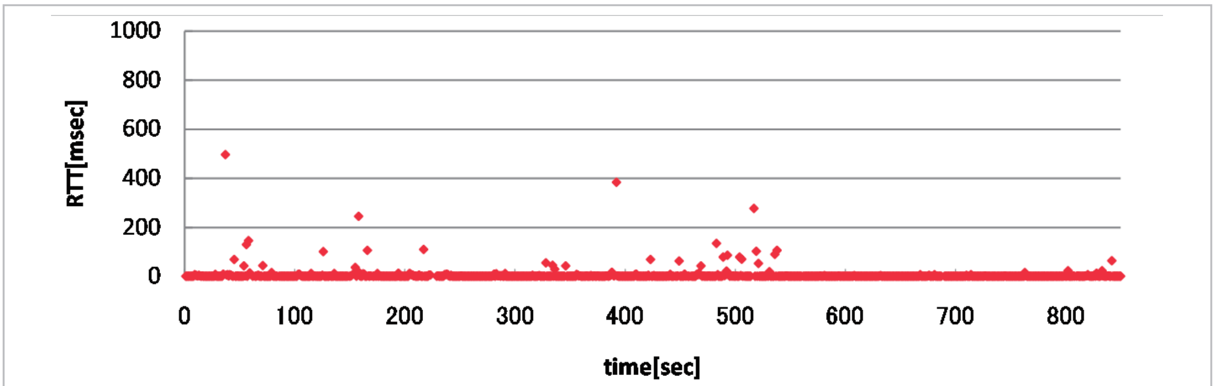

Fig.9 *Result of roaming performance verification when using wired-wireless hybrid ad-hoc network*

4.2.2 Technical problem 2: Effort related to reducing the image delay to support the person controlling the robot

Multiple cameras and sensors are mounted in the robot, and all data from these devices is transmitted in real time via the network to the person controlling the robot and/or the server. Since the communication conditions vary as the robot moves, the wireless link becomes unstable. Furthermore, since the transmission of large amount of data overloads the network when the robot is a long way from the relay nodes, phenomena such as delay, fluctuation and image stoppage occur.

To resolve this problem, we developed software known as UDP Agent to reduce the communication load and communication delay. It is intended that the above-mentioned problem can be resolved by converting the protocol of the camera images. This could only be used by TCP so far by means of a UDP agent mounted on the communication equipment. Therefore, we confirmed the improvement shown in Fig. 11.

4.2.3 Technical problem 3: Dealing with 5 GHz (increase in wireless transmission capacity)

The wireless LAN system can be used as a station that, under the radio transmission regulations, needs no license in the 2.4-GHz and 5-GHz bands. The 2.4-GHz wireless LAN is used in wide areas such as offices, retail premises and residences. According to a survey of

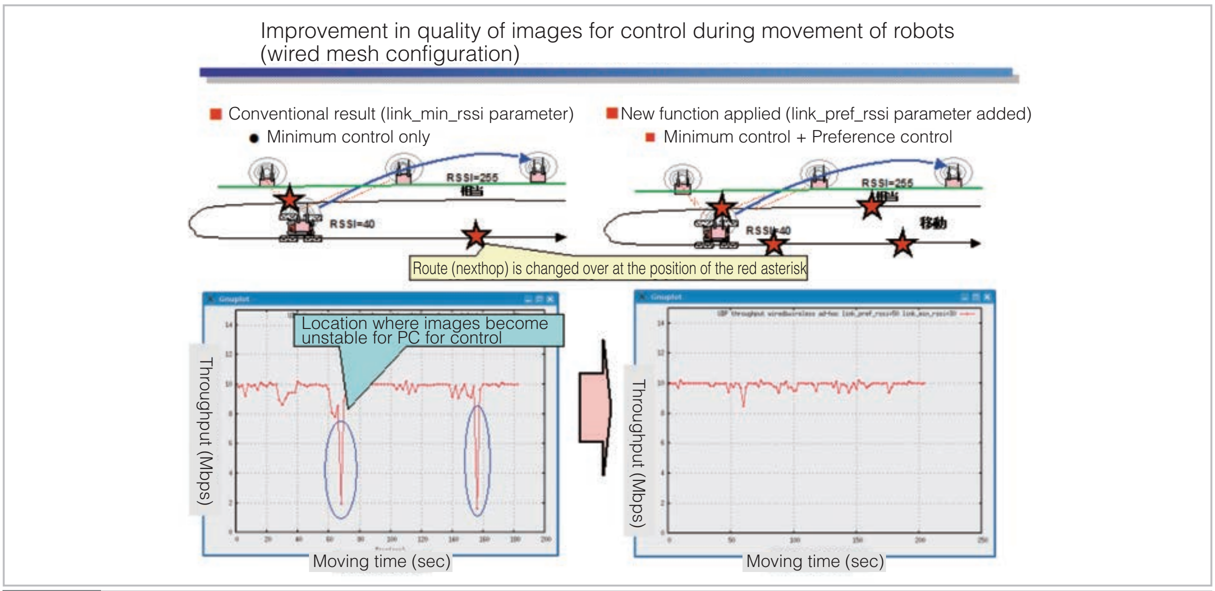

Fig.10 *Result of communication performance verification when changing over routes while the robots are moving*

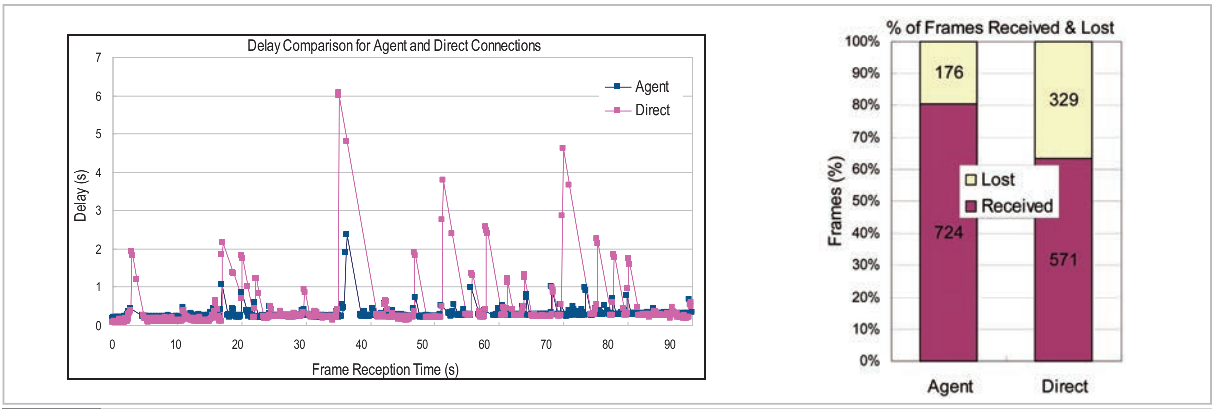

Fig.11 *Result of image delay reduction to support the person controlling the robot*

the circumstances of radio use in special places in commercial buildings, as shown in Fig. 12, several tens of devices were found to be using the 2.4-GHz band in channels 1 to 14, but few devices were found to use the 5-GHz band. Since many of the locations we encounter are considered similar to this example, it is considered that use of the 5-GHz band when searching an underground mall using robots is effective.

The 5-GHz band is divided into W52 (5150 to 5250 MHz), W53 (5250 to 5350 MHz), and W56 (5470 to 5725 MHz). In principle, W52 and W53 can be used only indoors, while W56 can be used indoors and outdoors from January 2007. Both W53 and W56 have a requirement to avoid interference with satellite radars by means of DFS (Dynamic Frequency Selection), which is an avoidance reaction when interference is detected. The NEDO project took countermeasures to prevent communication from being disrupted by using only W52 in the 5-GHz band.

4.3 Evaluation

Experiments to demonstrate the functionality of the wired-wireless hybrid ad-hoc network have been conducted repeatedly from FY2008 to November 2010, and we confirmed that the proposed system provides reliable communication. The last of these experiments was at the Tachikawa training range of the Tokyo Fire Department. The need for the relay nodes to be laid manually, rather than by the cable-laying robot, is a remaining problem.

We conducted an experiment that involved searching inside the floors of a large commercial building with a floor area of about one hundred square meters using robots controlled remotely only by the wireless network, without using the wired network. The robots were simplified robots for a communication performance test, and were equipped with two antennas, one 2.4 GHz and one 5 GHz. We confirmed the improvement shown in Fig. 13 for search areas.

As mentioned above, we believe that the three technical problems mentioned at the beginning of **4.1** are settled. The wired-wireless hybrid ad-hoc network is no longer at the experimental level, but in the early stages of the practical level. This network is also being used in areas other than the NEDO project.

In the case of the wireless ad-hoc network, we confirmed that the gross transmission capacity can be increased by combining the conventional 2.4-GHz band and the new 5-GHz band and that a throughput of about 18 Mbps can be obtained using a three-hop configuration (relayed twice).

5 Development of Trailer Robot

5.1 Summary

It is necessary to have a cable-laying robot in order to realize the wired-wireless hybrid ad-hoc network. Accordingly, we developed a robot system for laying the LAN cables and a wireless base station, as shown in Fig. 14.

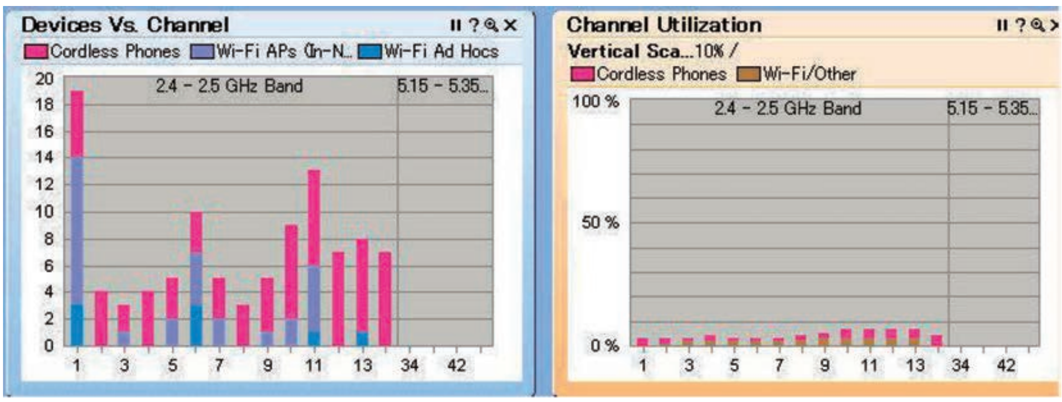

Fig.12 Comparison of result of investigation of status of use of 2.4 and 5 GHz in commercial buildings

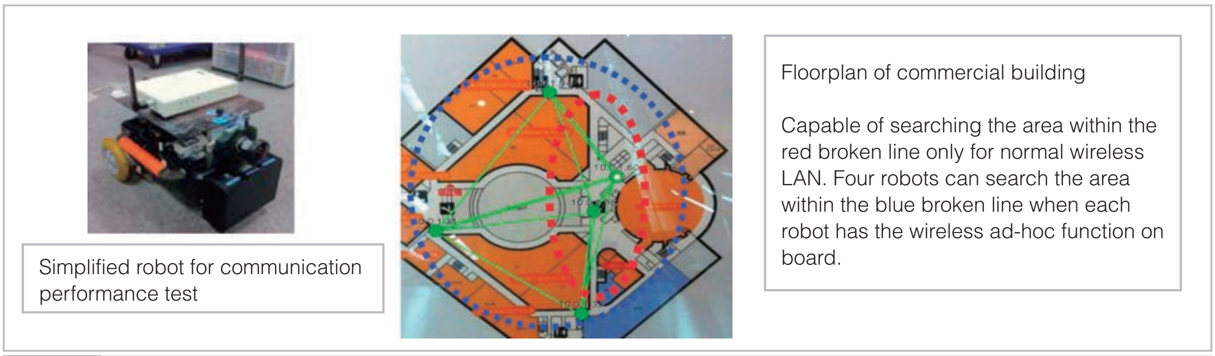

Fig. 13 *Four-robot remote control test by means of wireless ad-hoc communication in commercial buildings*

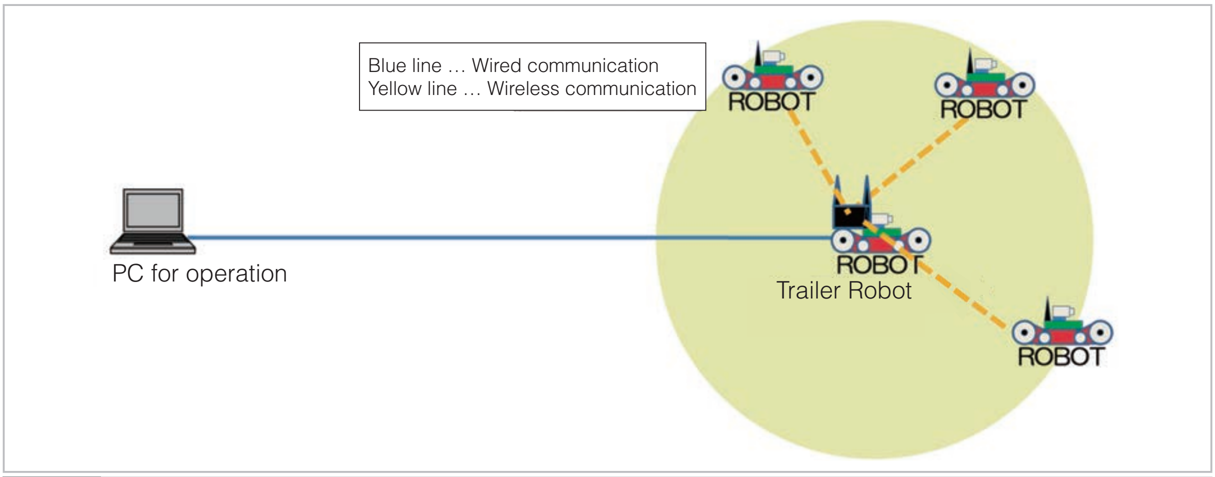

Fig. 14 *Robot system laying LAN cables and wireless base station*

5.2 Technical aspects and evaluation

We considered a method for mounting a cable unit on an automated guided vehicle with a robot and a method for delivery by means of a trailer as a means of laying the cable. It is necessary to prevent cables from twisting by synchronously turning both the cables extending up to 800 meters and a communication unit divided into 16 units. But it is difficult when using a slip ring method to send electrical signals through physical contact to obtain a communication quality of not much more than 10 Mbps. Furthermore, as shown in Fig. 15, it is also necessary to devise a method to prevent the cables from becoming entangled with the crawler by releasing the cables from the robot body.

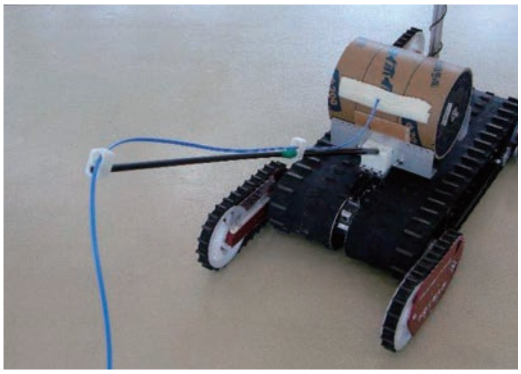

Fig. 15 *Device for preventing the cables from becoming entangled in the crawler*

Consequently, we developed an ad-hoc reel for the base station unit consisting of a flat cable 50 meters long, a power supply, and a router. Figure 16 shows the ad-hoc reel, Fig. 17 shows the trailer-type cable-laying system (Trailer Robot), and Fig. 18 shows the individual sequences for delivering the ad-hoc reel from the trailer-type cable-laying system before laying. The ad-hoc reel is described in detail in Chapter **6**.

The first cable-laying robot that we devel-

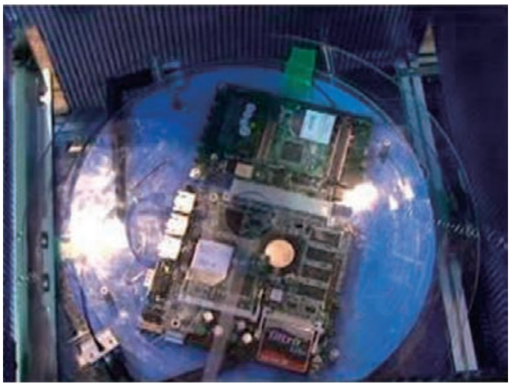

Fig.16 Ad-hoc reel (blue area is cable)

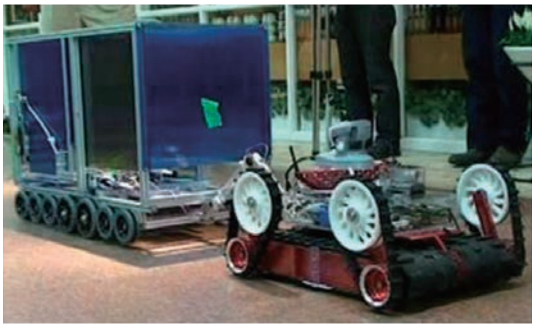

Fig.17 Cable-laying system using a trailer

Fig.18 Ad-hoc reel laying sequence

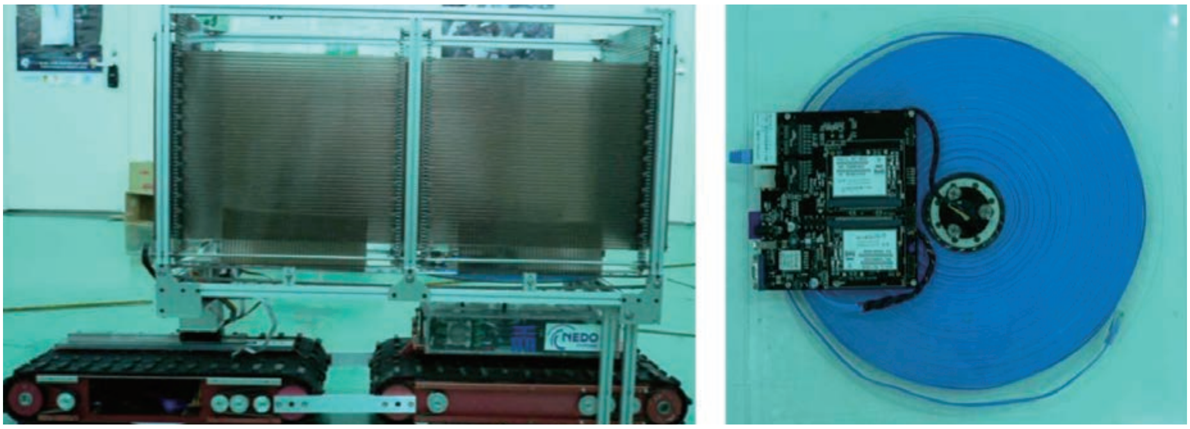

Fig.19 Left: External appearance of improved Trailer Robot, Right: Downsized ad-hoc reel

oped had the problem of being unable to traverse the stairs. We improved that point, and we improved the Trailer Robot and the ad-hoc reel, we reduced the size and weight, and enabled sensors such as a camera to be mounted. Figure 19 shows the improved system. In this way, we realized a cable turning/automatic delivery/cable drum exhausting mechanism.

6 Ad-hoc reel

6.1 Summary

The ad-hoc network is configured in an environment by being delivered by the Trailer Robot: We developed hardware and software for the ad-hoc terminals for connecting the PCs of each search and rescue robot and control console.

6.2 Technical aspects and evaluation

The ad-hoc reel is a relay terminal for realizing the wired-wireless hybrid ad-hoc network. Unlike existing wireless ad-hoc terminals, it has a feature whereby it performs wireless ad-hoc communication as well as wired ad-hoc communication by mutually connecting category 5e cables of 50-meter long provided in the terminals. The use of the wired network resolves conventional problems, such as the baud rate, delay and power supply (Fig. 20).

The ad-hoc reel comprises a Rokko mesh router, RMR7000, made by Thinktube Inc., a cable, and a drum for housing the cable. The RMR7000 has three wired LAN boards, two of which are used to connect cables to provide wired communication of 100 Mbps (theoretical rate). Furthermore, the RMR7000 has three wireless LAN (IEEE802.11/g) ports and can perform wireless communication of up to 162 Mbps (theoretical rate) through the use of multi-beam (Fig. 21).

This project completed cable-laying using the Trailer Robot described in Chapter **5** and an ad-hoc reel-dropping system. Future problems remain, such as experiments to demonstrate the functionality of the search and rescue robots, implementation of an upright antenna mechanism (or use of a low-head/flat antenna), implementation of a power supply mechanism into the reels using PoE and so forth, and a multi-beam setup.

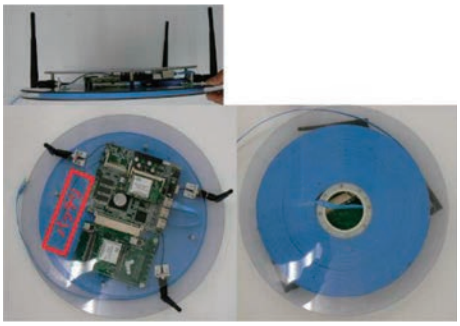

Fig.20 Ad-hoc reel

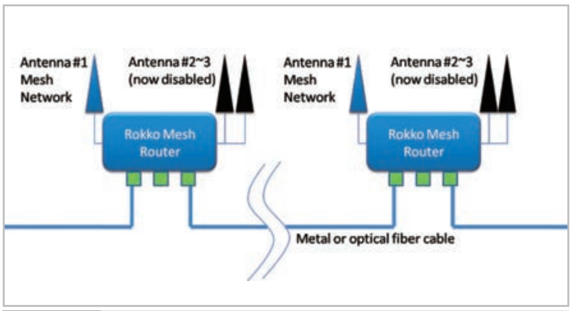

Fig.21 Configuration of ad-hoc reel

7 Ad-hoc communication system for the free search robot

7.1 Summary

Each robot has communication equipment for the wired-wireless hybrid ad-hoc network. However, wired and normal wireless communication can also be achieved by switching over between the two so as not to hinder individual research and training.

7.2 Technical aspects and track record

The internal controller of the research and development robot, the Kenaf, in the NEDO project is connected using a wired LAN hub. By connecting a Rokko mesh router, EMB503, made by Thinktube Inc., to this hub, the Kenaf can take part in the wired-wireless hybrid ad-hoc network as a single node of the ad-hoc network (Fig. 22).

In addition, during development and training, or when the wireless network cannot be utilized, the Kenaf can be operated by the following four methods. Each method can be switched over from the control console.

- **Use of a wired cable …** A method for connecting the operation PC and the Kenaf directly via a closed circuit.
- **Use of the 5-GHz band LAN (IEEE802.11a) …** A method for connection using a normal wireless LAN
- **Use of wireless ad-hoc network …** A method using the wireless ad-hoc communication of the Rokko mesh router
- **Use of wired-wireless hybrid ad-hoc**

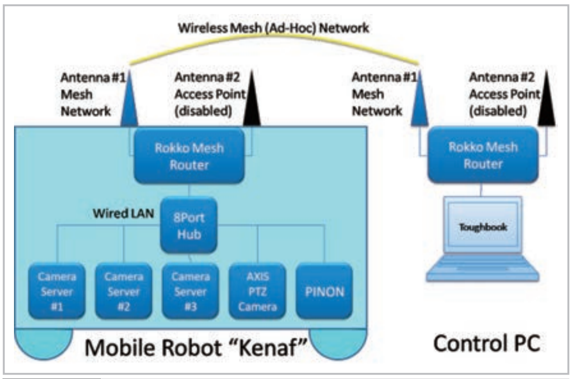

Fig.22 Communication configuration of robot and control console

network … A method using the wired and wireless networks together, described up to Chapter **6**

Furthermore, when using the wired-wireless hybrid ad-hoc network, the band used by the wireless LAN is determined to be 4 Mbps per robot. At this time, four web cameras (each with a resolution of 320 × 240 pixels and a frame rate of 15 fps) can be used with each robot. This band is sufficient for the purposes of conducting a search. In the wired-wireless hybrid ad-hoc network, these robots can be connected to up to four within the same wireless area and up to 17 within a different wireless area. In addition, the person controlling the robot can check the wireless band currently being used from the operation screen of each robot (Fig. 23).

Fig.23 *Network load monitor of control console*

8 Communication simulation with multiple robots

We verified the validity of the communication system through simulations conducted in parallel to robot development[4][5]. We conducted the simulations by measuring the image transmission rate of the wireless LAN while simultaneously representing the wired-wireless hybrid ad-hoc network on the network simulation software OPNET 11 and operating each robot in special patterns. The Trailer Robot (TR in Fig. 24) proceeds linearly along the environment to lay cables. In addition, the free search and rescue robots (SR in Fig. 24) proceed while simultaneously searching in random patterns, which are biased in the direction of travel. The number of the free search and rescue robots is 14 maximum.

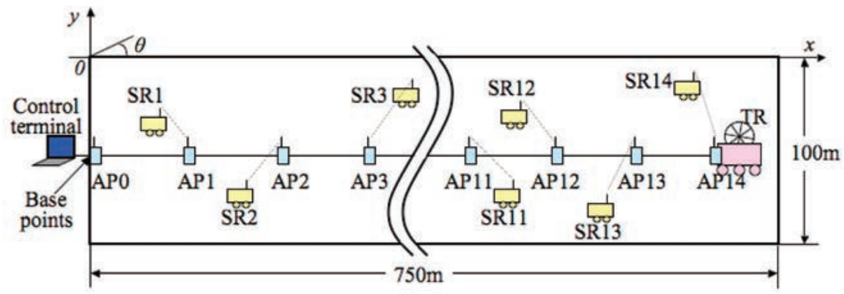

Fig.24 *Example of simulation environment*

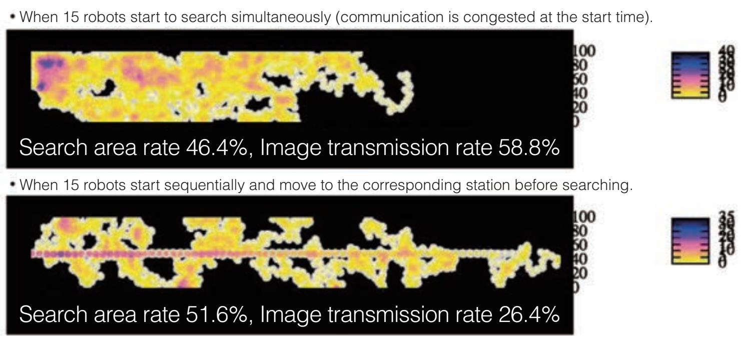

Fig.25 *Example of simulation results*

As an example, the result of simulation when 15 robots (one Trailer Robot plus 14 free search and rescue robots) are operated along a 750-meter linear route is shown in Fig. 25. In this simulation, when 15 robots start all together (upper diagram in Fig. 25), they search areas of 51.6% for 15 minutes, but the image transmission rate of 26.4% is unsatisfactory. On the other hand, when robots start one by one at regular time intervals (lower diagram in Fig. 25), it was found that the image transmission rate improves to 58.8%, although the search areas are rather small in the same period of time.

When several simulations were performed while simultaneously changing the parameters of communication and the robot action patterns, it was found that a maximum of eight robots can be utilized simultaneously when the robots start individually and a maximum of four can be used when the robots start to move simultaneously.

The result of this simulation is described in Reference [6] in detail.

9 VoIP system for phone calls between people affected by a disaster and members of the rescue team

9.1 Summary

We developed a system for phone calls between people affected by a disaster who have been found by the search and rescue robots, the people controlling the robots and members of the rescue team coming to someone's aid.

Although members of the rescue team currently communicate amongst themselves using exclusive wireless lines at the rescue scenes, they encounter the problem of phone calls breaking up when in a confined space, such as underground mall. Accordingly, our aim is to provide assistance to people affected by a disaster and members of the rescue team by means of VoIP (Voice over IP) communication. This means of communication has a clear tone quality even at extended distances by using the wired-wireless hybrid ad-hoc network placed by the Trailer Robot as infrastructure for phone calls (Fig. 26).

9.2 Technical aspects

The hardware requirements for VoIP are a server, multiple handsets and communication lines. The communication terminal turns to the server first to confirm the other terminal's position on the network, and then makes a phone call by means of P2P without using the server.

In this project, The Asterisk is used as a server and placed on the control console. Furthermore, the portable wireless IP phone, VP-71, made by Icom Inc. is used as a terminal. It is assumed that these are not operated on the ad-hoc network. Accordingly, one wireless LAN (IEEE 802.11b/g) line out of three possessed by the ad-hoc reels is operated in the master mode to provide a hot spot. Consequently, it becomes possible to join the wired-wireless hybrid ad-hoc network by bridging the ad-hoc reels even for terminals that do not have the ad-hoc communication function. In addition, since the flat subnet function is implemented on the ad-hoc reels, communication can be performed on the application layers with the same IP even when the position of the VoIP terminal is changed and the network composition is varied.

Consequently, the VoIP terminals can be

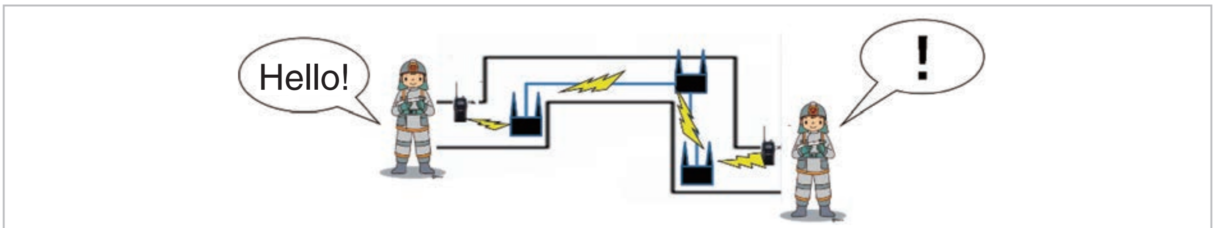

Fig.26 *Image of VoIP operating on the wired-wireless hybrid ad-hoc network*

operated on the wired-wireless hybrid ad-hoc network. Since traffic per line for a phone call is as much as 80 kbps, transmission on the wired-wireless hybrid ad-hoc network is sufficient.

9.3 Advanced communication material and equipment for the victim and the member of the rescue team in cooperation with the robot network

We developed a framework and physical equipment that allow the wired-wireless hybrid ad-hoc network to be utilized for robot operation as well as by members of the rescue team who enter disaster-affected buildings and victims of a disaster. We verified the effectiveness through experiments to demonstrate the functionality. As shown in Fig. 27, we confirmed that a camera-equipped IT helmet made by Tanizawa Seisakusho, Ltd., which is hooked up with the developed VoIP network, operates appropriately.

9.4 Network simulation

Assuming that, when putting a robot system into practical use, a number of robots are operated concurrently, we confirmed the effectiveness of the wired-wireless hybrid ad-hoc network by conducting a simulation. As a result, as shown in Fig. 28, we confirmed that the proposed method has a communication success rate of at least six times against the ad-hoc network with normal wireless only.

9.5 Problems and evaluation

Although the VoIP system successfully operates on the wired-wireless hybrid ad-hoc network, it is necessary to demonstrate the functionality through experiment and to verify the quality in a coexisting environment with robots and so forth. This system is operated irrespective of the robots. Therefore, this system is regarded as having a high level of practical utility as the system can be used even for normal rescue activities, without using robots, by incorporating the system into materials and

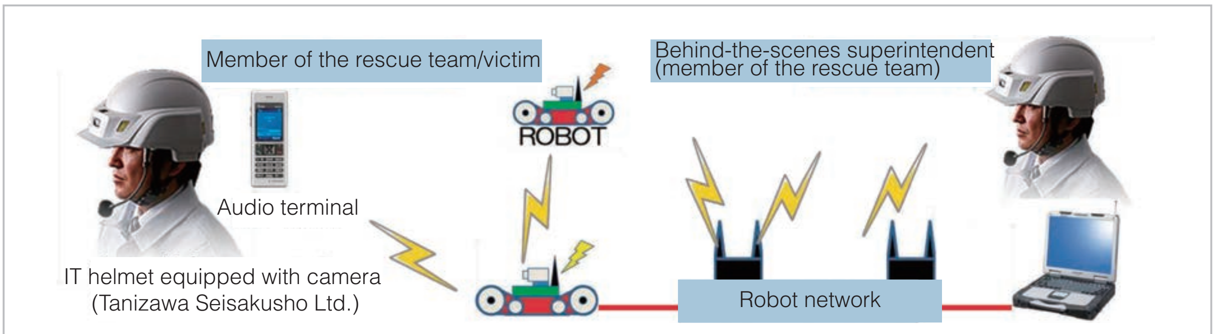

Fig.27 *Advanced communication material and equipment for victims and members of the rescue team in cooperation with the robot network*

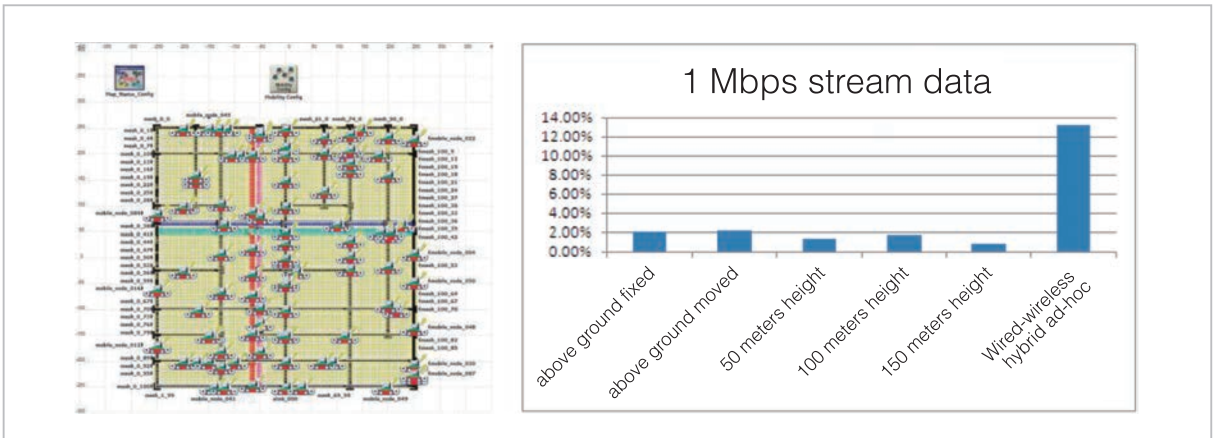

Fig.28 *Left: Simulator screen, Right: Simulation result*

equipment, such as the hoses and safety ropes used by the fire brigade.

10 Development of release-type pod communication system

10.1 Summary

Since the antenna power for the wireless LAN is limited to a maximum of 10 mW/MHz due to legal restrictions, the longitudinal coverage of the wireless link in an indoor environment is not much above 50 meters (in the case of a non-directional low-gain antenna). Therefore, in the case of the confined space extending to 700 meters, which is a target given to the NEDO project, 14 wireless relay nodes need to be placed. However, this is unrealistic in view of the stability of the connections. Accordingly, we developed equipment to provide a long-range wireless link that uses a directional antenna for the purpose of building wireless multihops, with the number of hops being four to six over 700 meters. This equipment complements the wired-wireless hybrid ad-hoc network system, such as in places where it is difficult to lay cables, or as a backup wireless link of the wired backbone part.

10.2 Technical aspects

A problem when using a high-gain directional antenna is the inability of previously determining the antenna bearing. This is because the position of the communication equipment and the location of the mobile robots cannot be decided in advance at disaster-affected sites. In order to resolve this problem, we developed a release-type pod communication machine with two directional flat patch antennas (gain: 8 dBi, size: 114 × 114 × 23 mm, half-power angle: about 60 degrees) installed on the top of a cylindrical enclosure (Fig. 29). We developed a hardware mechanism comprising a motor for driving the two antennas independently, a rotary encoder, a proximity sensor, a wireless ad-hoc router compatible with multiple interfaces, and a software mechanism. The software mechanism comprises built-in software to drive the antenna and a remote release-type pod antenna control program. In this way, it is possible to freely change the two flat antenna bearings according to the relative position of adjacent nodes based on instructions of the software. Its weight is 7.5 kg including the battery, and the dimensions are 540 mm high and 200 mm wide.

Fig.29 External appearance of the release-type pod communicator

We implemented two modes for the antenna bearing: an auto mode for autonomously deciding on the basis of the strength of the field intensity received from peripheral nodes measured by the release-type pod itself; and a manual mode for remotely controlling the unit from the control console using the aforementioned release-type pod communication machine operation panel (Fig.30). Based on the assumption that the mobile robot conveys and releases the pod communication machine, we tried to achieve a low center-of-gravity design to absorb the release impact while remaining upright.

10.3 Evaluation

In August 2007, we placed several release-type pod communication systems at intervals of about 100 meters in an underground mall and confirmed the basic functions. Subsequently, in September 2007, we verified the functions an in the outdoor environment near

IRS Kobe labo and obtained a performance of about −80 dBm (about 55 meters with the non-directional antenna) at a distance of about 200 meters. In December 2007, we gave a demonstration at the NEDO project progress meeting at Tohoku University and indicated that the antenna bearing tends to follow the destination of the mobile robot.

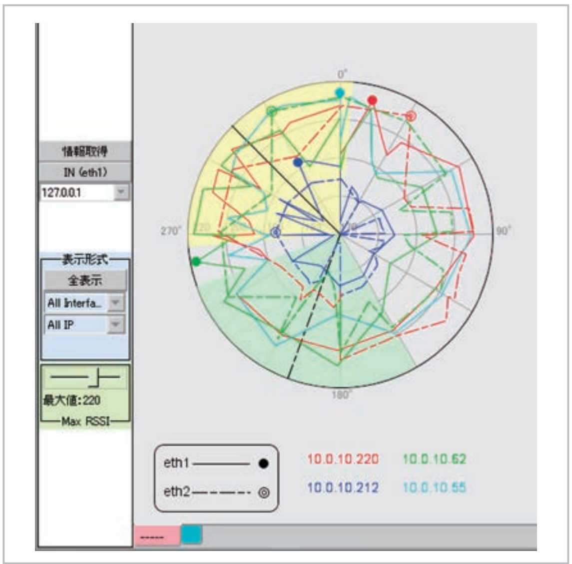

Fig.30 *Panel for operating the release-type pod communicator*

11 Directional variable antenna for mobile robot suitable to an environment with a difference in elevation, such as stairs

To resolve the problem of unstable communication with the existing antenna in an environment where there is a difference in elevation, such as stairs, we developed a new waterproof/dustproof antenna that is capable of electrically changing directivity. We then evaluated the basic properties, implemented them on a robot, and conducted experiments to demonstrate the functionality. Figure 31 shows a block diagram of the antenna, two kinds of vertical directivity, and the external appearance.

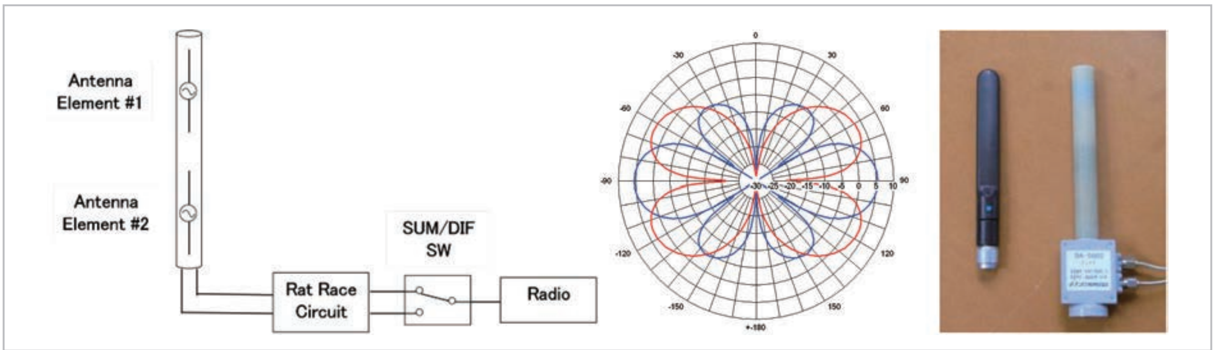

Fig.31 *Left: Block diagram of antenna, Middle: Two kinds of vertical directivity, Right: External appearance of developed antenna*

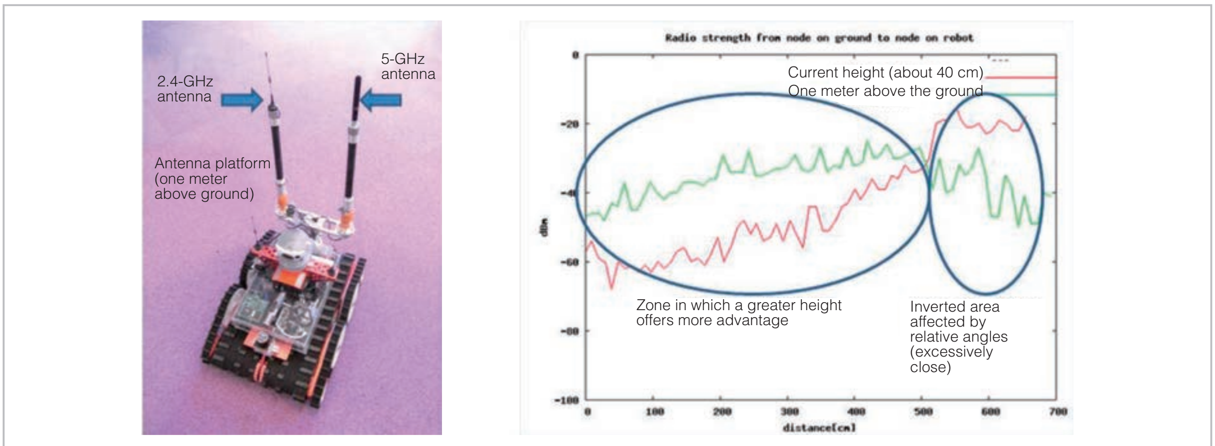

Fig.32 *Left: Prototype robot with waterproof/dustproof antenna platform installed, Right: Comparison of field intensity against variation of height*

12 Development of waterproof/ dustproof antenna platform

We found through simulation that having the antenna one meter above the ground significantly improves the communication gain. We made a prototype of an antenna platform that is capable of selectively raising the antenna and that also includes the waterproof/dustproof functions. We evaluated the functionality using the research and development robot, Kenaf, (Fig. 32), and implemented an improved antenna platform on Quince, the practical robot of the NEDO project (Fig. 33).

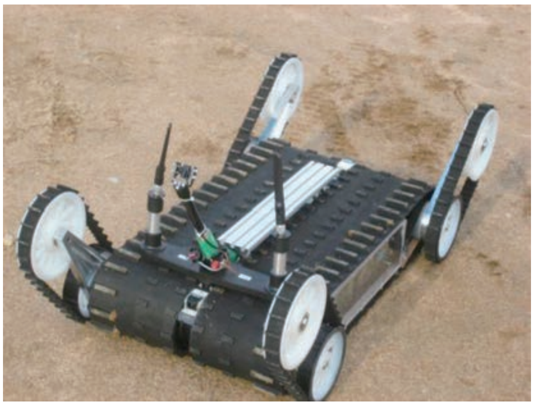

Fig.33 *Improved waterproof/dustproof antenna platform installed on the practical robot, Quince, of the NEDO project*

13 Development of autonomous return technique when wireless communication fails

13.1 Recovery of communication by means of autonomous movement of remote control robot out of communication area

To handle the problem that a robot unintentionally moves beyond its communication area and is unable to be manipulated, we developed a technique that enables the robot to perform autonomous movement on the basis of position history and previous field intensity, and return to the communication area. We conducted experiments to demonstrate functionality both indoors and outdoors. This system allows the person manipulating the robot to be engaged exclusively in manipulation, without worrying about a failure in communication (Fig. 34).

13.2 Redundancy of communication by securing multiple different wireless channels

We designed a system and developed a device driver to dynamically select available networks and maintain communication while ensuring that the robot and control console have a communication capability that enables them to use multiple communication channels. These channels are a wireless LAN using a normal 2.4-GHz access point, an ad-hoc net-

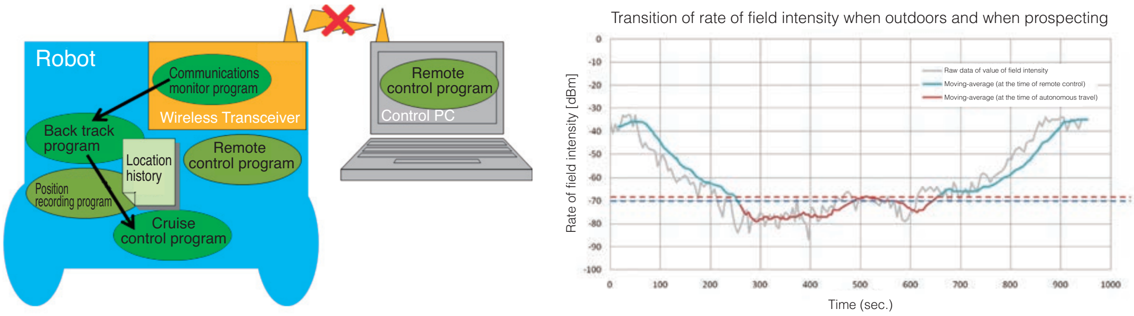

Fig.34 *Left: General description of communication coverage system, Right: field intensity coverage and control return by means of autonomous movement*

work using a 5-GHz wireless LAN, a third-generation cellular phone network, specified low power radio (SLPR), and so forth. We also designed the system to support wireless manipulation by means of an ad-hoc network using the 2.4-GHz band (Fig. 35).

14 Comprehensive evaluation

As described below, the communication system we developed satisfies the technical problems described in Chapter **2** and is regarded as being highly practical and having a high percentage of completion.

- **Technical problem 1: Search area (distance) …** We demonstrated utilization in an underground mall of 683 meters. We could also demonstrate utilization from the 1st floor to 10th floor through the use of the stairs in a ten-story building.
- **Technical problem 2: Scale (extendibility) …** We demonstrated six robots in an experiment and can theoretically use up to 15 robots simultaneously in the case of 4-Mbps throughput per robot. The wireless communication capability can be increased by making optimum use of multiple frequencies of 2.4 GHz and 5 GHz, described in Chapter **4**.
- **Technical problem 3: Stability of communication service …** We could confirm the stability and low delay performance via the verification implemented repeatedly through FY2009 and FY2010, including the abovementioned verification experiments.
- **Technical problem 4: Fault tolerance of the system …** We carried out hot-swapping of cables and verified that communication is not disrupted even when the cables are disconnected. We confirmed the presence of the backup function from the wired link to the wireless link.
- **Technical problem 5: Convenience …** The nodes on the cables and the communication equipment on the robots are operated simply by turning on the power. Special knowledge is not needed to use the system.

15 Conclusion

After five years, we have finished our research and development work for the NEDO project, and concluded with a public demonstration held at IRS Kobe lab (Kobe-city, Nagata-ward) on March 4, 2011. The accidents at the Fukushima Daiichi Nuclear Power Station that resulted from off the Pacific coast of Tohoku Earthquake that occurred on March 11, 2011, have highlighted the necessity of introducing Search Robots into disaster-affected sites that are inaccessible to humans due to radiation. The project members, including the authors, have been proceeding with the preparatory work for introducing a practical robot, Quince, developed under the NEDO project, into the Fukushima Daiichi Nuclear Power Station. This preparatory work is intended to continue beyond April 2011.

The NEDO project assumes that a robot can cover ground and engage in rescue at high-speed in a confined space containing rubble. However, The Great East Japan Earthquake created a disaster area containing radiation, seawater and high humidity, which were

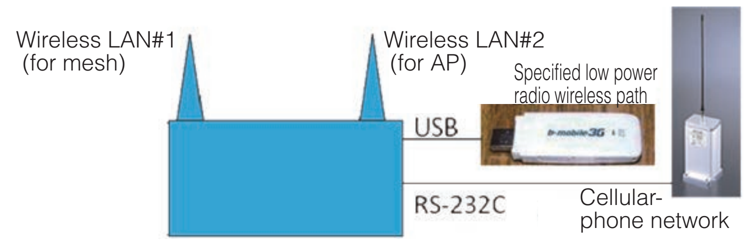

Fig.35 General description of communicator for integrally dealing with different/multiple wireless paths

not assumed at the time of development. We have quickly modified renovated the robots in accordance with the stringent environment recently presented by this disaster and hope that the outcome of our five years of research can help in the rehabilitation and reconstruction after this enormous disaster.

Acknowledgments

We would like to express our thanks for the kind cooperation of each person at IRS, commencing with the representative, Professor Satoshi Tadokoro of Tohoku University, when promoting the NEDO project, to Professor Eiji Koyanagi of the Chiba Institute of Technology for the development of the robot, to each person of Thinktube Inc. commencing with Takayuki Kaiso, and to Associate Professor Keiji Nagatani of Tohoku University for ad-hoc communication experiments.

References

1 Osamu Takizawa, "Introduction —The Aim and Strategy of the Disaster Management and Mitigation Group — ," Special issue of this NICT Journal, 1, 2011.
2 Hada et al., "Experiment of remote control of mobile robot using wireless communication on the premise of subway," Robomec2008, 2P2-A06, 5–7 June in 2008.
3 Hada et al., "Long-distance remote control of group of mobile robots using ad-hoc mesh network," 14th Robotics Simposia, 2009.
4 Koichi Gyoda et al., "Performance Analysis of the Network Model and Scenarios for the Search Robot Rescue System," SICE 2007, 3B16-4, pp. 2677 – 2681, Kagawa, 2007.
5 Koichi Gyoda et al., "Performance Analysis of the Network Models for the Search Robot Rescue System in the Closed Spaces," SSRR2007, 21S7, 27-29 September in 2007.
6 K. Gyoda et al., "Performance Evaluation of Wireless Ad Hoc Network for Disaster Communication," Special issue of this NICT Journal, 2-3, 2011.

(Accepted March 30, 2011)

***HADA Yasushi**, Ph.D.*[†1]

Expert Researcher, Disaster Management and Mitigation Group, Information Security Research Center (April 2007 – March 2011)

Robotics, Intelligent Systems, Ubiquitous Network

***TAKIZAWA Osamu**, Ph.D.*[†2]

Group Leader, Disaster Management and Mitigation Group (April 2006 – March 2011) / Group Leader, Security Fundamentals Group (May 2008 – March 2010), Information Security Research Center

Telecommunication for Disaster Management, Application Security

[†1] Currently, Associate Professor, Department of Mechanical Systems Engineering, Faculty of Engineering, Kogakuin University
[†2] Currently, Manager, Technology Transfer Promotion Office, Outcome Promotion Department