Outline of R&D of Satellite/Terrestrial Integrated Mobile Communication System

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NICT made a contract in research and development of satellite/terrestrial integrated mobile communication system from the Ministry of Internal Affairs and Communications in 2008. In this paper, we will introduce outline of this project, total system configuration and structural plan.

1 Introduction

“Research and Development of Satellite/Terrestrial Integrated Mobile Communication System” is a five year research and development project for which the Ministry of Internal Affairs and Communications solicited bids in 2008, as research and development funded by spectrum user fees. National Institute of Information and Communications Technology (NICT) received this contract. Aiming to use the convenience and advanced functions of mobile phones for disaster prevention, damage reduction, safety, etc., this project was to research on a new communication system integrating terrestrial systems and satellite systems.

Among the international satellite services at that time, Mobile Satellite Ventures LLC (currently LightSquared) etc. were developing the Skyterra satellite that was to be also used for providing terrestrial services, to complement satellite communications. It was meaningful for Japan to be engaged in this project. During this research, the Great East Japan Earthquake struck on March 11, 2011, an unprecedented disaster in Japan that left 18,400 dead and missing. It also greatly affected terrestrial mobile communication services, as the number of mobile phone base stations that stopped functioning peaked at 14,000, and their recovery took a long time: over a month. This made people look again at the importance of satellite mobile communications, which can communicate even if all mobile phone base stations collapse. After the earthquake, three major terrestrial mobile phone companies started satellite mobile services, and are greatly upgrading conventional services.

This “Research and Development of Satellite/Terrestrial Integrated Mobile Communication System” is for a more advanced system that integrates satellite and terrestrial systems, which are being reviewed for such earthquake disasters. In addition to earthquake countermeasures, this system shares satellite frequencies with terrestrial systems, and contributes to effective frequency use.

NICT manages this five year research and development, and hopes to serve as a bridge to future practical applications, etc.

2 Organization of this special report

This special report is organized as follows. Chapter **1** provides an overview and history of the research and development. Chapter **2** summarizes the research and development of “satellite/terrestrial coordination control technology”, which is called “Term A” during its research and development. Within this, **2-1** and **2-5** describe in detail the proposal for a frequency sharing method, and its evaluation. Also, in making the proposal for a frequency sharing method, it is essential to evaluate terrestrial system interference on satellite systems, and this was done with actual measurements. The experiments can be roughly grouped into three types and described separately. **2-2** summarizes results for transmission power evaluation of terrestrial mobile communications, mainly by driving an automobile on land and measuring reception power. **2-3** describes the results of using an airplane, to measure from above the interference waves of terrestrial mobile communications. **2-4** summarizes results of indoor/outdoor measurements, mainly measuring interference waves from a mobile phone placed inside and outside a building. **2-5** summarizes the results of these **2-2** to **2-4**, and evaluates the frequency sharing method.

Moreover, for research on layers above the network model’s physical layer, **2-6** describes the study of architecture and dynamic control algorithms for achieving terrestrial/satellite frequency sharing. Also, **2-7** summarizes the evaluation of satellite/terrestrial coordination control technology overall.

Also, Chapter **3** describes research and development on so-called “Term B”, which is “Technology for Interference Avoidance between Satellite and Terrestrial Systems and Frequency Allocation”. **3-1** describes the overall structure of a satellite communications system. **3-2** especially describes the antenna system design. **3-3** describes results of development of a high linearity low noise amplifier and high linearity solid state amplifier. For an antenna excitation distribution design algorithm, **3-4** describes a new algorithm focused on sidelobe suppression. Also for low sidelobe technology, **3-5** describes results obtained mainly from developed products. For super multibeam technology, **3-6** describes results of R&D on the “100 beams class”. **3-7** describes “resource allocation reconstruction technology” in this R&D, which is very important for industry when viewed as R&D on satellite digital technology, and finally describes this until the final satellite feasibility study.

Chapter **4** combines the research described in Chapters **2** and **3**, and describes results of an overall evaluation test done on this. Chapter **5** describes the results and current status of contributions to international standardization, as a by-product of this project’s research and development. Chapter **6** is a conclusion.

3 History of this research and development

In recent years, the social roles of mobile phones and other mobile communication services are increasing more and more. Especially with the convenience and advanced functions of mobile phones, their uses in disaster prevention and damage reduction etc. are also being studied. However, terrestrial communication systems are vulnerable to disasters, for example communications fail due to cut relay lines, base station and relay station transmissions stop due to power outages, communications are restricted due to congestion, etc[1]. There is also a need for countermeasures against dead zones users face in areas out of range, and for ships navigating near a coast, mountain climbers, etc. The Great East Japan Earthquake struck on March 11, 2011, demonstrating these vulnerabilities; the number of mobile phone base stations that stopped transmitting peaked at 14,000, and their repairs took over one month[2].

Achieving satellite communications on normally used mobile terminals could be especially effective as a countermeasure for these situations[1]. This system integrates terrestrial and satellite mobile communication systems, and provides services using dual-mode mobile terminals. Conventional satellite mobile communications (Widestar Duo[3], Iridium[4], etc.) can achieve wide service areas due to the wide area aspects that satellites have, but they have issues such as making terminals smaller and lighter weight, must use dedicated terminals, etc. Therefore, dedicated terminals for emergency satellite communications could require appropriate training and maintenance in normal times, and depending on the situation, they may be unusable during a disaster. So, by adding satellite communication functions to mobile terminals that residents normally use, they could normally connect to terrestrial mobile communications networks and use satellite circuits in terrestrial communication dead zones: mountain areas, coastal areas offshore, etc., and satellite circuits can be used during disasters.

Such research and development on networks designed for complementary integration of satellite and terrestrial communication systems is proceeding in various countries. Regarding integration of satellite and terrestrial mobile communication systems, in recent years in various foreign countries, frequency bands for Mobile Satellite Service (MSS) in the L-band (1.5 to 1.6 GHz band) or S-band (2 GHz band) are being shared with terrestrial services, and there are moves for regulatory changes and practical applications to achieve systems using geostationary satellites. In the U.S., the MSS/ATC systems using the Ancillary Terrestrial Component (ATC) technique[5], that mainly uses satellite mobile communications with complementary use of terrestrial, are now starting services or are being planned. And in Europe, a similar system is called Complementary Ground Component (CGC); for example, in terrestrial third generation mobile communications, Satellite Digital Multimedia Broadcasting (SDMB) services are starting[6].

In Japan, research and development is being done on “Satellite/Terrestrial Integrated mobile Communication System” (STICS), which communicate while sharing the same frequency band, to integrate terrestrial and satellite communication systems and effectively use frequencies[7]. This system integrates terrestrial and satellite mobile communications, and provides services to dual-mode terminals. For this purpose, in the Satellite Communications Subcommittee of the ICT Forum for Security and Safety (ICTFSS), studies are being done on use of satellite communications, and in fiscal 2008, the Ministry of Internal Affairs and Communications sought bidders for this as a research topic, and NICT received the contract for this

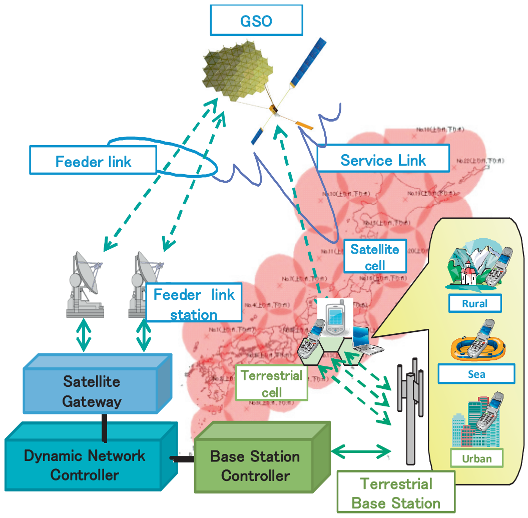

Fig. 1 Conceptual figure of STICS

research.

For the overall system, NICT is engaged in: evaluating interference amounts with sharing the same frequencies between terrestrial and satellite; studying dynamic resource allocation control methods; and evaluating frequency sharing methods through collection and analysis etc. of radio wave strength data of currently used mobile communication systems that serves as basic data for interference evaluation. For satellite hardware, NICT is also using digital technology to develop 100 beams class beam formation and a channelizer. For low sidelobe technology, NICT is studying sidelobe reduction technology of a 100 beams class phased array fed reflector antenna, developing power supply circuit technology including 100 elements class antenna elements, etc.

4 System considered

Figure 1 shows a usage diagram and features of a STICS. A STICS can be used in normal times as a countermeasure against the digital divide in mobile communication dead zones, such as in mountain areas and coastal offshore areas, etc. STICS can also be used as essential information and communications infrastructure during disasters, such as transmission of accurate disaster information to residents etc. and fast rescue activities, etc. Also, conventional terrestrial and satellite systems each have their own dedicated terminals, and they are allocated dedicated frequency bands; in contrast, in STICS, dual-mode terminals can connect to both terrestrial and satellite communication networks, and moreover, share the same frequency bands, and thereby achieve very efficient frequency use. For example, the frequency bands for an IMT-2000 Mobile Satellite Service (MSS) (in the S-band, up 1980–2010 MHz, down 2170–2200 MHz, for 30MHz each) were considered. In the overall system configuration shown in Fig. 1, dual-mode terminals such as mobile terminals and portable terminals have dual communication functions which enable them to connect to both terrestrial and satellite communication networks. The main service of these mobile terminals is voice communications via a mini satellite antenna, and the main service of portable terminals is data communications via a small satellite antenna. Terrestrial stations and base stations are each managed by control devices, with unified management via the core network, by terrestrial and satellite common control devices. This system can be summarized as follows.

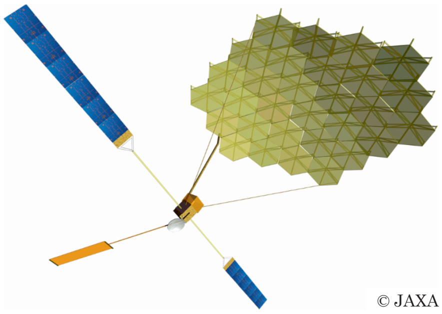

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Fig. 2 Satellite mounted large scale deployable antenna assumed for STICS

(1) Aim to effectively use frequencies by sharing with terrestrial systems the frequencies distributed to existing satellite communication systems.

(2) Aim to secure the communications infrastructure, even when terrestrial infrastructure is cut off during a disaster, by using a satellite system.

(3) Install a large 30 m diameter aperture class antenna on a satellite, and form a 100 beams class satellite beam, aiming to achieve dual-mode terminals that are about the same size and weight as terrestrial mobile phones.

(4) Allocate frequencies from terrestrial and satellite systems, and provide unified management of control information such as transmission power, and thereby aim to optimize interference avoidance.

Also, Chapter **3** describes the satellite system concepts, and various elements of the antenna installed on the satellite (Fig. 2) are assumed to be as follows. It has one offset parabola antenna for both transmission and reception, its diameter is about 30 m, and its feeding method is off-focal point feeding using a phased array feed. The assumed focal distance/aperture diameter ratio (F/D) is 0.6, and the number of elements and number of beams are both about 100. With this, the beam spot diameter is about 200 km. The service area targets Japan's territory and its exclusive maritime economic zone, and it is also flexible for nearby countries. While research and development was progressing, these values were decided in discussions by concerned people, especially members of the Satellite Communications Subcommittee in ICTFSS.

5 Research and development items and annual goals

The research topics are divided into two. "Research and Development of Satellite/Terrestrial Coordination Control Technology" that mainly studies satellite/terrestrial systems, and "Research and Development of Technology for Interference Avoidance between Satellite and Terrestrial Systems and Frequency Allocation" that mainly does satellite systems R&D needed for implementation. Within these, the latter is sub-classified into four items: high linearity amplifier technology, super multibeam technology, low sidelobe technology, and resource allocation reconstruction technology. The following subsections show the respective research topics in detail.

5.1 Satellite/terrestrial coordination control technology

For satellite/terrestrial coordination control technology, we mainly focus on study of the satellite/terrestrial system. Essentially, this system needs coordinated control the terrestrial system and satellite system which are different networks, so specific techniques for this are studied. We divided this research task into three research and development items: "A-1. Research and Development of Frequency Coordination Control Technology", "A-2. Research and Development of Dynamic Network Technology", "A-3. Overall Tests of Term A". Within these, it was decided to do A-1 and A-2 in a unified way. For these research items, the simulator type research and development is divided into the item for interference evaluation simulator and traffic monitoring management simulator, and the item for transmission power measurement of terrestrial mobile communication which creates interference waves; in the final fiscal year, these will be combined for overall tests.

First, we built an interference evaluation simulator that evaluates terrestrial/satellite interference. When terrestrial and satellite systems coexist, their interference always becomes a problem. In this research and development, when the frequencies of a multibeamed satellite beam are divided, the interference when the frequencies are shared with terrestrial is studied. The functions of the interference evaluation simulator of the terrestrial system and satellite system were extended, and evaluation was done to optimize effective use of resources such as time, frequencies and space. Within this, the number of stations accommodated in this system were approximated at 90 million stations[8], and we added functions to optimize the number of circuits during a disaster[9]. We also prototyped a monitoring management simulator that constantly monitors and manages terrestrial traffic (number of terrestrial users) and satellite traffic (number of satellite users); we are doing detailed interference evaluations[10], and evaluating interference in situations with traffic changed during disasters, etc. Also, as part of the integrated control techniques between terrestrial and satellite, we started studying dynamic control, and are constructing algorithms for basic functions of the management server that connects terrestrial with satellite[11]. As part of this, assuming a 3GPP terrestrial system, the satellite system can also be regarded as non-3 GPP[12]. Also, for means of circuit restrictions during congestion considered in these STICS systems, we proposed to set up in the satellite system's channels an important communications priority channel framework that is to be used only for important communication calls, so that channels outside that framework are shared by general calls and important communication calls, then we used simulation to show that the usage ratios of channels can be raised while maintaining important communications[13].

Also, for experiments to measure transmission output of terrestrial mobile communications, we developed experiment equipment to measure transmission output of terrestrial mobile communications with controlled transmission power, mounted it on an experiment automobile, drove it throughout Japan ranging from dense urban areas to low population density areas, took measurements while changing the places, times, etc., and thus accumulated data[14][15]. We also mounted the same equipment on an airplane, and in the airplane, by simultaneously receiving mobile communication uplink frequencies and mobile base station downlink frequencies, we directly measure the amount of interference in the direction of the satellite above. This test also measured from urban areas to suburbs like described above, and also over the sea, etc. As part of this, in all places, reception power in mobile communication uplink frequencies was found to be at least 20 dB lower than mobile base station downlink frequencies[16]. For base stations (downlink circuits), terrestrial communications antenna directivity was tilted downwards, and radiation towards the satellite was expected to be not very large, but we found that for the amount of interference on the satellite, the mobile communications uplink circuit has less. This shows that when we compare the amount of interference in normal mode vs. the amount of interference in reverse mode, reverse mode has more interference. We thus obtained guidelines for installation of this system.

Moreover, mobile terminals are not only used outdoors, and in evaluations of the amount of interference from terminals indoors, we did output measurement experiments in reinforced concrete buildings[17][18], and these help in interference amount evaluations[10].

Based on these, a denser interference model was used to evaluate the number of stations accommodated simultaneously by satellite/terrestrial circuits in STICS, and we confirmed that normally the satellite system side can always accommodate the maximum number of circuits, and the terrestrial system side can also accommodate on the order of 10 million stations[19]. Also for beam placement during a disaster, as one example, we confirmed that a similar number of circuits can be accommodated. Moreover, we combined the prototype evaluation results by fiscal 2011, and by constructing satellite/terrestrial overall network monitoring management equipment for overall tests, we worked towards a large scale system.

(i) We distributed functions among the overall monitoring management simulation equipment, satellite stations, satellite feeder link stations, and actual communication terminal devices, and did a simulation that is similar to real use.

(ii) We incorporated in the system an interface with a DBF channelizer that is a Term B development product, and confirmed actual dynamic control.

(iii) We enhanced simulation abilities, and in fiscal 2012, we made it possible to execute a large scale simulation with 80 times as many terminals as the previous fiscal year. This enabled simulation of conditions similar to the Great East Japan Earthquake. We used this to demonstrate more realistic coordinated control of a satellite/terrestrial integrated system.

(iv) We ran a simulation for an approximately 10 hour period after the Great East Japan Earthquake struck, and even with large scale terrestrial communication facilities damage, by applying certain call restrictions, it can be maintained by having priority terminals use satellite circuits. Thus the simulation confirmed effectiveness of satellite circuits.

5.2 Technology for interference avoidance between satellite and terrestrial systems and frequency allocation

This researches satellite system elemental technologies that are needed to achieve this system. This research was classified into 4 sub-topics: high linearity amplifier technology[20], super multibeam technology, low sidelobe technology, and resource allocation reconstruction technology. For high linearity amplifier technology, in low noise amplifier (LNA) of Satellite/Terrestrial Integrated Mobile Communication Systems, high level interference from the terrestrial system is assumed, so low noise figures while having linearity is desired. Therefore, we developed an LNA that works effectively even if the interference waves are 40 dB higher (or even a larger difference) than desired waves[21]. Also, to amplify multiple channels at the same time, advanced linearity and high efficiency operation are desirable in a solid state amplifier. Therefore, we developed a solid state power amplifier that has at least 60% power added efficiency, using a GaN device with IM3 of at least 16 dB.

Super multibeam technology forms many multibeams (even 100) on the satellite, and frequencies not used on the satellite can be allocated to terrestrial, for effective use of frequencies. First, we selected from among various types of antenna elements, made prototypes, and as the form with the best characteristics, we selected a close-coupling-fed patch antenna with parasitic-element and cavity[22]. For the high density antenna feed circuit, we prototyped the basic part of the duplexer feeding section, combining one radiating element, a diplexer for separating transmission and reception, and a high-power amplifier/high linearity low noise amplifier. Within this, we performed antenna array tests, etc. After that, based on these results, we constructed a 16 element small scale array, using parameters that consider various elements of STICS satellites.

Also, for low sidelobe technology, interference waves from terrestrial to satellite are received from the sidelobe that is near the main beam of the satellite beams, so there is the issue of reducing the sidelobe to reduce interference. But as a more difficult issue, it has become clear in recent years that in a satellite mounted large reflector antenna, there are changes over time in the orientation direction and sidelobe, and research on low sidelobe technology of satellite mounted antennas which can also help solve these issues has also become necessary at the same time. First, as part of the study of techniques to correct beam direction changes caused by changes in the satellite mounted antenna reflector and structure, we created an orientation change correction simulation software for beam direction changes[23]. This applied the rotating element electric field vector method (REV method)[24] via multiple terrestrial stations, and showed the effectiveness of estimating and correcting until a primary deformation of the orbit. For this technique, we ran an experiment using a large deployed antenna to show its effectiveness, and refined these software programs.

Resource allocation reconstruction technology is the name for channelizer technology that contributes to satellite mounted Digital Beam Forming (DBF) and effective frequency use. In recent years, there have been remarkable advances in terms of the integration density in digital technology, including in satellite mounted technology. Therefore, it is steadily becoming easier to configure low power consumption satellite mounted digital devices with advanced functions. In particular, reconfigurable satellite mounted digital devices that use Field Programmable Gate Arrays (FPGA) etc. have the benefits of ability to change satellite onboard functions[25]. Also, the digital bent pipe system has the benefit of being able to adopt various modulation schemes, so it was decided to use this in STICS.

For the DBF/channelizer, as part of the basic study we did, we prototyped basic circuits while considering the basic design of a processing method that integrates channelizing and DBF, then did individual evaluations and overall evaluation of AD/DA conversion, the quasi-synchronous detector, DBF, and the digital channelizer computing unit[26]. Moreover, we prototyped a channelizer/DBF device that is compatible with a feeding section that has 16 or more elements. We also prototyped a frequency conversion unit that connects the digital part and the feeding section. We ran tests, for example on beam formation and low sidelobe that use these small modules.

Moreover, for a larger scale experiment, we developed a channelizer/DBF device that handles very many beams[27], and for a test combined with the feeder section, we tested a 100 element equivalent array antenna, channelizer/DBF, and feeder section, implemented a 100 beam equivalent array antenna, channelizer/DBF, and feeder section, and demonstrated the feasibility the antenna system and effectiveness of the digital channelizer to achieve super multibeam and low sidelobe. Also, as a countermeasure for exhaust heat from digital equipment in the satellite, we proposed an exhaust heat technique that uses a heat pump with larger than conventional capacity, and we prototyped a heat structure model, then evaluated it by a vibration test and thermal vacuum test, and thus confirmed that a send and receive channelizer/DBF device that applies miniaturizing/weight reduction technology is structurally achievable. We also confirmed that by mounting this heat exhaust structure, for the estimated dimensions and mass of the reception DBF/digital channelizer considered for satellite mounting, we can reduce the dimensions (volume) by about 63%, and reduce mass by about 40%.

Moreover, we developed software for a reconfigurable channelizer/DBF to drive the digital channelizer/DBF equipment, and included these functions which are needed when mounting it on the satellite: reconfigure function, self-diagnostic function, and single event upset (SEU) countermeasures function, etc. We then confirmed its effectiveness, and utilized an overall test for Term B. We demonstrated that by developing this software further, it could be utilized in practical satellite mounted applications.

For satellite mounting, we extrapolated the prototype results and future technology development of SSPA which has a dominant influence, and of the channelizer/DBF, and calculated the required resources (mass, power consumption). From these results, for the condition of simultaneously accommodating 10,000 circuits, we obtained the expectation that it is feasible that a geostationary satellite that is 6 ton class at launch time could serve as a communications satellite to achieve this mission. In particular, we found that SSPA using GaN implemented as part of this research would contribute roughly a 10% to 20% increase in the number of circuits.

5.3 Overall evaluation test

As an overall evaluation test, we combined a Term A terrestrial/satellite overall network monitoring management device, with a channelizer/DBF device and feeding section etc. developed in Term B, plus a large deployable mirror module, and thereby developed an overall simulated evaluation device for doing large scale overall evaluations by an actual satellite configurations, to verify the low sidelobe technology and super multibeam technology. The goal was to do an overall evaluation test for both Term A and Term B.

We connected our Term A development product with our Term B development product, and developed an overall evaluation simulator to do overall evaluations, then used this as a Term C overall evaluation test. In the overall

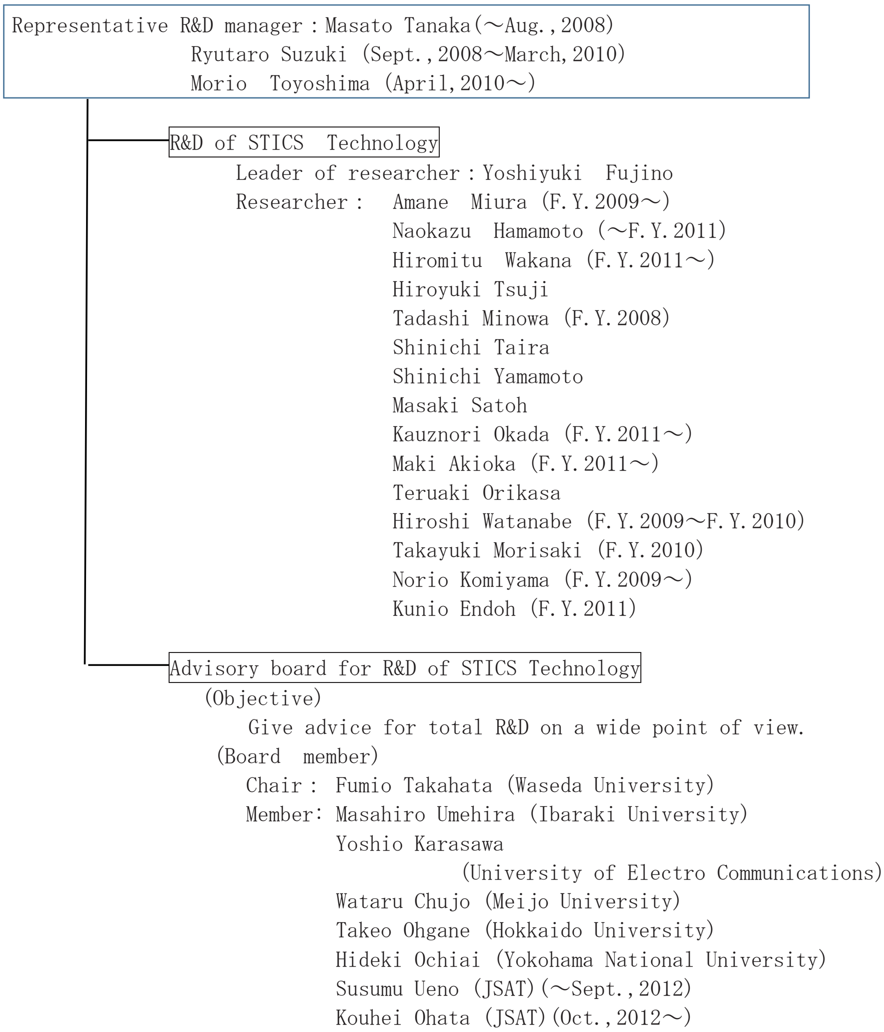

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Fig. 3 Figure of R&D organization

evaluation test, we simulated during normal times and during disasters, and by overall network monitoring management equipment based on dynamic network technology, we took as an example the traffic during the Great East Japan Earthquake, and regarding traffic concentration of disaster areas, showed that by dynamically allocating up to six times the normal resources (bandwidth) of the satellite, priority calls etc. could easily connect, and showed that the actual channelizer/DBF bandwidth could be dynamically changed[28]. We thereby showed that limited resources on the satellite could be utilized effectively during a disaster.

6 Implementing organization

Figure 3 shows the implementing organization. Basically, this research and development is done by NICT, under a contract from the Ministry of Internal Affairs and Communications. This work is done by the Space-info Network Group (currently the “Space Communication Systems Laboratory”) which is in charge of space communications related work in the New Generation Wireless Communications Research Center (currently the “Wireless Network Research Institute”) which is the wireless communications related section in NICT. To help the space communications lab work as a team to do the research, the Space Communication Systems Laboratory head was put in charge of this research.

Also, to receive suitable comments on research and development, we formed the Research and Development Operations Committee, and hold an operations committee several times a year to receive comments on the status of this research and development. These comments are reflected on our development policies. Moreover, the Satellite Communications Subcommittee of the ICT Forum for Security and Safety provided us with an opportunity to hear comments on this research and development from various standpoints: users, satellite development, businesses, etc.

7 Conclusion

In fiscal 2008, the Ministry of Internal Affairs and Communications provided a contract for research and development on Satellite/Terrestrial Integrated Mobile Communication System. This paper gives on overview of this, and describes the overall system configuration, project organization, etc.

This is research and development by long term external funding, for with no other examples are seen in the Space Communications Group. Therefore, we are very grateful for the generously provided resources such as staff, equipment, funds and time normally needed in research and development. It was especially important that we received excellent support in the human resources aspect, so we are somehow guiding this project towards successful completion. We are grateful for the support until now.

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