The Current and Future Trends of ICT
2023

Version 1.0

NICT

Contents

Outline of this report

Information Technology (IT) such as computers and software, along with Communication Technology (CT) represented by fiber optics and mobile phones has entered a phase of rapid spread and advancement since the late 20th century. Recently, ICT (Information and Communication Technology) has become a vital component supporting our society. At the same time, we are witnessing climate change, increasing demands for a sustainable economy and society, and societal changes such as aging populations, particularly in developed countries Undoubtedly, we face numerous challenges in our contemporary society. In this context, the ICT sector is expected to play a significant role in resolving various issues and creating social and economic infrastructures for the 21st-century.

This report aims to provide insight into the latest trends and future prospects of research and development (R&D) in the ICT field by examining the current trends. With this aim, the report is structured as follows:

In Chapter 1, we provide an overview of the global landscape surrounding the ICT field. With global pandemics and geopolitical changes, our social environment has dramatically transformed, with ICT playing a crucial role within it. This chapter focuses on the latest trends in ICT in North America, Europe, and Asia.

In Chapter 2, we discuss the latest developments in notable subfields within the ICT sector. First, in Section 2.1, we look at Beyond 5G, a fundamental cross-cutting technology expected to serve as the foundation for the future Society 5.0. In Section 2.2, we discuss R&D trends regarding the utilization of electromagnetic waves, an essential medium for realizing various information and communication technologies. Then, in Section 2.3, we discuss the core of the ICT infrastructure, or the communication network infrastructure. In Section 2.4, we discuss the latest trends in ICT devices required for it. In Section 2.5, we discuss the latest trends in the increasingly significant field of cybersecurity. In Section 2.6, we discuss the state-of-the-art R&D trends in quantum ICT, a promising new paradigm. In Section 2.7, we cover a recent major topic, or generative AI, including translation and dialogue technologies, from the perspective of universal communication. And in Section 2.8, we discuss the latest trends in brain science for ICT, which can lead one of the ultimate forms of communication, and Bio-ICT, a new fusion of life sciences and ICT. This report includes an appendix comprising a glossary, references, and other detailed information.

Chapter 1 Introduction

The field of Information and Communications Technology (ICT) is currently undergoing accelerated changes, fueled not only by the ongoing digitalization of traditional society but also by global-scale events such as the outbreak of infectious diseases, international conflicts, and fluctuations in related economic conditions. In this section, we will discuss the social context surrounding the ICT field with trends in various regions worldwide, citing several key examples.

1.1 Recent Global Conditions

1.1.1 COVID-19 and ICT

Since 2020, the outbreak of COVID-19 has significantly transformed people's lives. Global E-commerce market sales have exceeded 4 trillion USD (up 19.5% from the previous year in 2021), and the use of web conferencing systems for remote work and online learning, among other purposes, has rapidly increased, leading to a surge in internet traffic (Fig. 1.1-1).

Consequently, power consumption related to ICT has also been on an increasing trend. Projections suggest that if no technological innovations are implemented, by 2050 we could see over 4,000 times the consumption levels of 2016 (Fig. 1.1-2). In order for Japan to achieve its goal of carbon neutrality by 2050 which is the pledge by the government to the international community, Japan needs to improve its energy conservation in the ICT field through technological innovation (Green of ICT) and save energy consumption and improve operational efficiency through the active use of ICT (Green by ICT).

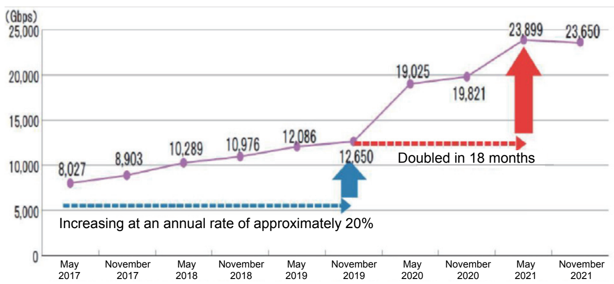


Fig. 1.1-1 Internet Traffic Trends [1]

IT power consumption (estimate)	2016	2030	2050
IP traffic (ZB/year)	4.7	170	20,200
Power consumption (domestic: TWh/year)	41	1,480	176,200
Power consumption (global: TWh/year)	1,170	42,300	5,030,000

Fig. 1.1-2 Predicted IT-related Power Consumption [2]

1.1.2 Changes in International Relations and ICT

In February 2022, Russia invaded Ukraine and the international political situation changed rapidly. Two days after invasion, Ukraine Deputy Prime Minister Fedorov requested support from Elon Musk, the founder of SpaceX via Twitter (currently X). Half a day later, satellite communication service by Starlink was launched in Ukraine. Many pieces of equipment were delivered to Ukraine, 150,000 people had used this service by May 2022. This event demonstrated the current state of ICT. It is rapidly developing as a social infrastructure as seen through swift responses on Twitter and next-generation communication networks expanding vertically to include airspace and outer space.

As tensions surrounding security in the international community increase, numerous attacks targeting government agencies and vital infrastructures are taking place around the world. In October 2021, 30 countries, including Japan and the United States, issued a joint statement declaring ransomware a global threat. In September 2022, at the Japan-Australia-India-U.S. (Quad) Foreign Ministers Meeting, a statement was issued regarding ransomware to strengthen their international cooperation against this global menace [3].

Significant transformations are also occurring in the field of AI. In November 2022, OpenAI released ChatGPT. Two months after release, the user base exceeded 100 million and it is rapidly expanding. Owing to the innovative advancements in machine learning technology, the chatbot has become impressively sophisticated for its ability to generate text, with expectations for fostering innovation across various fields. It has been observed that such recent advancements in AI technology are having a considerable geopolitical influence [4].

1.2 Conditions in Various Countries and Regions

In the societal context mentioned above, the ICT field is garnering unprecedented attention and expectations. In the following sections, we will discuss the latest trends surrounding the ICT field in North America, Europe, and Asia.

1.2.1 Conditions in North America

The United States has long been the global leader in scientific and technological innovation. However, the trend of federal government support for R&D since 2000 has sparked concerns about a decline in research capabilities, particularly in universities, and the consequent weakening of U.S. national power [5]. On the other hand, due to its rapid economic development, China has begun to catch up with or even surpass the United States in some fields in terms of scientific technology innovation indicators [6]. In response, discussions have intensified in the U.S., particularly during the Trump administration, about strengthening competitiveness and economic security through advancement of scientific technology innovation. Under the Biden administration, the demand for economic security has been increasing due to the COVID-19 pandemic and the invasion of Ukraine, and scientific technology innovation policy is regarded as an important issue.

The U.S. R&D ecosystem has evolved primarily through key entities such as higher education institutions, Federally Funded Research and Development Centers (FFRDCs), national research institutes, and private companies including big tech firms and start-ups. Across the nation, regional research hubs have been formed around universities and national research institutes, and the hubs have been fostering and exchanging highly skilled personnel able to serve for technological innovation and technology transfers.

The American Jobs Plan and a series of large-scale budget bills proposed by the Biden administration aim to boost regional innovation capabilities while prioritizing problem-solving through enhancing the capabilities of the national research institutes, which play a particularly crucial role in the regional R&D ecosystem, establishing new research centers, and providing direct support for the regional research hubs. These are referred to as once-in-a-generation investments aimed at gaining a lead over China, now America's only competitor [7].

In this context, ICT, including artificial intelligence (AI), quantum information science and technology (QIST), and 5G/6G, is gaining attention alongside green energy technology as an essential field. Furthermore, due to the expectations of these as dual-use technologies, defense-related agencies are actively supporting high-risk research and demonstrations [8]. In nurturing these emerging technologies, partnerships are being vigorously established not only between government and private sectors but also among allied countries under the leadership of the White House Office of Science and Technology Policy (OSTP) and the National Science Foundation (NSF).

Among these trends in the United States, the following recent developments should be of particular interest to Japan:

(a) Quantum ICT

While companies like IBM and Google are leading the development of quantum computing, in the United States, early blueprints for quantum networks have also been presented by the federal government. In locations across the country, including Chicago, New York, and Washington DC, test-bed construction is advancing around national research institutions and universities. These efforts have resulted in pioneering outcomes such as the world’s first commercialization of quantum memory by startups [9] and the construction of test beds in collaboration with regional telecommunications providers [10].

(b) Beyond 5G/6G

In 2020, the Next G Alliance, a private sector-led initiative to promote 6G, was established, and around 100 entities, including universities and national research institutions, are actively developing a roadmap. Also, in April 2021, the National Science Foundation (NSF) launched the RINGS (Resilient & Intelligent NextG Systems) R&D project. The NSF is providing up to 1 million dollars over three years for 42 selected research proposals in collaboration with 9 private companies. Concurrently, expert working groups from the Federal Communications Commission (FCC) [11] are discussing key technologies, candidate frequency bands, and use cases for 6G, and particularly it is interesting to regard 6G as one of the foundational systems for realizing the metaverse. In addition, 2022 saw partnerships announced between T-Mobile, Apple, and satellite communication operators, making it the inaugural year for Non-Terrestrial Networks (NTNs). It will be interesting to see how these trends go along well with 6G.

(c) AI

The unveiling of ChatGPT in November 2022 and the subsequent intensification of competition around AI among big tech firms have made it widely recognized that AI is rapidly evolving, while also pointing out its current technical limitations [12]. The Biden administration emphasizes addressing Ethical, Legal, and Social Issues (ELSI) in science and technology and published the “Blueprint for an AI Bill of Rights” in October 2022, advocating for both innovation through AI and the protection of civil rights. It is expected to reinforce such initiatives through collaboration with the EU and regulations such as the American Data Privacy and Protection Act (ADPPA).

As previously mentioned, as the importance of scientific technology innovation policy grows in the United States, cooperation in emerging technology fields will be surely enhanced between Japan and the U.S. and among Japan, the U.S., Australia, and India (QUAD). And, agreements for collaborations in the fields of quantum ICT and Beyond 5G/6G are made between industry consortiums to enhance their cooperation.

1.2.2 Conditions in Europe

In Europe, following the appointment of a new President of the European Commission in December 2019, the twin transition of green and digital has been positioned as a major policy of the European Union (EU). In "Shaping Europe's Digital Future," [13] (Appendix C-1-1) the EU emphasizes not only the development and deployment of cutting-edge digital capabilities and the advancement of 5G/6G, but also initiatives that take into account competition with the U.S. and China. These initiatives include data strategies, platform regulation, AI regulatory frameworks, and greening of ICT, marking the distinctive EU approach that covers regulatory measures.

With regard to research, development, implementation, and deployment in the ICT field in the EU, (1) various projects are being implemented through Horizon Europe [14], which funds research and innovation activities, (2) Digital Europe, which supports the implementation and deployment of digital fields such as AI and cybersecurity [15], and (3) Connecting Europe Facility, which supports the establishment of cross-border network infrastructure [16].

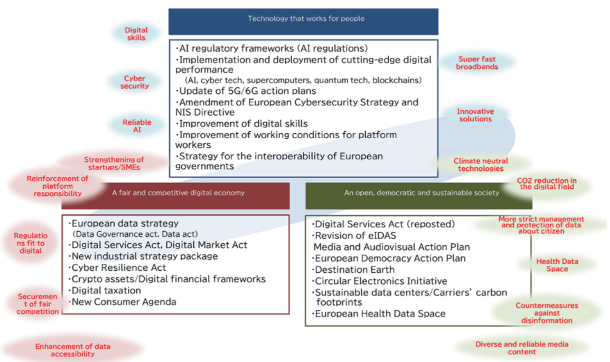


Fig. 1.2-1 Shaping Europe's Digital Future

Furthermore, geopolitical shifts have significantly transformed Europe's activities in the field of ICT. (Appendix C-1-2) In recent years, the EU has strongly promoted concepts such as technological sovereignty, digital sovereignty, and strategic autonomy [17], advancing policies and R&D in the ICT field that intertwine with security, including the construction of quantum communication infrastructure and satellite constellation projects. Various European countries, taking into account the EU's initiatives, are also actively pursuing initiatives in the ICT field.

Given these developments, we provide an overview of the trends in each field in Europe.

(1) Beyond 5G/6G (B5G/6G)

In Europe, Finland was the first in the world to start initiatives related to B5G/6G.[18] Subsequently, in January 2021, the EU launched the flagship project for B5G/6G, Hexa-X, and in November of the same year, it established a public-private partnership called Smart Networks and Services Joint Undertaking [17], which is implementing R&D projects by investing a total of 1.8 billion euros from both the public and private sectors over seven years (Appendix C-1-3). Among the European countries, the UK announced three R&D projects and the construction of experimental facilities in December 2022 [19], and Germany established four research hubs in August 2021 [20] and has been implementing individual R&D projects since the second quarter of 2022 [21]. The respective countries are actively conducting R&D, aiming at standardization from around 2025 (Appendix C-1-4). One of the main features of the R&D of B5G/6G is that it incorporates not only mobile-related technology but also technologies related to optical communication, photonics-electronics fusion, and NTN, considering energy efficiency, security, privacy, and the electromagnetic environment.

(2) Quantum ICT

In October 2018, the EU launched the Quantum Flagship project to invest 1 billion euros over 10 years [22] and advance R&D while also constructing testbeds through the OPENQKD project [23]. In June 2019, it announced the European Quantum Communication Infrastructure (Euro QCI) initiative to develop and deploy quantum communication infrastructure throughout Europe within 10 years [24], and currently, the construction of quantum communication infrastructure in each country is being advanced through individual projects centered on Digital Europe.

Among the European countries, France announced a national quantum strategy in February 2021 [25], and the UK also announced a new national quantum strategy to invest 25 billion pounds over the next 10 years in March 2023 [26].

(3) Cybersecurity, Network Security

Regarding cybersecurity, in December 2020, the EU announced the Cybersecurity Strategy for the Digital Decade, and the Amended Directive on Security of Network and Information Systems (NIS2) to expand risk management and incident reporting obligations [27). Also, in September 2022, the European Commission proposed the Cyber Resilience Act, which imposes mandatory requirements related to cybersecurity on all hardware and software products with digital elements, and it requires a CE marking. For R&D and implementation and deployment projects are being carried out in for Horizon Europe and Digital Europe, and Privacy Enhancing Technologies (PETs) and technologies that utilize encrypted data are being researched in light of the implementation of the General Data Protection Regulation (GDPR).

Regarding network security, the EU adopted the 5G Network Cybersecurity Toolbox in January 2020 and is promoting initiatives in each country to restrict high-risk vendors [28)]. In the UK, the Telecommunications (Security) Act was enacted in November 2021, and a legal notice prohibiting the use of Huawei in 5G was issued in October 2022 [29)].

Various European countries, including the UK in December 2021 [30)], France in February of the same year [31)], and Germany in September of the same year [32)], announced new cybersecurity strategies, strengthening their initiatives.

(4) AI

In the EU, in addition to R&D, there is a particular focus on ethical issues related to AI. In April 2021 [33)34)], the EU proposed the AI Act, which is the first-ever legal framework for AI systems. It also proposed an AI Liability Directive, which sets unified rules for civil liability for damage caused by AI systems [35)].

For R&D and implementation and deployment, numerous projects are being carried out under the frameworks of Horizon Europe and Digital Europe, and public-private partnerships have also been established.

Among the European countries, the UK announced a national AI strategy in September 2021, France announced the second phase of the national AI strategy in November of the same year, and Germany announced a revision of the national AI strategy in December 2020, indicating that national strategies are being rolled out (Appendix C-1-5).

(5) Data Strategy and Personal Data & Privacy Protection

In Europe, in addition to the enforcement of the GDPR in 2018, various policies related to data sharing and utilization have been announced with a focus on competing with platform operators in the US and China.

In February 2020, the European Commission announced the European Data Strategy [36)], and subsequently proposed the Digital Market Act [37)] to promote fair competition in the digital market; the Digital Services Act [38)] to protect consumers from illegal products, services, and content online; and the Data Act [39)] to promote data sharing of private industrial data. Thus, in Europe, rules regarding data handling are being formed one after another, and private companies are required to operate with awareness of these rules.

Also, regarding the promotion of data sharing and utilization within the EU, Germany announced the federal European cloud/data infrastructure concept Gaia-X in October 2019 [40)]. And, Germany holds up the European Data Strategy to make Data Spaces, which is designed to promote data sharing in strategic sectors, and it is advancing Data Space construction projects in each sector in line with Digital Europe.

(6) Green ICT

Another characteristic of Europe is that both the public and private sectors are actively promoting green ICT initiatives. The 26 EU member states and others have signed a declaration to accelerate the use of green digital technologies for the environmental benefits (Appendix C-1-6), and in the private sector, 26 CEOs have launched the European Green Digital Coalition [41)], pledging climate neutrality by 2040.

For R&D and implementation and deployment, R&D projects are being implemented in each country [42)], and sustainability-focused projects are being publicly solicited and implemented in each field such as B5G/6G.

In addition, as part of the green ICT initiatives, the EU has implemented legislative amendments regarding the unification of charging plugs on electronic devices to USB-C [43)].

(7) Main Initiatives for European Technological Sovereignty, Digital Sovereignty, and Strategic Autonomy

In the space sector, the EU announced the construction plan for the satellite constellation IRIS^2 [44)], which aims to provide secure, high-speed connectivity across Europe, including with quantum communications, to ensure

Europe's autonomy and digital sovereignty.

In the semiconductor sector, the European Commission has proposed the European Chips Act with the aim of strengthening the semiconductor supply chain and establishing Europe's technological leadership[45] (Appendix C-1-7).

In the standardization sector, the European Commission announced a new European standardization strategy in February 2022[46]. In the strategy, a proposed European Standardization Rule was included, which stipulates that only standardization bodies in the EU and the European Economic Area are allowed to be concerned with the European standards demanded by the European Commission. It demonstrates a strong awareness of European technological sovereignty and strategic autonomy.

1.2.3 Conditions in Asia

The ASEAN member countries (10 in total) have a total population of approximately 670 million people, equivalent to about five times the population of Japan. In recent years, the GDP per capita has been improving, and the GDP reached approximately $3.3 trillion. This represents 67.7% of Japan's GDP and 4.5% of the global GDP[47]. Despite the major downward pressure on the world economy due to US-China trade friction and COVID-19, Southeast Asia has often been in the spotlight as a stable destination for business expansion. Noteworthy recent developments in the research fields that should be strategically pursued by Japan are described below.

(1) Beyond 5G/6G

In Singapore, the Infocomm Media Development Authority (IMDA) collaborated with the Singapore University of Technology and Design (SUTD) to establish the Future Communications Connectivity (FCC) Lab within the university in September 2022, marking Southeast Asia's first 6G research institution[48].

In Vietnam, the country's Minister of Information and Communications, Nguyen Manh Hung, announced in January 2021 that the country would begin research on the 6th generation mobile communication system within the year[49]. Furthermore, in February 2022, a committee was established with the Minister of Information and Communications as its chairman to create a roadmap for the research and commercialization of 6G[50].

In addition, Indian Prime Minister Modi announced the 6G Vision compiled by the 6G Technology Innovation Group (TIG), a collaboration of industry, academia, and government, in March 2023[51][52]. The group is planning to develop a roadmap and action plan for 6G.

(2) AI

In Singapore, the country is advancing AI development and AI adoption through the formulation of the National Artificial Intelligence Strategy[53], which aims to realize national-level AI in the fields of transport and logistics, smart cities and real estate, healthcare, education, and safety and security. In a survey across 181 countries and regions on the preparedness of national governments for artificial intelligence (AI), Singapore was ranked second, following the United States[54].

In other ASEAN regions, national strategies for AI have been formulated in Indonesia[55], Thailand[56], Malaysia[57], and Vietnam[58].

In India, based on the national AI strategy National Strategy for Artificial Intelligence #AIFORALL[59] that was formulated in 2018, foundational research (COREs, Centres of Research Excellence in Artificial Intelligence) and application-based technological development and deployment (ICTAI, International Centre for Transformational Artificial Intelligence) are underway, with agriculture, healthcare, education, smart cities, infrastructure, and smart mobility as key areas. In addition, the country has planned to train 3 million government employees on AI[60], indicating a strong competitive edge in terms of human resources[54].

As for the Global Partnership on Artificial Intelligence (GPAI), an international initiative committed to the development and use of responsible AI based on a human-centric approach, Singapore joined from Southeast Asia as a founding member in June 2020, along with Australia, New Zealand, and India.

(3) Quantum ICT

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia predicts that the country's quantum technology could create a market worth 6 billion Australian dollars (approximately 570 billion yen) and about 19,000 jobs by 2045[61]. Quantum technology is one of the seven pillars in the "List of Critical Technologies in the National Interest" prepared by the Australian government in 2021[62]. Amidst these developments, a National Quantum Strategy is currently being formulated as an important measure to grow the quantum industry and introduce innovative quantum technologies. In April 2022, an issue paper for the strategy formulation (National Quantum Strategy: issues paper) was published, and comments were solicited until June 3, 2022 [63]. Also, in February 2023, the University of Sydney announced an investment of 7.4 million Australian dollars to expand its quantum technology facilities and establish the Future Qubit Foundry in the Sydney Nanoscience Hub of the university [64]. It is intended to be a key domestic hub for the development of future quantum computer technology, aiming for large-scale operation and the practical application of quantum computers.

The Indian government is pushing forward with a five-year plan based on the National Mission on Quantum Technologies & Applications (NM-QTA), which allocates a budget of 80 billion rupees for quantum technology R&D over five years [65].

Furthermore, in March 2022, it was reported that scientists from the Defence Research and Development Organisation (DRDO) and the Indian Institute of Technology (IIT) Delhi successfully demonstrated Quantum Key Distribution (QKD) between Prayagraj and Vindhyachal in Uttar Pradesh, more than 100 km apart [66]. Moreover, in April 2022, India hosted the Bilateral Workshop on Quantum Technologies (I2QT 2022) [67] with Israel. The DRDO, DRDO-Industry-Academia Centre of Excellence (DIA-CoE), and Indian Institute of Technology Delhi (IIT-D) sponsored the workshop, where 175 participants, including experts, scientists, and business people, discussed quantum technology roadmaps, quantum computing, and quantum communication in free space. India is promoting quantum research collaboration with other countries, and especially with Finland, it is planning to establish the "Indo-Finnish Virtual Network Center on Quantum Computing" [68].

In February 2022, it was reported that a Singapore-based quantum technology company, SpeQtral, started the SpeQtral-1 quantum satellite mission [69]. It is part of the Space Technology Development Program (STDP) by the Office for Space Technology and Industry (OSTIn) of Singapore and the SpeQtral-1 satellite, which is scheduled to be launched in 2024, will be one of the few quantum key distribution satellites launched by a private entity.

(4) Cybersecurity

In 2022, the Asia-Pacific region remained the region most attacked by cyberattacks, with manufacturing being the most attacked industry, accounting for 48% of all cases, significantly outpacing finance and insurance, each with 18%. In terms of case numbers in the region, Japan accounted for 91%, followed by the Philippines with 5%, and Australia, India, and Vietnam each with 1.5% [70].

In response to this situation, countries such as Singapore, Malaysia, and Thailand have enforced personal information protection laws, and legal systems for protecting personal information are being developed in Southeast Asia [71] [72]. In terms of risk management for critical infrastructures, Australia introduced a legal system in 2021 that requires the formulation of risk management plans and incident reporting and allows government intervention if critical infrastructure operators do not respond adequately to incidents [73]. In Indonesia, a presidential regulation was issued in 2021 on the protection of critical information infrastructures, which is expected to come into effect in May 2024 [73].

In such circumstances, the Japan-ASEAN Cybersecurity Capacity Building Centre (AJCCBC) [74], established in 2018 as part of the Japan's Ministry of Internal Affairs and Communications' cooperation on cybersecurity to develop cyber security human resources in ASEAN countries, has been conducting practical cyber defense exercises (CYDER) targeting government agencies and critical infrastructure operators. In February 2023, a signing ceremony was held between the Japan International Cooperation Agency (JICA) and the Thai government for a technical cooperative project aimed at further enhancing these efforts and improving cybersecurity response capabilities across the region [75].

Chapter 2　Trends in Key Areas

In this chapter, we will discuss the environment, current R&D trends, and future prospects in the ICT R&D field related to the social trends mentioned earlier. Starting with Beyond 5G/6G, which is a foundational cross-cutting technology, we will cover eight specialized fields and discuss their trends.

2.1 Foundational Cross-Cutting Technology

Beyond 5G, the next generation mobile communication system following 5G, is expected to play a role not merely as a communication infrastructure, but as a social infrastructure. In order for Japan, whose capital strength is not necessarily at the top, to make a comeback and break the sense of stagnation surrounding the current Japanese ICT industry, an integrated utilization of cutting-edge technologies that cut across industrial sectors is required, with Beyond 5G as a guiding principle, from 2030 onward.

In this section, we will show the challenges of the environment surrounding the current communication system in Japan, provide an overview of efforts towards R&D of Beyond 5G technologies, and discuss the expected future prospects.

2.1.1 Background

A common reflection on the efforts of the 5G business in Japan is that while we can win with technology, we often cannot win in the market. This is due to the lack of foresight and execution to turn our excellent R&D capabilities in cutting-edge technology into a business. To begin with, it is thought that there is a sense of stagnation in industries in Japan today, even beyond the ICT industry, because efforts are either not rewarded due to external factors or environments conducive to making an effort are not provided. One of the reasons for this is that social issues are more diverse, and it has become difficult for industries to solve these problems just with their own initiatives.

Examples of diverse social issues include balancing child rearing with a career, education disparities due to family economic resources, homogenization and passivity due to uniform education, employment limitations due to place of residence or physical constraints, an increase in social security expenses due to an increase in unhealthy life expectancy and caregiver fatigue, etc. (Fig. 2.1-1). It is expected that a society based on the information communication system of Beyond 5G can solve these issues and create a society that makes it easier to enjoy the richness of human nature.

For society after 2030, it will be necessary to create an environment where each industry and business operator can flexibly collaborate, appropriately share roles, and thrive in order to create new services that solve social issues. To this end, it is necessary to establish a mechanism that promotes the integration of technologies and collaboration across industries.

The new services born in this way may even influence the values related to society and human life. For example, human behavioral changes caused by AI or distributed exchanges of intangible assets have the potential to bring innovative value but also the potential to create ethical, legal, and social issues (ELSI). Because a wide range of things can be realized with Beyond 5G, a discussion that incorporates these aspects is integrally necessary.

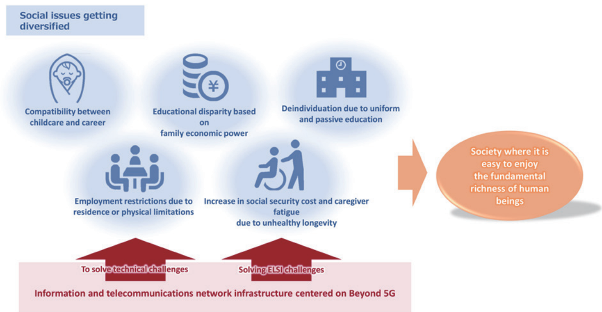


Fig. 2.1-1 Diversifying social issues and Beyond 5G

2.1.2 Current Research and Development Trends

A number of activities are being conducted in Japan towards the realization of Beyond 5G. First, regarding the vision, the Beyond 5G Promotion Consortium [76] has been steadily advancing collaborations by creating white papers, disseminating information to explore international collaborations, and signing MoUs with overseas research institutions. Also, the Beyond 5G New Business Strategy Center [77] conducts activities such as hosting seminars on intellectual property and standardization, publishing informative guidebooks, and making proposals for future society by leaders from outside of company frameworks.

Regarding R&D, NICT is implementing the Beyond 5G R&D Promotion Project [78] to establish Beyond 5G technology elements as quickly as possible. Based on the Ministry of Internal Affairs and Communications' grant, NICT has set up a fund and commissioned companies, universities, and others to conduct R&D.

The commissioned R&D project covers a wide range of fields from semiconductors to digital twins, and the collaboration and social deployment of their research results is highly anticipated. Moreover, NICT has conducted R&D for a long period of time and is working to integrate technologies and adapt them to achieve Beyond 5G.

There are also some movements related to forums and communities connected to Beyond 5G. IOWN is a concept regarding the network infrastructure of communication and computing resources, mainly focusing on optical communication technology, and is conducting international discussions on use cases and demonstrations through the establishment of a Global Forum [79]. The Terahertz System Application Promotion Council [80] is examining issues related to system development based on terahertz technology and users' need for terahertz systems. The Space ICT Promotion Forum [81] is conducting information sharing, coordination/strategic field organization, and strategy reviews regarding space communication technology. The Wireless Emulator Utilization Society Promotion Forum [82] conducts information exchange and dissemination activities related to a wireless emulator that can simulate wireless systems by building a radio usage environment in a virtual space.

2.1.3 Future Prospects

By the 2030s, it is desirable for all businesses and individuals to play an active and equal role in the Beyond 5G system, and by developing such an environment, new values will be created through open innovation. The companies or individuals who will play a leading role should not be confined to the same industry, such as the information and communication field, but should participate across multiple industries.

In this way, various resources (communication, computing, time, space, frequency, etc.) will be effectively used as a whole, leading to the creation of services that create new value. To achieve this, not only the advancement of component technologies but also mechanisms that connect them are necessary, as they are a crucial concept of Beyond 5G.

Fig. 2.1-2 shows the concept of the Beyond 5G system constituting a collective of all systems. To realize the services required by users, it is necessary to combine multiple systems across industries and set them up appropriately. Here, terrestrial mobile communication systems, HAPS (High-Altitude Platform Station), satellite communication systems, the metaverse, and digital twins of each industry are depicted, and multiple operators exist in each industry. Therefore, one or multiple systems are provided by the same industry. Moreover, multiple industries provide systems to implement services.

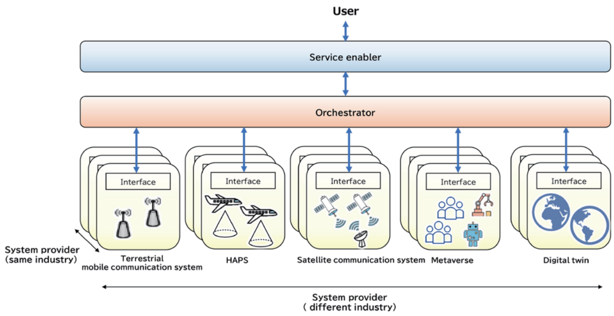


Fig. 2.1-2 Beyond 5G Services Realized by Connecting Different Industries

In order to realize this, a coordinator who can discover, select, and set up systems according to the services required by the users is needed to work across systems. In (Fig. 2.1-2), it is shown as the orchestrator who communicates with each system through a common interface. Moreover, it is impossible for users to handle such complex systems directly, so a service enabler exists as an intermediary. The service enabler has an interface to exchange user and service level requests and break them down, and hand them over to the orchestrator. It will be necessary to define this concept for the architecture of Beyond 5G and to work on specifying the necessary functions and interfaces.

In this way, Beyond 5G is expected to evolve from being just a mobile communication infrastructure to a social infrastructure that supports service creation. If this way of thinking is widely accepted, there is a possibility that a game change may occur in the business of the current information and communication infrastructure.

2.2 Utilization of Electromagnetic Waves

Modern society cannot keep its function without the utilization of electromagnetic waves such as radio waves and light. They support not only communication but also meteorological observation and forecasting, infrastructure system maintenance, ensuring the safe operation of electrical and electronic devices that are integrated into our daily lives, and disaster management. In short, our modern society is supported by the use of electromagnetic waves.

In this chapter, we discuss the R&D trends of the following five key technologies to utilize electromagnetic waves, which are necessary for realizing Society 5.0 [83]:

- Remote sensing technology that is essential for transferring information from physical space to cyber space.
- Technology to understand and predict the space environment (space weather forecast) necessary for realizing a network system (Non-Terrestrial Network, NTN) that seamlessly connects the ground, ocean, air (including the stratosphere), and space.
- Electromagnetic environment technology that accurately measures and evaluates the safety of radio waves in response to major changes in radio wave usage.
- Technology to generate, measure, and provide time and frequency, which is the basis of ICT and realizes a safe and secure social life.
- Digital optics technology that creates a next-generation communication environment causing behavioral changes through actuation.

2.2.1 Background

Abnormal weather and weather-related disasters occur frequently around the world, including in Japan. In particular, the intensification of recent heavy rain disasters has been reported by the International Panel on Climate Change (IPCC) to be undoubtedly due to ongoing global warming. Issues such as global environmental and climate change, safety and security of life, disaster prevention and reduction, and homeland resilience are becoming increasingly important. An approach using digital twins (Fig. 2.2-1) is effective for these challenges, and the importance of remote sensing technology is increasing as it serves as the entry point for information from physical space to cyber space.

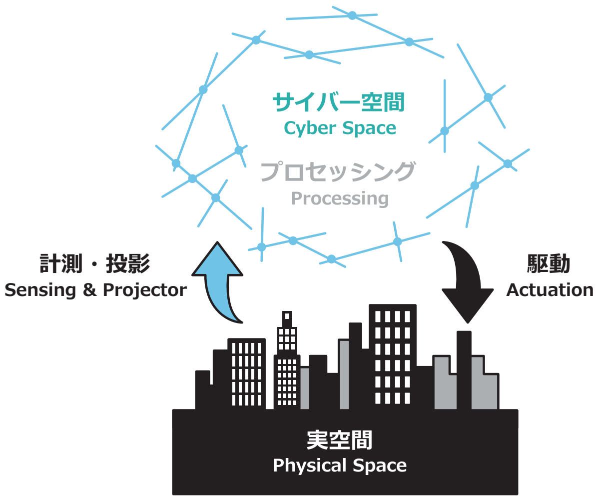


Fig. 2.2-1 Conceptual Diagram of Digital Twin

Changes in the space environment (in other words, space weather), such as space radiation and geomagnetic storms, originating from solar activity, can have a significant impact on social infrastructure such as aviation operations, power systems, satellite operations, telecommunications, and broadcasting in our highly ICT-enabled society. Sometimes, such space weather disturbances can disrupt the stable usage of social infrastructures (Fig. 2. 2-2). Solar activity, which follows an approximately 11-year cycle, is expected to reach its next peak around 2025. The size and frequency of solar flares are gradually increasing, and societal impacts such as malfunctions of low-orbit satellites have begun to appear. In order to predict these effects on societal activities in advance and minimize disruptions, precise understanding and forecasting of space weather is being implemented through international cooperation, along with promoting the R&D of technologies.

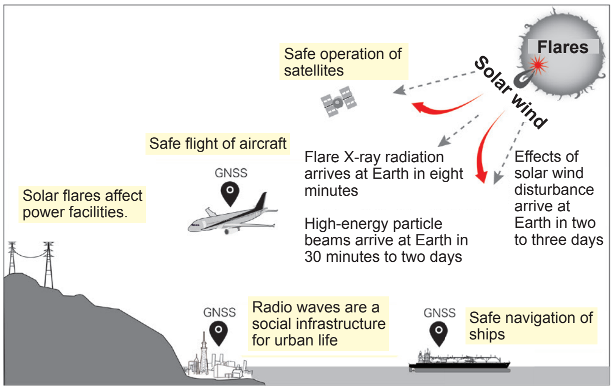


Fig. 2.2-2 Variations in the Space Environment and Their Impact

Meanwhile, our social environment is increasingly electrified and digitized. We are surrounded by various electromagnetic waves that cause various electromagnetic compatibility issues (Fig.2.2-3). In particular, electromagnetic noise from energy-saving appliances is becoming a problem as it interferes with the communication of nearby wireless devices. In addition, it is necessary to appropriately maintain and manage safety from the perspective of human exposure to the radio waves emitted by currently widely proliferating 5G systems and those from Beyond 5G/6G systems. Furthermore, improvements are being made in the performance of measuring instruments used for testing and inspecting the performance of wireless communication devices, and technologies to manage them are also becoming necessary. Electromagnetic environment technology aims at solving these issues.

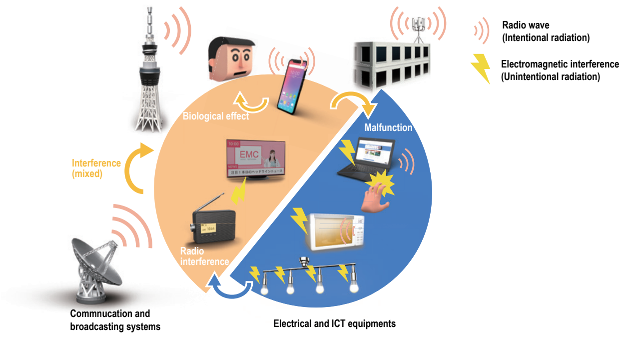


Fig. 2.2-3 Concept of the Electromagnetic Environment

In modern society, which is built upon advanced science and technology, it is essential for society to share standards time and frequency. Wireless communication is possible because there is a standard for frequency, and the operation of transportation systems, high-speed e-commerce, telecommunications, and broadcasting are possible because there is a standard time. High-precision time can be obtained first by preparing a high-precision frequency standard, represented by atomic clocks, and continuously operating it. High-precision frequency standards have been realized by atomic clocks since the middle of the last century, and the advent of atomic clocks has enabled the GNSS (Global Navigation Satellite System) positioning. The technology to generate, measure, and provide time and frequency provides the core of modern ICT.

Digital optics technology is a technique that upgrade the field of diffractive optics, with the core being techniques that numerically and accurately emulate the propagation of electromagnetic waves in the near-infrared to visible light range. As the technology that contribute to the realization of Society 5.0, it includes the sensing of the real world (natural light holography) and the manufacturing of semi-transparent optical elements for the AR/VR actuation side.

2.2.2 Current Research and Development Trends

(1) Remote Sensing Technology

Daily familiar weather forecasts can be seen as a close example of an approach using digital twins from a technical perspective, but there are still many challenges. While fairly high accuracy in predicting heavy rain up to about 10 minutes in advance has been achieved through short-term precipitation forecasting, the prediction of linear rainbands hours to a day in advance still lacks accuracy. Research for it is being conducted from various perspectives, such as numerical forecasting models, observations, and elucidation of phenomena.

Rain radars, one of the sensors that sense atmospheric phenomena, are starting to permeate on-site operations with Doppler radars that can observe wind speed and polarization radars that excel in quantitative observations. On the other hand, in cutting-edge research, the development of phased array radars capable of high-density observation in time and space is progressing, but they remain at the R&D stage in all countries. The multi-parameter phased array weather radar (MP-PAWR), developed by NICT and others, which combines Doppler, polarization, and phased array technologies, is one of the world's highest performance rain radars closest to practical use. Also, LIDAR is a useful technology for observing clear-sky atmospheres without rainfall. Various methods have been proposed, and Doppler LIDAR and water vapor LIDAR have started to be used experimentally for weather observation. The development of multi-parameter differential absorption LIDAR (MP-DIAL) capable of simultaneous observation of multiple parameters such as wind speed, water vapor, and CO_2 is also advancing.

Synthetic aperture radar (SAR), for observing the surface of the earth with high accuracy, is achieving higher resolutions (Fig. 2.2-4). NICT has achieved a resolution of 15 cm with the airborne X-band Synthetic Aperture Radar system (Pi-SAR X3). For satellite SAR, private companies are launching multiple small satellite SARs, and plans to observe the global surface condition every few hours for commercial use are progressing.

Earth observations using large satellites are being improving with international cooperation. The soon-to-be-launched Earth observation satellite, EarthCARE, is equipped with the first cloud radar to perform Doppler observations from a satellite. In satellite precipitation observations, studies are underway for a successor mission to the current Global Precipitation Measurement (GPM) project to achieve high-accuracy vertical Doppler observations.

With performance improvements in each sensor, the amount of data obtained is also becoming enormous. R&D of data compression and restoration and delivery systems to promote the utilization of these data are also being conducted.

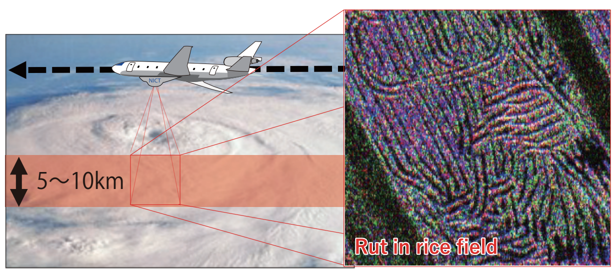


Fig. 2.2-4 Concept of Synthetic Aperture Radar

(2) Technology to Understand and Predict the Space Environment

For space weather, it is of utmost importance to understand and predict its occurrence and scale faster and to deliver appropriate information to minimize its impact. To prepare for severe space weather disasters, advancements are being made in understanding current state and forecasting technologies, which are the basis for space weather forecasts.

As a technology for nowcast, for observation from the ground, domestic and foreign organizations are cooperating with each other to observe a wide range of areas, taking their allotments. In Japan, NICT is the only institution conducting regular ionospheric observations. Also, the continuous 24-hour data collection of solar wind from spacecraft and the expansion of high-density ionospheric observation network in Southeast Asia are advancing in collaboration with domestic and foreign research institutions. In observations from space, international observations are conducted by satellites equipped with space environment sensors, and in Japan, the development of sensors is being advanced with the aim of the next-generation Himawari satellite scheduled for launch in 2028 in collaboration among the Japan Meteorological Agency, the Ministry of Internal Affairs and Communications, and NICT.

As for the technology for forecasting space weather, advancements are being made worldwide in technologies using supercomputer-based simulation, data assimilation and AI (machine learning). For the atmospheric-ionospheric coupled model, domestically, the NICT-led development of the GAIA data assimilation model is advancing under the leadership of NICT in Japan, and similar development is also advancing in the United States and other countries. Magnetospheric models are being developed by domestic and foreign research institutions, and only NICT can reproduce extreme phenomena. In addition, development of forecast model for radiation belt electrons, which cause satellite deep dielectric charging, Is underway in cooperation with domestic research institutes. Solar wind models are under R&D domestically and abroad. In Japan, NICT is developing SUSANOO. The prediction of solar flare occurrences using machine learning is fiercely competitive both in Japan and internationally, and NICT has developed Deep Flare Net, which has a world-class hit rate.

The development of services and applications to provide users with current and future information about space weather in an easy-to-understand manner is also progressing. In Japan, the solar radiation exposure warning system WASAVIES, the satellite surface charging risk assessment system SECURES, and the shortwave band radio wave propagation simulator HF-START have been developed.

For the monitoring and forecasting of global space weather phenomena, international cooperation is essential, and forecast services are being implemented in cooperation with the International Space Environment Service (ISES), which has 21 member countries. Standard and reference specifications for observation data and equipment are being determined in international organizations such as ITU-R, WMO, ISO, CGMS. The ICAO is advancing the use of space weather information in civil aviation operations, and information is being provided by the Global Space Weather Center, which Japan also participates in.

(3) Electromagnetic Environment Technology

In order to ensure smooth interoperability between electrical and electronic equipment and the coexistence of communication and broadcasting in a complex electromagnetic environment, especially when they are connected by a common power line, it is important to clarify the mechanism of electromagnetic noise generation and propagation among those pieces of equipment. R&D are underway to establish parameters evaluation methods for electromagnetic noise, which is dominant in electromagnetic interference for wireless communication such as 5G through theoretical studies, numerical simulations, and experiments (Fig. 2.2-5).

In order to appropriately evaluate the safety of exposure to radio waves from new wireless systems such as Beyond 5G/6G, R&D are being promoted to develop exposure evaluation technology, clarify the effects of radio wave exposure on the human body, and further extend radio radiation protection guidelines and realize certification methods that correspond to the latest wireless communication technologies.

In order to provide highly reliable data that can be used for risk communication and epidemiological surveys on radio wave protection, the acquisition, accumulation, and analysis of radio wave exposure level monitoring data are being carried out. In addition, efforts have begun to manage and operate the acquired and accumulated data over the long term.

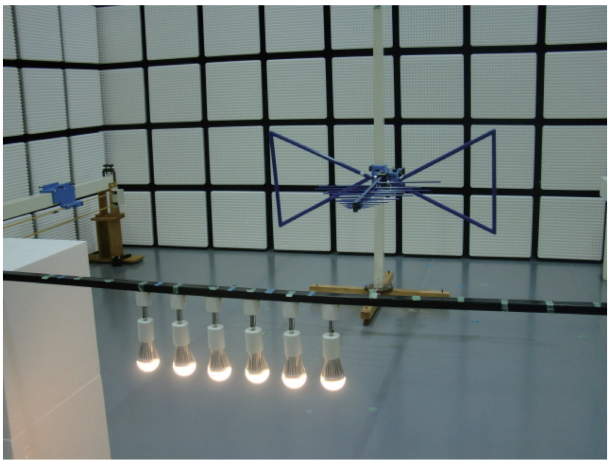


Fig. 2.2-5 Measurement of the Electromagnetic Emission from LED Lighting

(4) Technology to Generate, Measure, and Disseminate Time and Frequency

The standards time and frequency are currently heading towards a significant turning point for the first time in half a century. Until now, atomic clocks have used the hyperfine transition of alkali atoms in the GHz range, and the transition of cesium atoms is the definition of the second in the International System of Units. However, since around 2000, optical clocks, which use the atomic transitions of electromagnetic waves in the optical region with frequencies of 4-5 orders of magnitude higher, have made significant improvements in performance. The accuracy shows an improvement of more than 2 orders of magnitude compared to conventional atomic clocks, and in response to this, at the International General Conference on Weights and Measures held in 2022, it was resolved that the member countries of the Meter Convention would make further efforts so that the definition of the SI second could be changed in 2030.

On the other hand, in the process of its development, microwave atomic clocks have enabled positioning using GNSS. Japan's Quasi-Zenith Satellite System is aimed to achieve uninterrupted positioning without GPS, by around 2024.

In GNSS, atomic clocks are installed on satellites, but they are not installed in mobile terminals. Therefore, installing atomic clocks instead of conventional crystal oscillators on the client side such as on mobile terminals or autonomous vehicles are discussed to improve the accuracy of time and positioning. This is expected to realize space-time synchronization, where time can be shared with the required accuracy and cost in anytime, anywhere, and by anyone, and physical position can also be determined accordingly. In order to install atomic clock in mobile terminal, it is necessary to reduce the size and cost of the atomic clock. Additionally, the architecture is also required that can utilize a large number of atomic clocks via autonomous and distributed supply technology of time and reference frequency (Fig. 2.2-6).

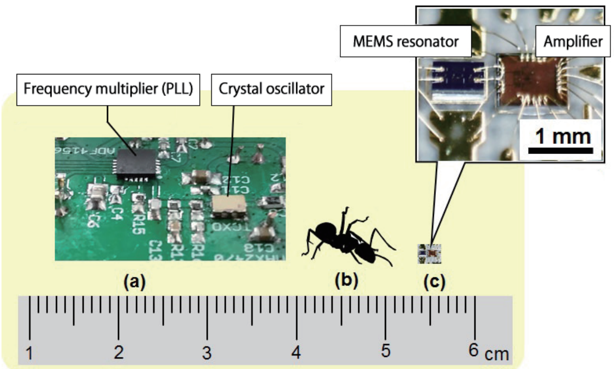


Fig. 2.2-6 Miniaturization of the Oscillation Circuit for Atomic Clocks
(a) Conventional Quartz Oscillator Type Microwave Oscillator
(b) Bullet Ant (Body length 7 mm - 12 mm)
(c) Newly Developed Microwave Oscillator

(5) Digital Optics Technology

R&D of technologies for systems that capture information as-is through three-dimensional image sensing are being conducted globally. Such systems cover life science, material science, industry, art, and everyday life. The field of natural light holography sensing has advanced with the emergence of Fresnel Incoherent Correlation Holography (FINCH). Currently, there is vibrant R&D of it, broadly divided into applications for microscopes, cameras, and wavefront sensors. The Ben-Gurion University in Israel, led by J. Rosen, originally proposed FINCH and its application in three-dimensional fluorescence microscopes. Currently, they are focusing on fundamental research such as improvements in the theoretical spatial resolution and three-dimensional tomographic measurements. They are also expanding international networks, collaborating with A. Vijayakumar at the University of Tartu in Estonia and S. Juodkazis at Swinburne University in Australia. G. Brooker, another inventor of FINCH, established the venture company CellOptic, Inc., offering the market a 3D fluorescence microscope device based on FINCH with a resolution of about 100 nm. Also, T.-C. Poon's group at Virginia Tech University has been continuously conducting R&D of holography using a single-pixel sensor for over 40 years. They are emphasizing activities with international networks, progressing through collaborations with China, Taiwan, and Hong Kong. In Japan, the number of research bases has greatly increased with the emergence of FINCH. Japan is one of the countries with the highest number of research bases in natural light digital holography in the world. Kobe University Professor Matoba's group is actively applying it in the field of fluorescence microscopy. Professor Takagi's group at Tokyo University of Agriculture and Technology has opened up new measurement applications by proposing its use in endoscopes. NICT has succeeded in the world's first development and demonstration of a full-color holography movie recording and playback system using sunlight. They are also developing a new portable wavefront sensor system.

The development and application of transparent optical screens are also progressing (Fig. 2.2-7). An AR-HUD for vehicles is being developed as a promising application for transparent optical screens using hologram technology. Since 2016, auto parts manufacturer Continental AG has been advancing collaborations with DigiLens Inc., which has holographic projection technology. DigiLens Inc. established unique hologram light guide plate display technology. Start-up company Ceres Holographics Ltd. is also aiming to establish its own optical screen development technology. In Japan, remote and contactless technologies have been greatly focused on due to the global coronavirus pandemic. Significant progress has been made in the practical application of the aerial display technology, which has been started before COVID-19 pandemic. Asukanet Co., Ltd. and Parity Innovations Co. Ltd. have developed technologies to display images in mid-air away from touch panels or monitors. Both started providing aerial displays with non-contact interfaces in collaboration with various businesses and municipalities between 2020 and 2021. Also, their technologies have been implemented in self-checkout registers used at convenience stores and bookstores through collaboration with private companies.

Fig. 2.2-7 Transparent full-color animation 3D display for AR

2.2.3 Future Prospects

As stated at the beginning of this chapter, electromagnetic wave utilization technologies that support the next generation of social infrastructure will become increasingly important. With respect to future prospects, it is expected that fusion of communication and sensing, interdisciplinary movements such as the introduction of quantum technology, and R&D of space weather which may have a significant impact on ICT infrastructure, will continue to advance. Also, it is important to integrate these technologies and incorporate them in society. For example, information from these technologies should lead to behavioral changes of people.

Radio waves for communication, which are increasingly used in Beyond 5G/6G society, can be used and applied not only for communication but also for sensing. In the future, examinations on systems that integrate communication and sensing are expected to progress. Machine learning is already being used and expected to expand in various ways, such as for short-term rainfall prediction, data quality control, data compression and restoration, and data analysis.

Detection sensitivity of LIDAR using single-photon detectors will be improved by utilization of quantum technology.

In a future society with further development of space infrastructure (a society realized by NTN), as the impact of space weather becomes more serious, it will be essential to take measures according to space weather forecasts. Space weather forecast will be required on a daily basis, like conventional weather forecast in order to response to the social needs such as dealing with satellite charging and orbital changes of communication satellite for mega constellations, which are indispensable in the B5G era, dealing with radiation and communication failures in the development of private spacecraft and space travel, and dealing with satellite positioning failures in autonomous driving and drones, which are spreading in various industrial fields (Fig. 2. 2-8).

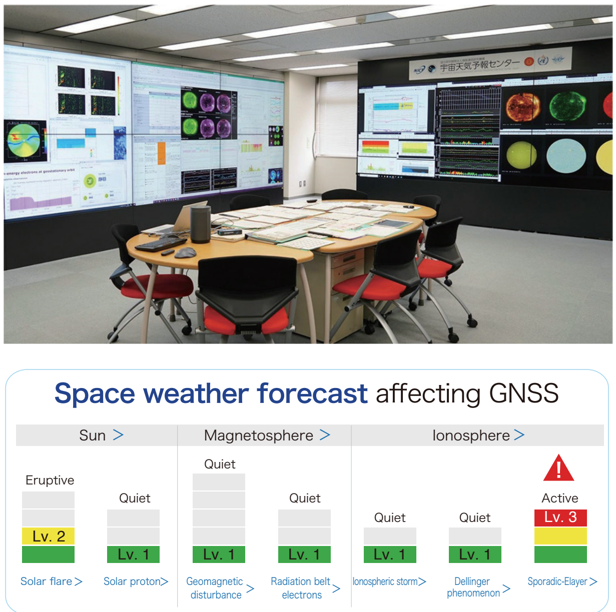


Fig. 2.2-8 Space Weather Forecast Center

On the other hand, in response to changes in the radio interference from electronic and electrical appliances due to future technology developments, the advancement of the communication and broadcasting systems, and changes in lifestyle, it is expected that R&D of electromagnetic noise evaluation technology, which should be the core of industrial development, will continue to progress in order to constantly maintain an appropriate electromagnetic environment. The promotion of R&D of basic infrastructure technologies for accurately evaluating human exposure from low frequency waves to terahertz waves, etc., is expected to continue to maintain a safe and secure radio usage environment both domestically and internationally.

The space-time synchronization technology will realize the level of time accuracy that GNSS does game change and will become basis for delay-guaranteed communication, cryptographic communication, quantum communication, and so on. In order to widely distribute the benefits of quantum computation and quantum cryptography, quantum transmission will be also necessary. To realize quantum transmission, it is essential to share stable time, at the level of an optical clock, between two locations. It is also expected that the method of supplying time will change drastically when space-time synchronization is realized.

In terms of natural light holography sensing, many research results are seen at the stage just before breakthrough research progress and application development. Microscopy and wavefront sensing technologies, proposed at the dawn of this field, have already been put into practical use in new measuring instruments. The XR market, including transparent optical screen AR displays, is expected to have a market size of about 3 billion dollars in Japan and about 160 billion dollars worldwide in 2023, and is expected to continue to grow in the future.

2.3 Communication Network Infrastructure

The fundamental performance requirements of communication network infrastructure, such as broadband wide area communication, low latency, and high reliability, are increasing over time. In order to realize these, R&D to enhance basic and system technologies such as optical communication, wireless communication (terrestrial and satellite), and networking are essential in every generation. Indeed, in the transition from 4G to 5G and to Beyond 5G, the basic direction remains the same, while the goals and functions are more sophisticated, and functions with new vectors are added. Here, we take an overview of the environment surrounding the communication network infrastructure desired in Beyond 5G, the current R&D trends, and future prospects to realize the society expected between 2030 and 2050. Fig. 2.3-1 shows the overall picture of the future communication infrastructure targeted in this section. On the ground, there are wireless systems, and in the cloud and near users, there are computing devices and storage devices (server computers). These devices are virtualized and shared among multiple services. Optical fibers connect devices that make up trunk lines and base stations, and between server clusters inside and outside of data centers. In the sky, there are drones and HAPS, and even higher, non-geostationary satellites and geostationary satellites serve as relay points in the communication network, and they can also communicate directly with users. In the sky, not only wireless but also optical communications appear. There is a limit to the amount of data that can be carried by radio waves, and it is the optical communication technology with overwhelming data transfer capacity supports it.

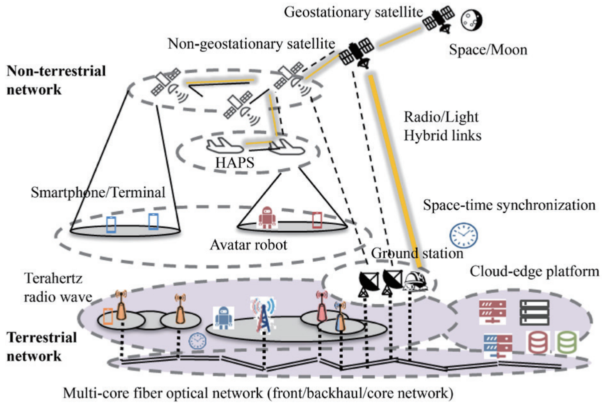


Fig. 2.3-1 Future Communication Network Infrastructure

2.3.1 Background

For internet access at home, network access was about 9.6 kbps with a modem when the internet began to be spread for consumer use in the 1990s. Since then, access speed has increased using ISDN, ADSL, CATV, FTTH, etc., and now, 10 Gbps optical access services are available. Over this period, communication speed has increased by a million times.

In the optical backbone network that supports such high-speed communication, the transmission capacity per fiber reached 10 Gbps in the 1990s, 1 Tbps in the 2000s, and 10 Tbps in the 2010s, increasing by more than a thousand times in 20 years. During this period, technologies such as time division multiplexing, wavelength division multiplexing, simultaneous wideband optical amplification technology, quadrature amplitude modulation and demodulation technology, and digital signal processing technology have matured.

Regarding wireless access, Wi-Fi, which appeared in 1999 as an 11 Mbps standard (IEEE802.11b), has become 9.6 Gbps in the IEEE 802.11ax standard established in 2021, about 1000 times faster in 20 years. orthogonal frequency division multiplexing, quadrature amplitude modulation and demodulation technology, and MIMO technology have matured.

The communication speed of mobile communication systems has increased by a hundred thousand times in about 20 years, from 64 kbps in 2G (digitalization) in the 1990s to 384 kbps (3G), from 100 Mbps to 1 Gbps (4G), and to 10 Gbps in the 5G era. Technologies such as high frequency support, quadrature amplitude modulation/demodulation technology, and MIMO technology have matured, and the concept of functional separation has permeated.

For satellite communication, high throughput satellite communication systems (HTS) started being launched with gigabit per second geostationary HTSs in around 2004, with a 10 Gbps HTS launched in 2005 and a 100Gbps class HTS launched in 2012 [84]. Recently, the communication capacity has increased to hundreds of Gbps. Some operators are planning to launch terabit satellites from 2023 onwards.

As for network software, recommendations and standards based on documents were the main focus in the past, but the availability as open-source software has been rising. For example, multiple open-source software for 5G has been released and is available.

When consumer use of the Internet began, the on-premises type, where users or their organizations installed server computers and software for access, was the mainstream. However, cloud services began in the mid-2000s, and virtualization technology advanced in the 2010s, accelerating the use of computers, storage, and software in the cloud. Some mobile services have started using cloud software instead of their own.

In Japan, the percentage of houses that can use ultra-high-speed broadband such as FTTH was 99.98% in 2015. For mobile communications, the number of 4G subscriptions exceeded the population, and the 5G coverage rate was 93.2% as of March 2022 [85) 86)].

Going forward toward Beyond 5G, wireless access is expected to increase tenfold and the backbone network is expected to increase a hundredfold in capacity, as indicated in MIC's Beyond 5G Promotion Strategy, etc. To address this, we need to aim for a thousand-fold improvement at the R&D level. Furthermore, as will be discussed later, the aerial network is expected to provide communication paths with a wide range and low latency, and the provision of a terabit per second three-dimensional network between nodes is expected.

2.3.2 Current Research and Development Trends

Here, we focus on spatially multiplexed optical fiber communication and non-terrestrial networks to discuss the R&D trends.

As one type of spatially multiplexed optical fiber communications, R&D of multi-core optical fiber transmission, in which multiple optical paths are provided in a single optical fiber are progressing. The progress of its transmission capacity is remarkable. In March 2011, NICT achieved a world record transmission capacity of 109 Tbps. In September 2012, NTT updated the record to 1 Pbps. Later, in September 2015, NICT achieved 2.15 Pbps. In September 2017, KDDI further updated the world record to 10.16 Pbps. Not only the capacity but also the distance is being challenged, and in September 2013, NTT and KDDI achieved a capacity-distance product of 1 Exa bps × km. In March 2020, NICT achieved 10.66 Pbps with 38 core fibers and 172-Tbps 2040-km transmission with coupled 3 core fibers.

As for multimode optical fiber transmission, in September 2019, KDDI demonstrated a world record transmission capacity of 407 Tbps using a 10-mode fiber for a standard cladding diameter (125 micrometers). Later, in September 2020, NICT achieved a transmission capacity of 1.01 Pbps with a standard cladding diameter 15 mode fiber, the first for a multimode fiber. In recent years, as a challenge to multimode, in September 2022, NICT achieved 1.53 Pbps in the C band using a standard cladding diameter 55 mode fiber. Furthermore, aiming at early practical use, NICT has been breaking the records of standard cladding diameter optical fiber transmission with an cladding diameter of international-standard 125 micrometers. For example, the following results have been achieved.

- June 2021: Achieved a world record capacity-distance product for standard cladding diameter fibers (319 Tbps x 3001 km = 957 Pbps km). The highest at the time was 881 Pbps km (single-mode fiber) by TE Subcom [September 2017].
- May 2022: Successfully conducted a large capacity transmission experiment of 1 Pbps with a standard cladding diameter 4 core optical fiber. Used a frequency band of 20 THz (801 wavelengths) [87)] .
- March 2023: Successfully conducted a large capacity transmission experiment of 1.7 Pbps with a standard cladding diameter 19 core optical fiber.

Next, we describe the trends in research and development of non-terrestrial networks. China successfully launched the practice (Shijan) 20 satellite at the end of December 2019. This satellite is equipped with an optical satellite communication function with a transmission speed of 4.5 Gbps. NASA (USA) successfully performed optical communication from the moon exploration satellite LADEE to the ground at 622 Mbps in 2013, and in 2014, experiments were conducted ISS equipped with the optical communication device OPALS. In addition, they launched the Light Data Relay Satellite System (LCRD) into a geostationary orbit in the 2021 fiscal year, which provides communication at a speed of 1.244 Gbps. ESA (Europe) installed a coherent communication optical communication device produced by Germany's TESAT, which operates at a wavelength of 1.06 μm, on geostationary satellites Alphasat, EDRS, and Sentinel series, and they have been continuously conducting demonstration tests using satellites such as Sentinel-1A, Sentinel-1B, EDRS-A, etc. DLR (Germany) developed small optical communication terminals OSIRIS as a series, and is conducting optical communication experiments at a wavelength of 1550 nm installing them in the Flying Laptop satellite and other satellites launched in 2017. There are also other examples.

Looking at private companies, SpaceX (USA) is advancing the Starlink project, a large-scale satellite constellation plan in low earth orbit (LEO). It is planned to equip the next generation of satellite groups, known as ver. 2, with inter-satellite optical communication functions. In Amazon's (USA) satellite internet project Kuiper, Amazon is leading the development of satellites and user terminals for LEO constellations. In addition, its affiliated company, Blue Origin, is developing rockets, and AWS is providing not only cloud services but also pay-as-you-go services for satellite ground stations.

In Japan, the Space ICT Promotion Forum was established in 2020 as part of a system to promote research, development, and utilization of innovative technologies in Japan based on the revision of the Basic Space Plan (satellite development and demonstration platform construction) [88]. It aims to form a private community in the space field, which is showing new developments, and it includes a wide range of stakeholders, including companies from different industries and venture companies. As a place to discuss the direction of initiatives in Japan through the understanding of the latest trends and consideration of future strategies, and as a private forum that can respond to and reinforce government movements, the number of members as of March 2023 has exceeded 160. In this forum, domestic communication operators are sharing the following concepts:

Space Compass envisages space RAN and space data centers, planning for optical data relay services in 2024 and HAPS services in 2025. NTT DoCoMo and SoftBank each envision a service that combines terrestrial systems with HAPS, low Earth orbit satellites, and geostationary satellites, aiming to cover the entire domestic area directly with smartphones for HAPS. KDDI started mobile services using Starlink with LEO satellites in addition to geostationary satellite services in 2022, and they plan to expand to offshore areas. Rakuten Mobile is promoting the Space Mobile plan, envisioning direct communication between satellites and terminals covering all of Japan with LEO satellites.

2.3.3 Future Prospects

The communication network infrastructure contributes to the stabilization of social life through its advancement and high performance. For example, as mentioned in Section 2.1.3, it is essential to build an orchestrator so that services can be smoothly conducted throughout the network. However, to cope with the declining birth rate and the increasing number of devices connected to the network, it is important to facilitate the control and operation of large-scale networks. For this purpose, it is necessary to achieve automation level 4 through autonomous distributed cooperation among multiple Ais. This automation contributes to the service performance maintenance and improvement of Beyond 5G networks in the 2030s, prevention of equipment failure, and instant avoidance of negative effects. Also, while the utilization of digital twins is promising across society, in order to effectively use the limited frequency resources and quickly establish a wireless environment in undeveloped areas, it is necessary to construct a wireless system in the cyber-physical space, provide radio wave models and orbits of radios, etc., and provide wireless emulator technology that can verify the wireless system without measuring and evaluating the real wireless environment and put this into full use by the 2030s. Furthermore, in order to solve the depletion of wireless resources by utilizing other resources, it is necessary to realize a short- and medium-range terabit access ICT infrastructure that harmoniously uses light waves and radio waves by around 2040.

In the following, we further present prospects for increasing the capacity of the terrestrial backbone network and expanding the communication range.

Spatial multiplexing optical fiber communication is essential for the backbone lines of mobile communication networks, broadband networks, and data center networks. When the start of domestic 5G services in 2020 is regarded as the reference and, the communication capacity of the backbone network must increase tenfold in 10 years 100 times are needed by 2040. It should be at least 1,000 times that to establish a buffer, and if the communication capacity per fiber of the backbone network in 2020 is 10 Tbps (see 2.3.1), it is necessary to have a backbone network on the order of tens of petabits in 2040. Optical fiber communication technology utilizing spatial and wavelength domains is indispensable for that. Also, since it is still difficult to imagine that the growth of communication demand will stop, continuous R&D is essential. To solve such problems, technologies such as spatial multiplexing, broad banding, and long-distance communication are still required. The advancement of these technologies will realize large-capacity implementation of international communication, data centers, and terrestrial trunk lines.

Non-terrestrial networks will become new media through as coverage extension lines, extreme delay services, and backup lines. Around 2030, new applications using LEO constellation services, low delay (HAPS within 1 millisecond and low orbit satellites that communicate with the ground in several tens of milliseconds), and wide coverage will be more readily available. Services where user terminals communicate directly not only with ground stations but also with HAPS and LEO satellites will also expand. Also, in the 2030s, a communication service environment that connects seamlessly through 3D integrated network control will be realized. Various high-altitude optical satellite communications will advance, and services with wider bandwidth will also expand. As NTN spreads in the future, there are concerns about the exhaustion of wireless frequencies. For this reason, around 2040, a system for 3D frequency sharing targeting radio equipment operated in the sky will likely be institutionalized in a form in which the existing frequency sharing framework is enhanced.

Furthermore, R&D of devices that support communication network infrastructure are also important. In response to the computational processing capabilities and increasing communication performance required in information and communication, new device development is also underway. Details are discussed in Section 2.4.

From the perspective of next-generation communication network infrastructure, the trends in the field of quantum ICT, where R&D are currently underway, are also important. The infrastructure supporting today's Internet has developed while each wired and wireless network brings about technological innovation, but quantum ICT technology is expected to bring about a more fundamental innovation. The trends in this field will be covered in Section 2.6.

2.4 ICT Device Technology

In the field of information and communication, improvements in information processing capabilities and high-speed, high-capacity communication continues to be pursued. Although discussions on the limits and necessity are always carried out in parallel, the increase in demand and capabilities continues to advance without stopping. While discussions on necessity will continue to be necessary, progress is expected to continue due to the cloudification of information systems, advances in IoT and AI, and the spread of 5G to Beyond 5G. The foundation for improving the performance of information and communication systems lies in the devices (ICT devices) used. Not only improvements in traditional device performance, but also the integration between devices using different technologies and the utilization of new devices that are not bound by conventional concepts are eagerly awaited.

In this chapter, we discuss R&D trends for ICT devices to realize more advanced information and communication infrastructure.

2.4.1 Background

(1) High-speed and large-capacity information processing and communication

With the progression of cloudification, IoT, AI, and the expansion of 5G, high-speed and large-capacity data processing capabilities are required in data centers (DC) and high-performance computers (HPC). In addition, toward the expansion of multimedia services, the increase in mobile traffic, and the realization of cyber-physical systems (CPS) proposed in Society 5.0, ultra-high-speed and large-capacity information communication is required. In response to these social demands, the introduction and spread of 5G is progressing, and research on Beyond 5G/6G as the next-generation wireless communication technology is becoming active. AI-based automated driving systems are expected to help solve current car-related issues such as accident prevention and congestion mitigation. For future autonomous vehicles, radar/LiDAR, etc., will be installed and highly accurate distance measurements will be required in real-time. In addition, from the perspective of time-space synchronization, which is important for the realization of CPS, it will be necessary to install a precise clock in an easy-to-carry form, and a small and highly stable (low noise) signal sources that are commonly needed for them will be required. On the other hand, when response is made to data processing capabilities and communication speeds, keeping conventional devices as they are, the required power consumption will only increase. It will be necessary to increase processing performance while suppressing an increase in power consumption.

(2) Utilization of unused frequency bands and expansion of usage scenarios

In achieving high-speed processing and communication, if the range (usage environment and supported frequency bands) that ICT devices can handle can be expanded, it is possible to expand the utilization range or improve performance. As the electromagnetic waves that ICT devices process, terahertz waves demanded that are intermediate frequency bands of radio waves and light that have been traditionally used. Also, conventional semiconductor electronic devices, which are widely used in ICT devices, have difficulty operating under high temperatures or strong radiation, so high-performance ICT devices that can operate even in such extreme environments are also required.

In addition, light with a wavelength shorter than 280 nm, which is in the UVC region, is all absorbed by the ozone layer in the atmosphere and does not exist in the natural world (it is not found in sunlight that reaches the ground), so it is called the solar blind region. As such, it is expected that it can be used for optical space communications and sensing that are not affected by the background noise from sunlight. Also, the DNA of organisms that has evolved in a natural environment without deep ultraviolet light has a strong absorption structure in the UVC region, and it is anticipated that by using deep ultraviolet LEDs, effective sterilization and inactivation of harmful bacteria and viruses without the use of chemicals like chlorine, refinement of photo-processing and 3D printers, hardening of resins, printing, decomposition of environmental pollutants, spectroscopic analysis, and medical applications, and others are expected to play a significant role in diverse technical areas.

2.4.2 Current Research and Development Trends

(1) ICT Devices Targeting the Utilization of New Frequency Bands

Research on Beyond 5G/6G is becoming more active. The enhanced functionalities of 5G, such as ultra-high speed, large capacity, ultra-low latency, and ultra-numerous connectivity are expected to be realized by wireless communication technology in high-frequency bands such as the terahertz band. The terahertz wave, an electromagnetic wave that has a frequency between radio waves and light and combines the characteristics of both, requires an approach and integration of both electronics and photonics. Research on terahertz band wireless communication circuit technology using Si CMOS, which is suitable for mass production and widespread use, is becoming more active both domestically and internationally (Fig. 2.4-1). For example, Intel in the United States has developed a 150 GHz band wireless receiver chip and demonstrated performance at a communication speed of 128 Gb/s. In Japan, the Tokyo Institute of Technology and NTT's group is developing a 300 GHz band wireless transceiver chip, and NICT is demonstrating beam steering technology in 300 GHz band wireless communication. As for high-power GaN devices, Sumitomo Electric has a top share for 5G base station transistor applications, and NICT has reported the highest maximum oscillation frequency in Japan (see Appendix C-2-1). R&D are being conducted at many institutions abroad, including HRL Laboratories, the University of Notre Dame, and Rockwell Scientific Company. For high-stability signal sources essential for high-frequency systems like the terahertz band, there are optical frequency combs, which have evolved from solid-state laser-generated combs to fiber laser-based ones and even to optically modulated combs for which NICT also possesses the technology. Recently, R&D on micro-optical combs (μ-combs) using miniature optical resonators for even higher portability have been advancing abroad. In Japan, work is underway by NICT, Keio University, and Tokushima University as well as by Osaka University, who is collaborating with IMRA America, Inc.

For light source devices in the deep ultraviolet frequency band, mercury lamps have been mainly used industrially. Although mercury lamps are high-output and inexpensive and are still widely used, they are environmentally burdensome products that contain mercury, which is harmful to humans and the environment. In order to eliminate mercury, the Minamata Convention on Mercury has come into effect, and since 2020, gradual restrictions have begun on the manufacture and import and export of products containing mercury. Therefore, expectations for deep ultraviolet LEDs as new, compact, low environmental load light sources to replace mercury lamps have skyrocketed. However, mercury lamps still have an overwhelming advantage in both light output and cost, and a situation where they are fully replaced has not been reached. In the future, to respond to UVC high-output needs for optical communication applications, sterilization applications (virus inactivation) such as water purification and infection prevention, photo-processing, and mercury lamp replacement while keeping costs down, the major issue is how to increase the light output of deep ultraviolet LEDs per chip. There is fierce competition in R&D for the issue around the world, including in Europe, the United States, China, and South Korea.

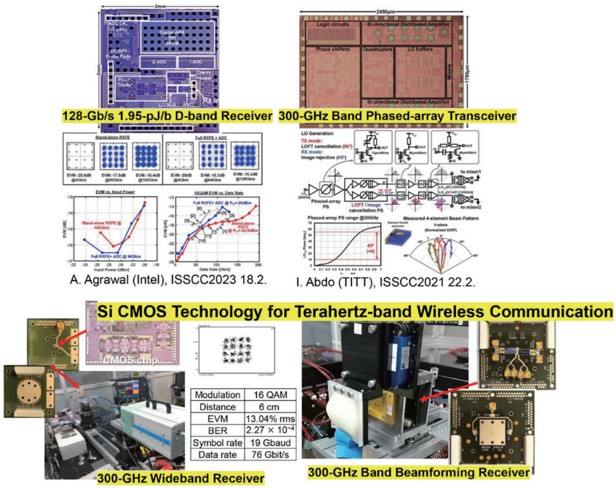


Fig. 2.4-1 Terahertz Band Wireless Communication Technology

(2) ICT Devices Utilizing New Materials

The R&D of organic devices that potentially allow the flexible design of composition and properties are being advanced as opposed to inorganic material devices that have been primarily used for traditional ICT devices. Important applications include fast light modulation, electro-optic conversion, and the generation and reception of terahertz waves. The R&D of thin-film LN, Si, InP, and electro-optical polymer (EOP) hybrid optical modulators are progressing as fast optical modulators (Table 2.4-1).

These types of fast optical modulators have different modulation characteristics (bandwidth, VπL), levels of optical loss, device footprints, etc., depending on the applications and uses. Therefore, there is a situation where they cannot serve as an ideal optical modulator for all applications and uses due to a single material or device structure. In the future, it is assumed that there will be differentiation depending on applications and uses. These high-speed optical modulators are core devices of optical information communication, and the competition is fierce for R&D in Japan, the United States, and Europe.

Table 2.4-1 Types of High-Speed Optical Modulators

Optical modulators	Thin-film LN	Si	InP	EOP hybrid
Bandwidth [GHz]	–50	–40	–80	>100
VπL [V·cm]	2	0.2–2	0.8	0.03–0.3

As high-speed wireless communication utilization, for methods that use terahertz modulators to directly convert terahertz signals into optical signals, for instance, a transmission experiment at the 100 GHz band at 70 Gbit/s using a THz modulator with a thin-film LN, and direct terahertz modulation from 100 to 375 GHz using an EOP THz modulator have been reported.

As a spatial light modulator (OPA), research on methods using organic EO polymers (EOP-OPA) is progressing. Compared to methods using silicon (Si-OPA) and Liquid Crystal on Silicon (LCOS), higher performance in terms of optical scanning speed and power consumption is expected (Appendix C-2-2). R&D of EOP-OPA are primarily being conducted in Japan (NHK Science & Technology Research Labs and NICT), and given the specialized nature of the device manufacturing process, it is believed that Japan can take the lead in this field.

Gallium oxide (Ga_2O_3) is a new semiconductor device that is expected to be used in high-efficiency power electronics devices and extreme environments with high radiation. In this field, pioneering device research was conducted by Dr. Higashiwaki at NICT (at that time), and there has been a significant increase in the number of academic papers published since 2012, but the number of papers in the last 2 years has been consistent at just under 500 per year (Fig. 2.4-2). It is widely recognized as a new semiconductor field and has seen a surge in R&D in recent years, but recently there has been a sense of calm. The current general direction of R&D in the Ga_2O_3 field is as follows:

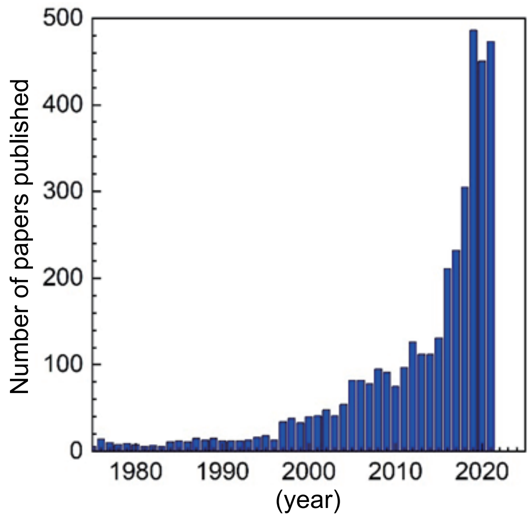


Fig. 2.4-2 Number of Papers Published in the Gallium Oxide Device Field

In terms of bulk single crystal growth of β-Ga_2O_3, which corresponds to the most stable crystal structure, the largest wafer manufacturer, Novel Crystal Technology, Inc., sells wafers of up to 4 inches on the market. Also, as a new development, C&A Corporation, a venture company originating from Tohoku University, has reported bulk single crystal Ga_2O_3 growth using a new crystal growth method that does not use precious metal crucibles. On the other hand, the progress of thin-film epitaxial growth is remarkable with metal-organic chemical vapor deposition (MOCVD) technology.

Device development has become more active in China, in addition to Japan and the United States, and there have been more transistor and diode development results announced in the last two years than ever before (Appendix C-2-3).

2.4.3 Future Prospects

By the 2030s, R&D of terahertz band wireless communication infrastructure technologies are expected to bear fruit. With the implementation of the ultra-high speed, large capacity, ultra-low latency, and ultra-numerous connectivity features of Beyond 5G/6G, it is anticipated that a society where anyone can benefit from ultra-fast information communication will be realized through the use of technologies such as terahertz band MIMO wireless LAN and high-precision video (8K) wireless distribution and transmission technology (Fig. 2.4-3). However, to achieve this goal, there are several challenges, such as increasing the output of transmitters, developing packaging technologies that support multiple-element antennas, and developing signal synchronization methods. In terms of these technical challenges, there is a need for technology integration in the electronics field (Si CMOS + compound semiconductor hybrid), integration with wireless communication technologies established up to 5G, and the establishment of fusion technologies with the photonics field. Additionally, it is considered that Japan, which has many excellent manufacturers of materials such as dielectrics, should plan differentiation by material.

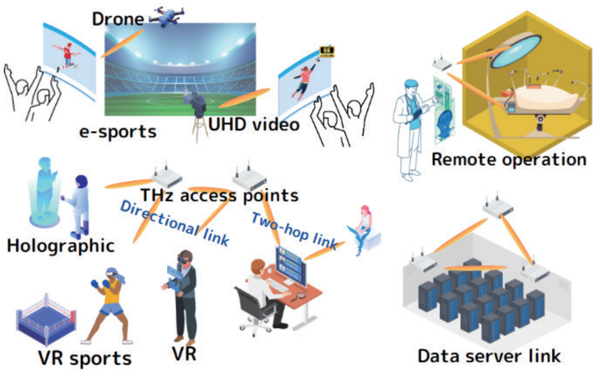


Fig. 2.4-3 Future Usage Scenarios for Ultra-High-Speed Wireless

In the field of deep ultraviolet (DUV) light devices, it is envisioned that the benefits of DUV LED device technology, which offers low environmental impact and high output in a small, portable format, will be utilized to bring about revolutionary technological innovations for life and social infrastructures in a wide range of sectors, spanning from optical information and communication fields to medicine, the environment, industry, and disinfection fields. For instance, it is anticipated that the dramatic expansion of the light frequency resources that can be used for optical information communication technologies and innovative communication technologies such as non-line-of-sight (NLOS) optical space communications, which cannot be achieved with traditional visible and infrared light technologies, will be realized. Along with the increase in such applications, it is expected that technological development aimed at further improving the performance, functionality, and reliability of small DUV solid light sources will progress. This should lead to further sophistication of foundational device technologies for advanced DUV ICT utilization, such as DUV laser diodes and ultra-high sensitivity sensing devices.

In terms of organic material ICT devices, along with aiming for the realization of 200 Gbaud (100 GHz band) and drive voltages below 1V for speeding up data communication and high-efficiency conversion between light and wireless in terahertz modulators for accelerating wireless communication, high-speed, large-capacity, and low-latency transmission using 100-400 GHz electromagnetic waves is also being targeted while the realization of an optical phase array (OPA) with visible light, which is required for new information communication technologies such as 3D image reproduction and smart glasses, is also expected (Fig. 2.4-4).

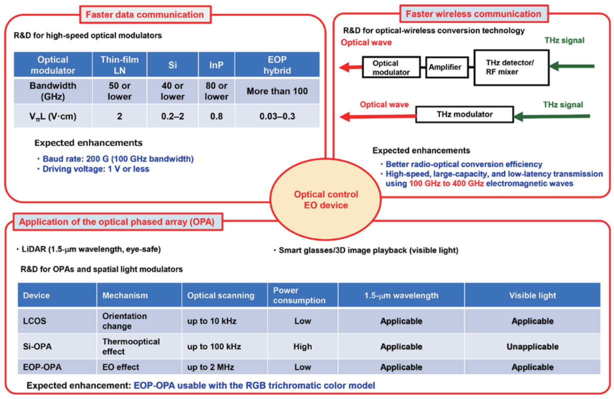


Fig. 2.4-4 Prospects of Organic Material ICT Devices

In the field of gallium oxide devices, it is necessary to concurrently explore solutions for the challenge of designing device structures without using p-Ga_2O_3, which possesses hole conductivity, while also diligently advancing the development of foundational technologies for bulk/thin-film crystal growth and device processes with future applications in mind. This includes, in terms of materials, the need to address fundamental challenges such as increasing the size and quality of wafers, controlling the conductivity of epitaxial thin films, heterostructures, and controlling surfaces and interfaces. Additionally, in the development of device processes, extensive work is required on substrate and epitaxial layer etching techniques, gate insulating films, edge termination, and more.

2.5 Cybersecurity

The rapid increase in cyber attacks is an urgent issue of national importance. In the field of cybersecurity, it is crucial to collect large amounts of data related to cyber attacks and to cultivate experts who can analyze these data and respond appropriately. However, in Japan, the primary approach has been to adopt and use foreign security products and technologies. This has led to stagnation in R&D due to the inability to accumulate know-how and insights related to core technologies, causing a decline in the self-sufficiency of security products and technologies. Based on the awareness of this issue, this chapter will provide an overview of trends in cybersecurity, as well as trends in R&D related to cybersecurity. We will discuss how we should approach R&D to improve Japan's cybersecurity capabilities.

2.5.1 Background

The environment around cybersecurity is changing rapidly. The following points will be discussed:

1. Increasing threats in cyberspace
2. IoT devices misused for cyber attacks
3. The evolution of social engineering
4. AI and cybersecurity
5. Technology transition towards the era of quantum computing

(1) Increasing Threats in Cyberspace

The outbreak of COVID-19 since 2020 has significantly changed people's lives. As teleworking and online business activities increase, the targets of cyber attacks are also increasing. In Japan, the NICTER Project [89] conducted by NICT continuously monitors communication packets arriving at approximately 300,000 unused IP address spaces (darknets) both in Japan and overseas. The number of these packets is an indicator of the extent of malicious activities on the Internet, such as malware infections. The annual total number of monitored packets per address in the large-scale cyber attack monitoring network in the NICTER project, as shown in Fig. 2.5-1, has increased by 50% compared to the previous year in 2020, and has remained at a high level [90].

While some cyber attacks aim at social and political targets, there is an increase in economic and organizational criminal activities targeting organizations, critical infrastructure, and nations. In 2022, 27% of cyber attacks had the goal of extortion. The most targeted region is Europe, where cyber attacks are believed to be taking advantage of geopolitical tensions. In particular, ransomware attacks, which encrypt an organization's data and demand a ransom for decryption, are evolving. Not only the recovery of encrypted files, but also threats to expose confidential information and personal information stolen from organizations to leak-sites on the dark web are being used to intimidate and increase the ransom. This is called double extortion, and it is becoming more common and is one of the causes for the increase in data leaks due to ransomware attacks. Moreover, as ransomware becomes a business model and more specialized (RaaS, Ransomware as a Service), a new ecosystem has been established. In this ecosystem, RaaS operators develop and distribute packages that allow organizations without the technical expertise to launch ransomware attacks. They do this through attackers known as affiliates, who are essentially "hired" to carry out the attacks. This has formed an ecosystem where affiliates execute the attacks. Also, duration of time to get a ransom has been shortened. While it took over two months to get a ransom in 2019, it may take less than three days as of 2022, increasing success rates at a lower cost. The targets of cyber attacks are not only large corporations, but also diversifying, including small and medium-sized enterprises, public institutions, and medical institutions.

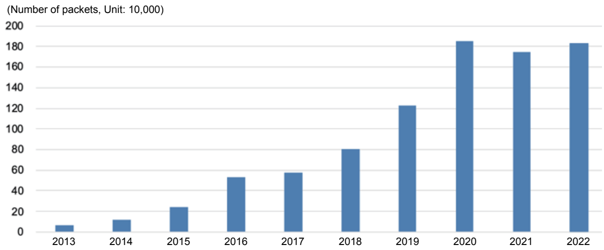
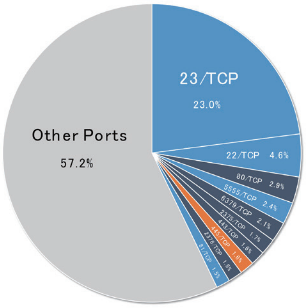


Fig. 2.5-1 Total Annual Packets Per IP Address Observed by NICTER (Past 10 Years)

(2) IoT Devices Misused for Cyber Attacks

Internet of Things (IoT) devices, such as internet-connected devices, home appliances, and surveillance cameras, are becoming targets of cyber attacks. Fig.2.5-2 shows the top ten main targets (destination port numbers) observed by NICTER in 2022. The light blue portion of the pie chart represents communications related to cyber attacks targeting IoT devices, such as web cameras and home routers.

These IoT devices have characteristics that make them vulnerable to cyber attacks, such as limited device performance, insufficient serviceability, and long lifecycle. If vulnerabilities exist in IoT devices, attackers can control these devices to launch large-scale cyber attacks (DDoS attacks), enabling them to amplify the attack. Particularly in 2022, several digital video recorder products in Japan were infected with a malware called Mirai, and these devices were misused as springboards for DDoS attacks. Regarding the defect, through the aforementioned NICTER project, the vulnerabilities of the devices were investigated with the cooperation of the product developers, and an unknown vulnerability was revealed. It was also observed that attacks that exploit the vulnerability are sent to only the targeted devices with high precision. Rapid sharing of information about incidents, countermeasures, raising awareness, and prompt implementation of vulnerability countermeasures to prevent the spread of damage are becoming increasingly important.



Port Number	Target
23/TCP	Telnet (Router, Web camera)
22/TCP	SSH (Server, Router)
80/TCP	HTTP (Communication control)
5555/TCP	ADB (Android debug bridge)
6379/TCP	Redis
2375/TCP	Docker REST API
443/TCP	HTTPS (Web server)
445/TCP	Windows SMB
2376/TCP	Docker REST API
81/TCP	HTTP (Home router)

Packets by destination port number
(excluding scan packets for investigation purposes)

Fig. 2.5-2 Main Targets of Cyber Attacks (Destination Port Numbers) in 2022 as Observed by NICTER

(3) The Evolution of Social Engineering

Social engineering is a method of attack that takes advantage of human psychological tendencies and social behavior, exploiting these vulnerabilities. Specifically, it is a method of obtaining information necessary for intrusion without using advanced technology, compared to cyber attacks. This can include, for example, posing as a network administrator, feigning urgency, and phoning the target individual to extract their password. Phishing is a type of social engineering where fake websites are created, inducing users to click the URL through emails or other means by making it indistinguishable from the real website, with the aim of stealing personal information such as user IDs and passwords. In 2022, phishing remained the top method of intrusion, accounting for 41% of incidents [91).

Unlike attack methods that exploit technical vulnerabilities, social engineering attacks target human nature and social psychology. Therefore, approaches from the perspectives of psychology, human factors, and practical security are indispensable.

(4) AI and Cybersecurity

Methods of utilizing AI technology in cybersecurity measures, such as automatic malware analysis and threat detection/prediction, are advancing. At the same time, there is a risk that AI technology could be misused for more sophisticated cyber attacks. For example, there are concerns that attackers could use AI to improve the accuracy of phishing attacks, enabling more effective attacks. In addition, numerous attack methods against AI itself have emerged, making the establishment of AI security technology, which defends AI, an urgent task [92)].

(5) Technology Transition towards the Era of Quantum Computing

The current public-key cryptography will become less secure if large-scale quantum computers are realized. The remarkable development of quantum computers will become a significant threat from a cybersecurity perspective. In preparation for this risk, the National Institute of Standards and Technology (NIST) in the United States initiated the standardization of new cryptographic technology called Post Quantum Cryptography (PQC), which can withstand attacks by quantum computers, in 2016 [93)]. In July 2022, multiple methods were announced as the subject of standardization from among candidates submitted from all over the world.

The challenge going forward is how to transition from the current encryption methods to PQC. It will be necessary to replace all widely deployed cryptographic modules, which will require significant costs and a long transition period. On the other hand, the time when quantum computers capable of decrypting current encryption are developed is fast approaching. Responding to the transition is already an urgent issue.

2.5.2 Current Research and Development Trends

We will discuss the current R&D trends in the field of cybersecurity, focusing on several cybersecurity technologies and the underlying cryptographic technologies.

(1) Cybersecurity Technologies

■ Data-Driven Cybersecurity Technologies

The establishment and advancement of following technologies are required: observational techniques that analyze cyber attacks from various angles based on real data, visualization methods that aid in situational understanding, and automated analysis and counteraction tools utilizing AI technologies such as machine learning. The observation and analysis results from the previously mentioned NICTER project are shared with the government and related organizations to aid in a response, and some of the results are also publicly available on the NICTERWEB [94)].

■ AI x Cybersecurity

To integrate AI technologies, such as machine learning, and cybersecurity technologies, following technologies are currently under R&D: detection and analysis of malware campaigns on the internet, analysis of a large amount of malware to infer its functionality, extraction of crucial alerts that truly require a response from the alert information reported by various security appliances, detection of dangerous web pages from JavaScript or user access history, and threat intelligence extraction and analysis. These technologies obtain high-value information in real time from the vast amount of collected cybersecurity data.

■ Cyber Attack Observation Technology

In targeted attacks aimed at specific organizations, it is extremely rare for detailed information about the attack to come from the affected companies or organizations, making it difficult to understand the actual situation of targeted attacks and derive appropriate countermeasures. As a method of observing what kind of behavior attackers are exhibiting in the intrusion destination, it is possible to build a huge dummy network that intricately mimics a real organization, lure attackers by running malware such as targeted attacks, and observe them stealthily (Fig. 2.5-3). The attribution of human attackers and the identification of the true origin are possible by embedding beacons in the dummy data.

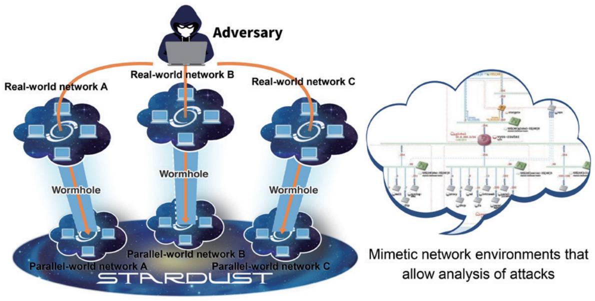


Fig. 2.5-3 The Targeted Attack Attraction Infrastructure STARDUST

■ 5G/Beyond 5G Security

Commercial use of 5G has begun, and networks with the characteristics of ultra-high-speed large capacity, high reliability and low latency, and multiple simultaneous connections are beginning to spread. In 5G networks, a wide variety of devices are connected, and while the realization of various services such as autonomous driving, remote medical care, smart agriculture, smart factories, and high-definition video production is expected, concerns about new security threats that were not anticipated in the traditional environment are emerging due to the introduction of new technologies.

In Japan, the R&D of joint 5G security testbed has started in 2020 by KDDI, NTT Docomo, NEC, NICT, and others. Within the communication network of NICT, a 5G verification environment was built to conduct technical verifications such as anticipating security threats in the 5G environment and perform modeling analyses and take mitigation measures. The testbed includes a 5G core network using the open-source software OpenAirInterface and free5GC and a wireless access network with Software Defined Radio (SDR) devices. The knowledge gained from various verifications has been published by the Ministry of Internal Affairs and Communications as the "5G Security Guidelines" [95].

■ Hardware Security Verification Technology to Address Supply Chain Risks

With the spread of IoT devices and increasing supply chain risks, the importance of technology to verify whether a device has vulnerabilities or intentionally implanted backdoors (hidden entrances that can be infiltrated from the outside) is growing. As an example, R&D of security technologies in areas closer to hardware, such as firmware, kernel modules, FPGA (Field-Programmable Gate Array), IC chips, and sensor devices, are being conducted (Fig. 2.5-4).

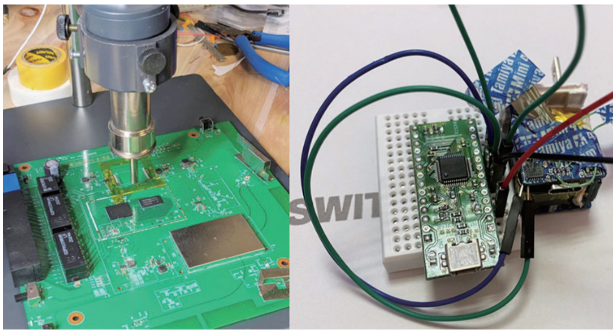


Fig. 2.5-4 Hardware Security Verification Technology for Addressing Supply Chain Risks

■ Usable Security

When considering security issues, the human perspective (users, system developers, and service providers) cannot be ignored. Particularly, the usability of the system or service is crucial when users are utilizing them. However, the system could become complex in order to ensure security, potentially compromising usability, leading to a typical trade-off relationship between security and usability. Therefore, the concept of usable security, which ensures security without compromising the effectiveness, efficiency, and satisfaction of users to achieve their original goals becomes important. For instance, issues include general users agreeing to privacy policies without understanding them when downloading apps, or the inconvenience for people with physical disabilities in security authentication. Other ongoing R&D efforts include appropriate methods of notifying general users who are using vulnerable devices about security and countermeasures, as well as methods to encourage user behavior changes in the desired direction by utilizing nudges.

(2) Cryptographic Technologies

■ Cryptographic Technologies for Trusted Data Flow

DFFT (Data Free Flow with Trust) aims to ensure the cross-border flow of data to solve business and social issues, promoting international free data flow while ensuring trust for privacy, security, and intellectual property rights. DFFT was advocated by Japanese Prime Minister Abe (at the time) at the World Economic Forum annual meeting (Davos conference) held in Geneva, Switzerland in January 2019, and it gained support from world leaders at the G20 Osaka Summit in June 2019, resulting in its inclusion in the leader's declaration. While R&D on cryptographic technologies to ensure security and privacy at every stage of data provision, collection, storage, analysis, and deployment has been conducted for a long time, the R&D of cryptographic techniques such as secret computation, which obtains computation results while ensuring data confidentiality and privacy, is a field where Japan excels. This is included in the third phase of the Strategic Innovation Creation Program (SIP) in Japan. For example, collaborative machine learning among independent nodes while preserving privacy has been developed as a federated learning technique. This technique has been utilized in demonstration experiments conducted by NICT and several financial institutions, working towards solving societal issues such as more accurate detection of fraudulent transactions [96)].

■ Cryptographic Technologies for the Quantum Computing Era

In anticipation of an era where quantum computers are available, various countries are actively conducting R&D on quantum cryptographic communication, post-quantum cryptography, and the design, development, safety assessment, and implementation of quantum-resistant security protocols to establish secure systems that can be safely used. Specifically, R&D are being advanced on lattice-based cryptography and multivariate public-key cryptography, which are expected to become the global standards for post-quantum cryptography, and the security assessment of widely used RSA encryption and elliptic curve encryption. In Japan, based on these achievements, safety evaluations of cryptography recommended for e-government and considerations on proper implementation methods and operational methods of cryptographic technologies, are being conducted [97)]. For quantum cryptographic communication, please refer to Chapter 2.6.

■ Blockchain Security

In the Web3.0 era, blockchain technology is a core technology aiming to achieve a more decentralized, secure, and transparent web environment. Research on its security is being actively conducted at academic conferences both domestically and internationally. Notably, smart contracts implemented on the blockchain and NFTs (Non-Fungible Tokens) that guarantee the ownership of digital content and assets are attracting attention.

2.5.3 Future Prospects

In order to strengthen Japan's international competitiveness in the cybersecurity field and avoid dependence on foreign security technologies that support the services of government agencies and key infrastructure operators, it is essential to have a domestic environment capable of generating, accumulating, and providing cybersecurity information. Furthermore, to protect the safety of society against the increasing cybersecurity risks due to rapidly evolving technologies, it is critical to have professionals with specialized cybersecurity knowledge. However, there is still a shortage of such professionals, and there is a need to further accelerate their development.

Based on such problem consciousness, in Japan, the Cybersecurity Nexus (CYNEX) [98)] was established in April 2021, aiming to construct advanced infrastructure that serves as a nexus of industry, academia, and government, utilizing vast data related to cyber attacks and expertise in human resource development. This initiative is expected to improve Japan's cybersecurity response capabilities by collecting, accumulating, analyzing, and providing cybersecurity information domestically and providing a common platform for developing cybersecurity talent across society.

In recent years, cybersecurity has become an increasingly important element for national security. Considering that cyber attacks occur across borders and that modern supply chains are deployed globally, there are limits to independent responses by a single organization or country, and global cooperation is needed. For instance, there are movements to build a cooperative security relationship, including for cyberspace, between the North Atlantic Treaty Organization (NATO) and Japan. Building trusting relationships among stakeholders, sharing information, and building cooperative systems can realize more effective measures [99)]. Establishing a global hub for cybersecurity R&D is crucial for this purpose. This involves utilizing the neutrality of national research institutions, for example, and building close relationships with overseas research institutions.

2.6 Quantum ICT

As mentioned in Chapter 1.2, R&D in the ICT field using quantum technologies is currently being actively pursued in various regions around the world, including Japan. These are challenging attempts to open up entirely new ICT schemes that are not present in traditional concepts by directly manipulating the quantum mechanical properties of matter, such as quantum entanglement and quantum interference. The possibilities include quantum computing technologies that enable large-scale superparallel information processing, quantum information communication technologies that realize functions not achievable with conventional communication, and quantum sensing technologies that realize ultimate measurement performance by utilizing quantum mechanical effects. In fact, quantum internet as a form of quantum information communication and quantum computers implementing quantum computing technologies are attracting attention. On the other hand, fundamental and ultimate technological innovations that require going back to physical principles are necessary, and many research groups are advancing R&D through various approaches from both theoretical and experimental perspectives. This chapter focuses on (1) Quantum Computing Technology, (2) Quantum Communication Technology, and (3) Quantum Device Technology, and it provides a technological overview.

2.6.1 Background

(1) Quantum Computing Technology

Many projects are being launched worldwide due to papers by Google claiming to implement a quantum computer and perform information processing far faster than conventional computers and the roadmap presented by IBM for large-scale quantum computers in the near future. Recently, it was reported in Japan that a quantum computer available for general use has been implemented. These are quantum computers in the category known as NISQ (Noisy Intermediate-Scale Quantum), which are experimentally available for use, such as through commercial releases, but from the perspective of practical quantum computers, sufficient performance has not yet been achieved. There are numerous technical requirements to be met for implementing quantum bits, the basic unit of quantum information processing, such as enabling arbitrary operations and extending coherence time sufficiently, but no method satisfying all of these has been found yet. Currently, efforts are being made to maximize the performance of quantum bits in various ways such as superconductivity, ions, light, and spin, and we are at the stage of assessing their technological potential. Note that significant improvements in accuracy are being achieved through these efforts to improve performance, leading to a reconsideration of traditional concepts regarding the number of physical quantum bits needed for error correction mechanisms and an intense competition in R&D is unfolding with the realization of universal quantum computers 30 years from now in mind.

Quantum annealing is one method of quantum computation. This is a method of information processing using quantum bits, which was first commercialized by D-wave in Canada. These are sometimes positioned as a type of quantum computer from the perspective of information processing with quantum bits, and they theoretically have the same capacity as quantum computers depending on the conditions, but on the other hand, whether combinatorial optimization problems, which are considered typical applications of quantum annealing, can be solved more effectively than with conventional computers is not yet theoretically clear, and there are many unknowns regarding their effectiveness.

(2) Quantum Communication Technology

Quantum communication, which uses the properties of quantum mechanics, is a highly useful secure communication technology for which information secrecy is needed because it can detect eavesdropping of information based on the principles of quantum mechanics. In particular, quantum cryptography makes the sharing of secret keys with absolute security possible and is already being used in practice. In fact, network-like testbeds for quantum cryptography are being planned or built on optical fiber networks in Japan, the EU, the United States, China, South Korea, and other countries, and the main focus of applied research now shifts to how to implement and use quantum cryptography networks as systems. On the other hand, there is also the theoretical consideration that the limit of the optical fiber communication distance over which quantum cryptography can be exchanged is about several hundred kilometers, which is a major factor limiting the use cases for this technology, so technical innovations to address this are being explored.

Technology that conducts direct communication using laser light without using optical fibers is one direction of R&D because it can solve the maximum communication distance problem, which is the biggest technical issue in quantum cryptographic communication. This technology is being used in satellite-to-satellite secret communications, and China, which was the first in the world to realize quantum cryptographic communication using satellites, has a head start in terms of technical and experience.

(3) Quantum Device Technology

As R&D centered on the keyword “quantum” becomes increasingly active globally, there are many approaches to how to actually implement various quantum states in devices, but the presence of devices using superconducting phenomena is notably increasing. Superconducting quantum bits realized using superconducting phenomena are the most integrated in terms of integration among the numerous quantum bit candidates, such as ions, light, spin, and atoms, due to their excellent integrability and scalability.

The development of stable single-photon sources and high-sensitivity receivers, which are key technologies used in quantum communication, is also progressing because the technology for generating and detecting single photons is extremely important. In particular, the superconducting nanostrip single-photon detector (SNSPD), which uses superconducting phenomena, not only has excellent performance with high detection efficiency, low dark count rate (low noise), high counting rate, and low jitter at communication wavelength bands, the technology to integrate the elements on a substrate is progressing, it is widely spreading in the field of quantum information communication, and R&D towards practical use is ongoing (Fig. 2.6-1).

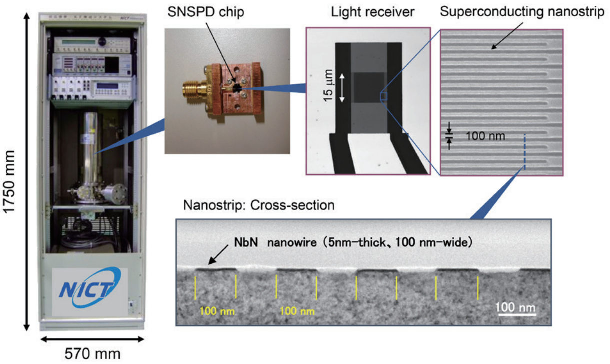


Fig. 2.6-1 Single Photon Detector Developed by NICT

2.6.2 Current Research and Development Trends

(1) Quantum Computing Technology

For the establishment of quantum bit operation technology, the use of various physical quantities such as superconductivity, light, spin, atoms, and ions is being considered. We are currently verifying to what extent a large-scale quantum computer can be realized with each method and resource. Both theoretical and experimental efforts are being made to expand the indicators that represent the feasible scale of meaningful quantum computing (for example, Quantum Volume) and to improve the calculation accuracy of the basic quantum computing.

In the case of superconducting quantum bits, which are currently the most successful at integration, multiple efforts are being made toward the realization of a large quantum computer, assuming a situation where the number of quantum bits in a refrigerator increases to about 100,000, and using high-density wiring cables, reducing heat inflow by turning control sequences into light pulses, and examining miniaturization and on-chip implementation of microwave components. In the case of ion and neutral atom methods, which have long coherence times and can achieve high calculation accuracy, there is also a movement to realize a quantum computer by using physical quantum bits directly without error correction by maximizing the calculation accuracy. Other theoretical attempts are being made to improve accuracy (Appendix C-4-1), but it is a common understanding that time is still needed (at the earliest, by 2030) to demonstrate the superiority of a quantum computer that has been theoretically proven at a practical level. Because of this current situation, from a theoretical point of view, there are attempts to realize a quantum computer that can withstand practical use by maximizing the use of existing technology, such as research on quantum computing algorithms that can be implemented with only the existing NISQ devices and research on quantum advanced computational information processing that combines a small quantum computer with a conventional type of supercomputer.

(2) Quantum Communication Technology

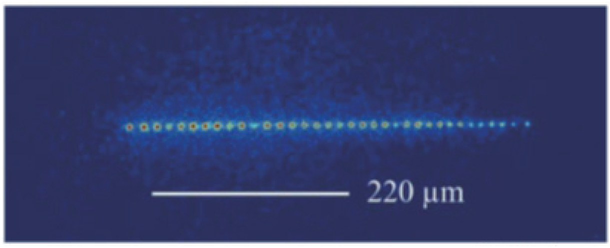
Experimental research is being conducted in various fields to realize a proposed method to extend the feasible distance of quantum communication (quantum relay). The realization of this requires the implementation of nodes that can process quantum information as it is (quantum nodes, thus, for example, many resources are being invested in research to convert and transmit quantum information between different media, such as light and matter. In terms of application-oriented research, there are attempts to implement practical functions using a quantum cryptography network. Specifically, there is a variety of research directions ranging from simple ones that enable key sharing over long distances by performing key relay via intermediate nodes, to those that combine the secret keys supplied by quantum cryptography with classical network protocols such as secret sharing and network coding, to achieve security that could not be realized with traditional classical protocols.

For fundamental research related to quantum information communication technology using optical fibers, efforts are also being made to improve fundamental device performance, such as with high-transmission-rate fibers and low-noise light receiving elements. These not only contribute to improving the theoretical limit of the distance possible for quantum communication, but also to improving the performance of general communication technologies, and are issues that should be steadily addressed.

As for quantum communication technology using satellites, although the high cost of satellite launches limits the technology to specific research bases, development is steadily progressing. For example, China reported a successful experiment of on-satellite quantum cryptography in 2017, and in Europe, the EU has announced a plan to conduct orbital tests of its own in 2025 and to start services in 2028.

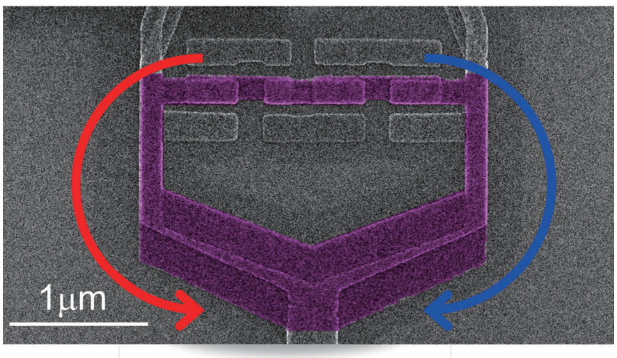
(3) Quantum Device Technology

Various physical concepts are being considered as candidates for quantum devices, but devices using superconductivity have a clear advantage due to their excellent integration and scalability. For superconducting quantum bits, the extension of the quantum state retention time (coherence time) has been a long-standing issue, but in recent years it has become possible to stably achieve a coherence time of more than 0.1 ms by using tantalum (Ta) or nitride superconductors as electrode materials. On the other hand, the ability to set circuit parameters arbitrarily for each element is also an advantage of superconducting quantum bits. Therefore, development is progressing on methods for adjusting element characteristics by individually irradiating finished elements with a laser (post-annealing). In addition, the number of elements that can operate with one refrigerator is constrained by the number of wires that can be introduced into the ultra-low temperature environment of several 10 mK; the installation space for low-noise amps, circulators, and other peripheral parts; and power consumption. Therefore, efforts are being made toward miniaturization, low power consumption, and control circuits that operate at ultra-low temperatures (Fig. 2. 6-2).



Source: NICT press release

(a) Ion-trapped qubits



(b) Superconducting qubit

Fig. 2.6-2 Examples of Quantum Bits Used in Quantum Computers and Quantum Repeaters

2.6.3 Future Prospects

(1) Quantum Computing Technology

By 2030-2040, it is believed that large-scale quantum computers will be achievable. However, it is not yet clear which of the many quantum bit techniques will come to fruition as implementation technologies. At this point, it is not wise to narrow down the direction; instead, exploratory research that broadly investigates technological possibilities through various approaches will remain important for some time. Also, to scale up quantum computers, it is necessary to distribute the system, making the development of quantum media conversion technology, which can convert quantum information into light and move it spatially, essential. Coherently connecting adjacent refrigerators using a cooled microwave cable method, with a refrigerator group equipped with about 5000 quantum bits, can be expected to realize a quantum computer of about 100,000 quantum bits in about five years, it could serve as a rough milestone.

(2) Quantum Communication Technology

To realize a global quantum cryptography network via terrestrial optical fibers, establishing quantum relay technology is crucial. To achieve this, it is essential to develop technologies such as 1) single-photon generation devices and 2) quantum media conversion technology and to 3) accurately implement simple quantum operations on quantum bits.

On the other hand, from the perspective of national security, Japan needs to develop and possess its own satellite-based quantum cryptography technology. During this process, the following technological requirements are important: 1) communication should be possible even during daytime, 2) communication should be possible even in cloudy weather, and 3) satellites should not require security. If each of these can be realized, it is thought that usability and reliability will dramatically improve.

(3) Quantum Device Technology

With superconducting quantum bits, if a coherence time of more than 1 ms can be stably achieved, further improvements in gate fidelity are possible, leading to a drastic improvement in computational accuracy. Meanwhile, reducing the variance in circuit parameters is also crucial. Not only post-annealing by laser but also the development of a manufacturing process that fundamentally suppresses variance will be essential. To achieve these, it is necessary to work on circuit types and material processes, and the superiority of using “quantum” in practically effective calculations beyond such R&D will be proven in near future. On the other hand, the realization of a universal quantum computer requires increasing the number of elements by 4-5 orders of magnitude compared to NISQ computers, and there are numerous problems to be solved, thus it will still take some time to realize it.

(4) Conclusion

When these various problems are solved, and quantum information processing matures in the future, it is believed that the fusion of the current (classical) network and the new quantum network will progress. There, the network will become multi-layered, and along with the establishment of ultimately secure communication using quantum networks, enhancements to quantum computing and the realization of quantum sensor networks via quantum networks are expected (Fig. 2.6-3).

In conclusion, this overview of the quantum ICT field has addressed the surrounding environment, current R&D trends, and future prospects. The effort for this technology can be seen as an ambitious attempt to implement quantum mechanics, which has often been discussed from an academic viewpoint, as a technology that can be used for information processing and communication. A generation ago, quantum computing, quantum cryptography, and quantum communication were just fantasies, but various technological innovations in recent years have brought them within reach. If this technology is actually used, it will undoubtedly bring many benefits to people's lives, such as the realization of secure information communication, the acceleration of useful material exploration, and contributions to reducing the environmental impact from an energy perspective. Since this is also one of the areas where Japan has superiority, continuous development is essential.

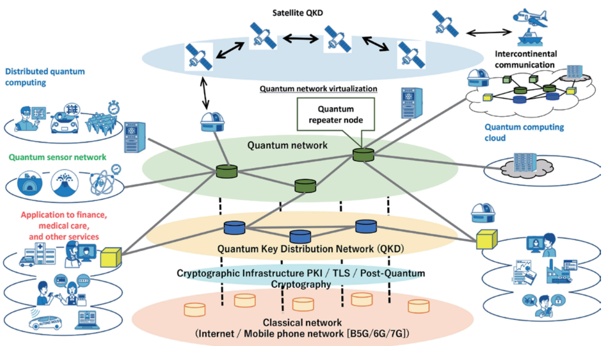


Fig. 2.6-3 Future Vision of Quantum Internet (Modified from NICT Quantum Internet White Paper

2.7 AI/Universal Communication

We are on the verge of a future society where individuals can freely communicate not only with each other, but also with objects such as robots, or where objects can communicate among themselves. In a human-centered society, major means of communication can be language, facial expressions, gestures, and actions. In this chapter, we consider comprehensive communication that overcomes various barriers, including both verbal and non-verbal information as Universal Communication, together with an overview of its trends (Fig. 2.7-1). Generally, the barriers that hinder smooth communication include language barriers, knowledge barriers, and even cultural barriers, and various R&D efforts are being carried out to overcome these barriers. In particular, AI technology that supports diverse communication has been rapidly developing in recent years.

AI technology, a topic of frequent discussion these days, is classified into technology for a discriminative system and technology for a generative system. The former is suitable for tasks such as classifying input data, such as document classification, and the latter is suitable for tasks like generating synthetic samples of data, such as sentence generation. Recently, the performance of generative AI technology has greatly improved. Along with this, AI technology is beginning to be used widely in commercial applications with the support of users, and new services utilizing generative AI technology (such as automated email generation and design assistance) are being created one after another.

As an example of generative AI, there have been reports of over 20 major companies announcing the provision of services utilizing a conversational AI, ChatGPT, from early on. In multilingual processing technologies that handle human language, such as speech recognition, machine translation, and speech synthesis, a transition is occurring from discriminative AI to generative AI technologies.

In recent years, AI technologies that handle multimodal information, not just speech and text, but also images and various IoT data, are attracting attention, and the types of handled information have been diversified from individual information such as speech, text, and images to their combinations. In a future society where the real world (physical space) and the virtual world (cyber space) are highly integrated, digital twins (Appendix C-3-2) model the real world (Appendix C-3-1), reproduce it in cyber space, and provide feedback on the analytical results in the real world, which lead to changes in communication and subsequent behavior will be implemented and utilized in city planning and more. Even in this field, AI technology that handles multimodal information is being increasingly utilized.

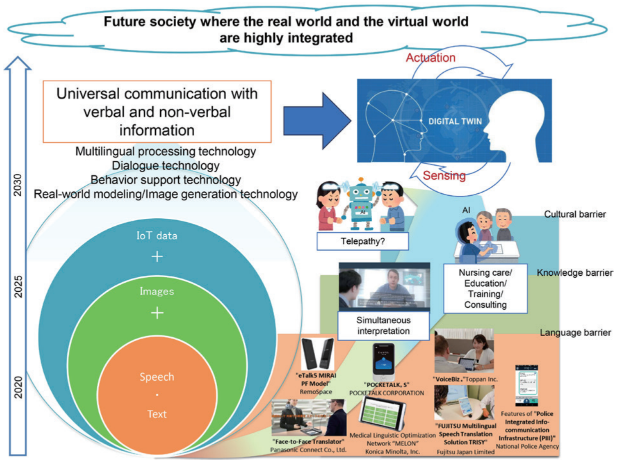


Fig. 2.7-1 Future of Universal Communication

On the other hand, it has been pointed out that AI can generate disinformation that is indistinguishable from the truth, biased information, or information that infringes on privacy or copyright. It is feared that AI incorrectly learns such information as appropriate information, and inappropriate information is further spread by users who use the AI, or exploited for fraud, impersonation, and other unfair practices, which will spread and lead to social confusion. Moreover, there are concerns about the distortion of individual decision-making due to the prevalence of unidentified texts generated by AI that do not disclose what training data was used, and there are also claims that discussions about the impact of AI on human rights and democracy are not substantively being held as an emphasis is placed on industrial development and technological innovation [100].

In terms of the global trends for generative AI, there are cautious movements such as announcements prohibiting the use of ChatGPT due to difficulties in limiting falsehoods and biases, as well as infringements on privacy and copyright and establishment of ethical regulations for AI in the EU. Japan also needs to establish ethical norms, guidelines, and legal frameworks not only for technical considerations but also to prevent social turmoil and business delays. In particular, considerations for transparency, fairness, diversity assurance, clarification of responsibility, and protection of rights such as personal information and copyright are important in the collection of data and the use of content generated by AI.

In the following, we will focus on the R&D trends of technologies related to language, specifically (1) multilingual processing technology, which is the basis of communication, and (2) large-scale language models and conversational technologies that support them.

2.7.1 Background

(1) Multilingual Processing Technology (Speech recognition and synthesis, machine translation, simultaneous interpretation)

Regarding speech recognition and synthesis, statistical-based approaches were the mainstream until around 2010. However, with the emergence of deep learning technology, hybrid technology that replaced some functions of statistical-based approaches with neural networks became widely spread. Subsequently, from around 2016, R&D of End-to-End technology, which conducts all speech recognition and synthesis processes with neural networks, became the mainstream. After the rise of deep learning, in the field of speech recognition, Big Tech companies such as GAFA, Microsoft, and IBM fiercely led R&D, and various methods were proposed. Various products such as voice search apps and smart speakers were developed and widely used. In speech synthesis, starting with Google DeepMind's WaveNet in 2016, neural network-based speech synthesis models have become mainstream, and currently, many fast and high-quality models that can be processed only with CPUs have emerged. Recently, multiple speaker models that can synthesize voices of any speakers, such as Microsoft's VALL-E, have also been proposed.

For machine translation, since Google Translate introduced Neural Machine Translation (NMT) in 2016, its accuracy has been greatly improved. In addition to Google and Microsoft, DeepL has become widely used both domestically and internationally as a major machine translation provider. On the other hand, while R&D of simultaneous interpretation is actively carried out, practical applications have just begun. Research on multimodal translation using images is still in the research stage. For these machine translation technologies, although they have reached about 80 to 90 percent accuracy for general text and their accuracy has been improving, there is still room for development in terms of versatility and usability.

(2) Large Language Models (Dialogue Technology)

Large Language Models (LLMs) are massive neural networks trained on vast amounts of text data (primarily web text, ranging from several hundred GB to several TB). They can perform a wide array of language processing tasks, such as question-answering, text generation, machine translation, with high accuracy by further training, known as fine-tuning on data specific to the final target tasks. As an LLM can execute various tasks based on one model, it is also called a foundation model [101]. It generally follows the Transformer architecture [102] (see Appendix C-3-3).

In traditional language processing R&D, a machine learning device such as a neural network was designed by task, training was made using data specific to the task, for the task to be executed. LLMs are expected to be a desirable technology where all language processing tasks can be done with high accuracy using a single model. LLMs can learn not only natural languages used by humans but also programming languages, and some can generate program code. In particular, generative LLMs, capable of executing various tasks including program code generation, are drawing attention for potentially revolutionizing the way white-collar work is done. However, as discussed later, there are risk factors for practical use compared to cognitive LLMs.

The first famous LLM was GPT-3 (175 billion parameters, Brown et al. [103]). ChatGPT [104], the improved version of GPT-3, has become a social phenomenon by attracting billions of users in a short time due to its high capability. Increasing the number of parameters and making the neural network larger for higher accuracy has become a trend. Following GPT-3 (see Appendix C-3-4), larger models like Google's PaLM with 540 billion parameters, Chowdhery et al.[105] and Wudao 2.0 from China with 1.75 trillion parameters [106] have appeared (Fig. 2.7-2).

Chatbots that utilize LLMs, like ChatGPT, are also called conversational AIs. While it is not a totally new app, ChatGPT can be considered the world's first conversational AI widely recognized by general users for its utility.

As mentioned at the beginning of section 2.7, there are technical issues with generative AI (see Appendices C-3-5 and C-3-6), and indeed, there are many concerns pointing out the various negative impacts on society. However, in February 2023, Microsoft announced the integration of ChatGPT into its search engine, Bing, and started to release a preview version. Google has also started a similar service using Bard. Moreover, as of this writing, OpenAI has announced GPT-4 [107], which is available on ChatGPT and Bing. Also, ChatGPT is accessible through API, and various services and apps have been born, and Japanese companies have started to utilize them [108]. Numerous other private companies and research institutions have announced similar efforts, and R&D on conversational AI utilizing LLMs is fiercely competitive.

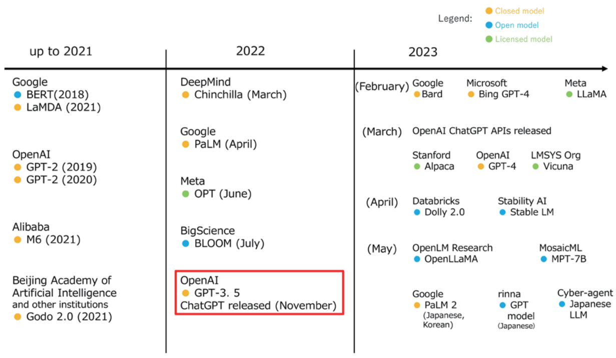


Fig. 2.7-2 Recent Trends in LLM

2.7.2 Current Research and Development Trends

(1) Multilingual Processing Technology (Speech recognition and synthesis, machine translation, simultaneous interpretation)

In speech recognition, besides Big Tech, there has been an upsurge in Asian companies like Baidu, iFlyTek, and LINE (acquired by Works Mobile Japan) intensifying competition in foundational technology R&D. Also, domestically, companies like NTT and Yahoo Japan are gaining momentum. Technically, composite speech recognition techniques that incorporate speaker identification, language identification, and various acoustic signal processing techniques within an end-to-end framework have been proposed. While paid speech recognition APIs are provided by Google, Microsoft, and other big companies, high-quality speech recognition APIs that can be used for free, like OpenAI's Whisper and Reason Speech have been released, causing increasingly intense competition in product development.

In the realm of speech synthesis as well, besides Big Tech [109], companies like South Korea's Kakao Enterprise are competing fiercely in R&D. In particular, a large number of high-quality neural speech synthesis models for single and multiple speakers have been proposed.

Regarding machine translation, currently, high-precision machine translation is possible by scaling up NMT for languages like English and German, which have a large number of parallel corpora. For cases that require domain-specific parallel corpora, such as specialized fields, there are studies improving machine translation accuracy by searching translation memories. For translation between low-resource languages with few data samples, there are studies creating translation models by fine-tuning large language models like BART. On the other hand, there has not been significant progress in translating long texts like documents with consistency. Research is also actively ongoing to determine the reliability of machine translation results. There has been a recent trend of studies that detect errors not only in machine translation but also in human translation or evaluate specific linguistic phenomena (disambiguation of word meanings, anaphora, etc.). In simultaneous interpretation, there are studies aiming to increase translation processing speed while maintaining high translation accuracy. Furthermore, multimodal machine translation that utilizes image or video information is at the research stage.

(2) LLM (Dialogue Technology)

Pre-training and fine-tuning an LLM require vast computational resources, hence, it is not easy for anyone to readily develop applications utilizing LLMs beyond connecting their services to the likes of ChatGPT via APIs. Additionally, it has been pointed out that the large-scale implementation of LLMs and reward-based reinforcement learning alone are insufficient from the perspective of realizing artificial intelligence [110], and R&D into new architectures and learning methods are also being promoted.

Regarding the research and development of constructing LLMs, further scaling is likely to continue as an extension of the current trajectory. However, when considering operational costs for the deployment of commercial services, there is a demand for more efficient models of a scale that are accessible to everyone, and progress is expected in the development of medium-scale LLMs. Meta's announcement of LLaMA [111] in February 2023 can be seen as indicative of this direction. For example, LLaMA-13B with 13 billion parameters showed higher accuracy than GPT-3 with 175 billion parameters in almost all benchmarks. With LLaMA made available for research purposes, the subsequent announcements of Vicuna with 13 billion parameters and Alpaca with 7 billion parameters, which were fine-tuned from LLaMA, quickly followed. Notable among commercially available open-source LLMs is BLOOM with 175 billion parameters, and since the start of 2023, commercially available LLMs, such as Dolly2.0 with 12 billion parameters, StableLM with 7 billion parameters, and OpenLLaMA with 7 billion parameters, have been developed and released, thus the development of such open-source LLMs is expected to accelerate further.

Within Japan, rinna Co., Ltd. has released a Japanese LLM with 3.6 billion parameters, and CyberAgent has released a Japanese LLM with 6.8 billion parameters, both under commercially available licenses. At NICT, while the learning data is not large, a GPT with 40 billion parameters has already been constructed and the large-scale expansion of learning data and models is considered in the future.

2.7.3 Future Prospects

(1) Multilingual Processing Technology (Speech recognition & synthesis, machine translation, simultaneous interpretation)

To achieve high-accuracy End-to-End speech recognition, it is necessary to collect and organize more speech corpora that are pairs of spoken words and their labels (voice and transcriptions) than ever before and implement model learning for speech recognition. The preparation of a large amount of speech corpora requires enormous financial and human costs, and it is easy to foresee that there will naturally be a limit. For the limit, research on model learning using a large amount of unlabeled audio data is becoming a significant trend. The two mainstream methods are semi-supervised learning, which uses pseudo labels generated by speech recognition, and self-supervised learning, which pre-trains an audio feature extractor using a large amount of unlabeled data and then tunes it with a small amount of labeled data according to the application. These are promising technologies for the future development of speech recognition.

Meanwhile, no organization has started working on speech synthesis technologies such as speech speed control for simultaneous interpretation, so it is crucial to conduct focused research on this. Also, it was found that an End-to-End model for multiple speakers using speech recognition corpora can achieve a recognition rate equivalent to the original sound. This means that the learning data for speech recognition can be generated not only from real speech but also from models. Since natural text can be generated infinitely by neural language generation models, it is possible to generate a learning set for speech recognition that can handle unknown words, etc. However, as technologies like VALL-E become capable of synthesizing any voice in high quality, technologies such as digital watermarking for the secure use of synthetic voices will become increasingly important.

Regarding machine translation, first, for high-resource languages (for which large-scale parallel corpora are available), continuous research for further improvement of machine translation accuracy is needed. For example, even between high-resource languages, translating low-frequency events such as technical terms, colloquial expressions, and idioms is challenging. Also, to improve the translation accuracy of specialized fields, it is necessary to continue developing parallel data for various fields (such as Translation Banks [112]) and research on domain adaptation. In terms of machine translation between low-resource languages with few data samples, continued research on fine-tuning large language models is likely to remain mainstream. Given the numerous languages around the world, there is likely to be a trend towards improving machine translation accuracy between many languages through global collaboration. Furthermore, although the accuracy of machine translation has been improving, current Neural Machine Translation (NMT) systems do not have a mechanism to guarantee the accuracy of translation results, requiring users of NMT to verify the accuracy on their own. At present, a method is being used where the translation output of MT is back-translated to the original language, and this is compared with the input original text to verify the accuracy of machine translation results. However, in the future, we will need to develop and research various other methods that allow even users who do not understand foreign languages to verify the accuracy of machine translation results. With respect to simultaneous interpretation, there will likely be research on multimodal machine translation that uses image information, such as lecture slides, and others.

(2) Future prospects of LLM and its applications (Dialogue technology)

ChatGPT is regarded as a good example of the potential application of LLM, which allows various natural language processing tasks, e.g., information retrieval, summarization, question answering, and narrative generation. They are executable by only providing simple prompts, such as commands to be executed by the system or providing examples to help command execution. The potential of conversational AI demonstrated by ChatGPT is interesting; however, given the risk of generating false or ethically problematic expressions, the generated results cannot necessarily be used as they are. In addition to methods that distinguish text generated by LLMs from that by humans and only present text written by humans or automatically generate text based on only human-written text, R&D towards solving issues of generating unintentionally inaccurate or inappropriate expressions, LLMs fine-tuned to specific tasks (such as the automatic generation of movie scripts), and LLMs that can simultaneously generate other modalities, such as video, are expected to progress. GPT-4 [113)], announced in March 2023, reportedly required six months to become safer to use, and it has been announced that it can now accept image inputs, albeit experimentally.

As conversational AIs using LLMs become widespread, there will likely be deeper discussions on how to handle such technology in society. At present, there are studies comparing the results of question-answering by ChatGPT and human experts [114)], but in the future, the data may develop further for such comparisons and evaluation methods from various perspectives, including the ethical aspect.

Furthermore, conversational AI is expected to be integrated into various applications. For example, if a conversational AI is integrated into a document creation app, it is anticipated that confidential information such as the importance of information and intent could be completely exposed to the conversational AI provider. Also, code generated by conversational AI may potentially infringe on others' patents or copyrights without knowing it, so caution is needed in its use.

Moreover, there are concerns that fake information generated by conversational AI placed on the web could lead another conversational AI trained with that data to generate similar fake information, potentially disrupting previously functioning error checks [115)]. As a result, fake information could potentially proliferate across the web. Academically, there are also concerns, as reported in the Nikkei newspaper in March 2023 [116)], text possibly generated by an AI could slip into academic papers and distort human scientific knowledge.

From these considerations, it is anticipated that the establishment of various rules regarding the use of conversational AI and regulations on its use will become necessary. In fact, in the United States, a letter was published on March 22, 2023 calling for a pause of at least six months in the training of advanced AI systems, and as of the end of March 2023, it is reported that over 1,000 people, including prominent individuals like Elon Musk, have signed it [117)].

(3) Conclusion

This chapter has mainly overviewed trends focusing on technologies that support communication through language. However, when we rethink communication more broadly, we can consider further possibilities. For example, with the advancement of brain interface technology (covered in Chapter 2.8), if we can consider the diverse information processed in the brain through our five senses as part of multimodal information, it is expected that even more advanced communication will become possible. Beyond communication through language, by further integrating advanced ICT technologies into humans, a world of telepathy, enabled by brain-to-brain communication, could become a reality.

2.8 Bio-ICT and Brain Science for ICT

In recent years, R&D in the fusion of life sciences and ICT, such as bioinformatics, has been actively pursued. As mentioned in Chapter 2.7.3, the advancement of AI technology is not only enabling communication through text between humans and AI, but it is also creating the expectation of new fields as life sciences and ICT become more closely integrated. This chapter provides an overview of the trends in Bio ICT, a field combining life sciences and ICT, and particularly focuses on brain science for ICT.

2.8.1 Background

Anxiety and awe, triggered by the rapid technological innovation of AI, are manifesting as natural responses among people (Fig. 2.8-1). In specific functions, AI has already surpassed human capabilities, and in future may handle more complex tasks and emulate human thoughts and emotions. Such progress has potential to infringe on basic human rights and individuality, raising questions about the meaning and essence of human existence. These questions have become socially significant.

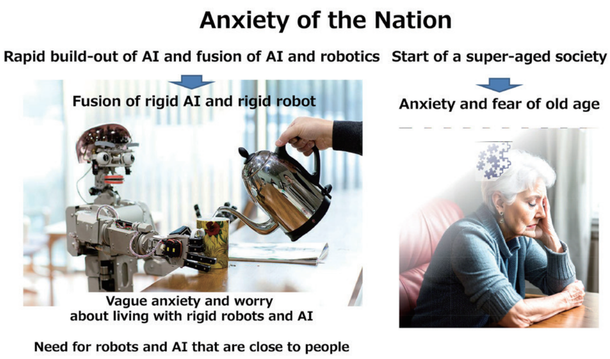


Fig. 2.8-1 Concerns about evolving AI and the super-aged society

Also, risks related to safety are highlighted by the evolution of AI. The evolution of AI also highlights safety risks: AI systems can cause serious accidents and damage through bad decisions, and new threats can be created by those with malicious intent to exploit AI. Ethical and social issues are also concerns (see reference: papers on AI ethics) [118] . There is potential for invasion of personal privacy and biased decision-making based on race, gender, and other factors. Identifying these issues held by AI and aiming for their resolution requires discussions around ELSI (Ethical, Legal and Social Issues), and while considering both technological advancements and societal needs, there is a demand to maximize benefits obtained from AI and minimize risks.

Technical issues related to AI include the energy consumed and emitted for vast calculations and the challenges arising from the significant amount of space and power required for data storage. As AI takes on more complex issues, the amount of computation required to train AI systems is increasing tenfold annually. In addition to R&D aimed at improving the energy efficiency of devices as a solution to this challenge, there are also expectations for research on learning about the trade-offs among computational capabilities, resources, size, weight, and power consumption (SWaP) from living organisms.

Another anxiety that citizens have is related to the super-aged society that Japan is currently facing. Along with the fear of cognitive decline, there is a desire to lead an active and healthy lifestyle even at an older age. Accordingly, the nation has a high interest in extending their healthy life expectancy, value preventive medicine, and desire a situation where they can participate in society with a healthy lifestyle. The nation is expecting that technologies like ICT, caregiving robots, and smart healthcare devices will reduce the burden of caregiving and medical care and enhance and support the lives of the elderly (Fig. 2.8-2). Even in the super-aged society, AI is expected to play a significant role.

However, as often depicted in science fiction movies, people are highly wary of themes such as AI developing consciousness or the transfer of consciousness to a computer as a result of the advancement of AI. One of the sources of anxiety towards inorganic AI is probably the absence of behavioral norms that humans naturally have in intelligent machines represented by AI. The source of modern human behavior is the mind. In research fields of life sciences and AI research, the mind is an important issue but not the central theme. Therefore, it is difficult to guarantee people's spiritually rich lives with these R&D efforts alone. The answer to the question of what kind of technology should support the future human-centered society should be provided by a broad field of brain sciences (neuroscience, psychology, human sciences, life sciences, philosophy) focusing mainly on the human brain.

Fig. 2.8-2 Expectations for Technologies Supporting Daily Life

Currently, in order to realize a human-centered society advocated in Society5.0 [83], R&D efforts focusing on Neurotech/BrainTech and Neuromorphic computing are attracting attention both domestically and internationally. Various foundational research and technological developments are underway globally, viewed from the perspectives of efficient information communication and presentation through understanding the brain; AI, energy-saving information processing, and wireless communication inspired by the brain science; and next-generation interfaces using brain information. Moreover, there has been a resurgence in biological function research as a clue for energy-saving information processing technologies, with both academic and private sector entities, including startups, entering the field.

Technological developments discussed on a span of about 10 years often build on research results accumulated over several decades and frequently achieve breakthroughs through interdisciplinary integration. Therefore, in predicting the human-centered R&D that will emerge in the next 10 years, it is necessary to look not only at the current trends in relevant R&D but also at the potential of fundamental research across various fields.

2.8.2 Current Research and Development Trends

The environment surrounding the R&D of brain science for ICT and Bio ICT is considered in three related fields: AI-related research, life science research including brain function analysis, and ICT research including brain function measurement devices.

(1) AI-related Research

With the rapid evolution of generative AI through transformers [102], AI has acquired advanced linguistic abilities and has begun to handle a wide range of intellectual tasks that had been performed by humans. Already, single-function AI has demonstrated high learning abilities, rather than brute-force large-scale data exploration, by defeating world champions in chess and professional Go players. Deep learning for analyzing large-scale data has brought significant progress in AI applications such as image recognition and speech recognition. Even protein structure prediction, a long-standing challenge in life sciences, can now be used to predict structures with high accuracy from the primary sequence of amino acids, dramatically transforming life sciences, especially protein structure research.

(2) Life Science Research

With the advancement of bioinformatics, life science has formed a partnership with data-driven science, and together with the development of observation equipment and technologies such as advanced optical microscopes and cryo-electron microscopes, it has made remarkable progress. Protein structure research can describe the 3D structure of proteins with high spatial resolution thanks to the improved performance of cryo-electron microscopes and predict their dynamics through molecular dynamics simulations [119]. Furthermore, machine learning using accumulated structural data has made it possible to predict the three-dimensional structure of a protein using only the primary sequence of amino acids.

Significant advancements have been seen in optical microscopy technology as a fundamental technology supporting research using biological entities. Techniques to observe and manipulate cells and other entities three-dimensionally with high spatial resolution are being extended to deep parts of biological entities. In addition, genome editing technology has made the creation of new life possible, and iPS cell research is causing a significant revolution in artificial organ/tissue technology. Genetic engineering technology has greatly developed the field as a useful tool for life science. The derived technology, optogenetics [120], has become essential for neuroscience research as a technique that can stimulate specific neurons at specific times. Function-complementing life medical science technologies, represented by artificial joints and artificial inner ear technology, are producing high-performance, robust, durable alternative organs one after another through collaboration with materials science, significantly extending people's healthy life expectancy. Not limited to macro-level alternative organs, the emergence of technologies like microparticles that mimic cell functions and artificial cell technologies are establishing new communication concepts that perceive intermolecular interactions as information communication.

In neuroscience, studies using experimental animals continue to report connectomes that provide detailed descriptions of neuronal networks in the brain [121]. For the model organism *Drosophila melanogaster*, a connectome database has been published that comprehensively describes the connectivity of all the neurons constituting the brain [122) 123) 124], and along with the introduction of behavioral experiments using genetic manipulation technology and virtual reality (VR) technology and behavioral analysis technology utilizing deep learning, it has become possible to analyze information processing within the nervous system in accordance with the characteristics of specific circuits. The introduction of optogenetics has also made it possible to link neuronal activity to behavior. Molecular mechanisms of learning and memory are also being elucidated. In addition to gene switching methods, technology to express light-responsive channel proteins in specific cells allows for local stimulation of specific nerves through light irradiation from the outside. This technology can be used to externally control the behavior of living organisms, and may have a wide range of applications in the future. Already, studies have been conducted that change the behavior of *Drosophila* and mice with external light stimulation. Insects have a small nervous system that can rapidly produce a wide variety of adaptive behaviors, and attempts are being made to apply these functions to engineering information processing, such as navigation using landmarks and the central mechanism of action selection [125] These recent initiatives have been invigorated against the backdrop of growing needs for more power-cost performance in information communication technologies represented by IoT and edge devices. They are focused on insects to create new AI that functions within constraints of size, weight, and energy consumption, understanding the integrated sensory and nervous systems of small insects, mapping them onto computer hardware, and emulate their functions.

On the other hand, research targeting the human brain is accelerating due to the sophistication of large-scale measurement devices and their analysis technology, moving towards the essence of higher brain functions. Magnetic resonance imaging (MRI) systems are becoming increasingly sophisticated in terms of spatio-temporal resolution as the magnetic field becomes higher and higher. At the same time, R&D of neural activity measurements using non-BOLD signals are advancing [126]. As a result, mathematical modeling of various brain information processing mechanisms is progressing.

(3) ICT-related Research

In ICT R&D, sensor networks represented by IoT (Internet of Things) and their supporting high-speed, high-capacity communication networks are being established. Communication equipment is becoming smaller and more portable, and an environment where one can connect to the network anytime, anywhere is about to be established. In response to the development of ICT, the following technologies are being pursued in the "Neurotech/BrainTech fields," which are areas where brain functions and ICT are merged. For example, electroencephalogram is not only useful for diagnosis and treatment in the medical field, but it is also used in fields such as brain-activating games and biometric authentication. Brain-Computer Interface (BCI) and Brain-Machine Interface (BMI), which mainly apply electroencephalogram to link brain activity to a computer are researched to operate various devices according to the user's intentions. They are used in the medical field for patients to operate prosthetic hands/arms and legs and in the e-sports field to stimulate brain activity. Neuromarketing technology uses brain information analysis technology to analyze the roots of consumer behavior and consciousness, and it is applied to market research and advertising effectiveness analysis. From the planning stage of products and advertisements, it is possible to read the psychology of customers and establish more effective marketing strategies. Neurofeedback technology [127] uses brain information analysis technology to measure the brain activity of subjects and provide feedback to the subjects as visual and auditory information, thereby enhancing training effects and activating unconscious brain activities. This has been attempted to improve cognitive function and relieve stress. In addition, the construction of chemical sensors that detect odors, tastes, and trace amounts of biologically active substances through the combination of biological functions and machine learning has been widely conducted from basic research to the private sector.

2.8.3 Future Prospects

Considering the accelerating progress of peripheral fields, it is expected that the research fields of bio-ICT and brain science for ICT will develop at an accelerated pace as a result of synergies generated by the active fusion of these peripheral fields. We would like to discuss the future prospects for 2030 and beyond. (Fig. 2.8-3).

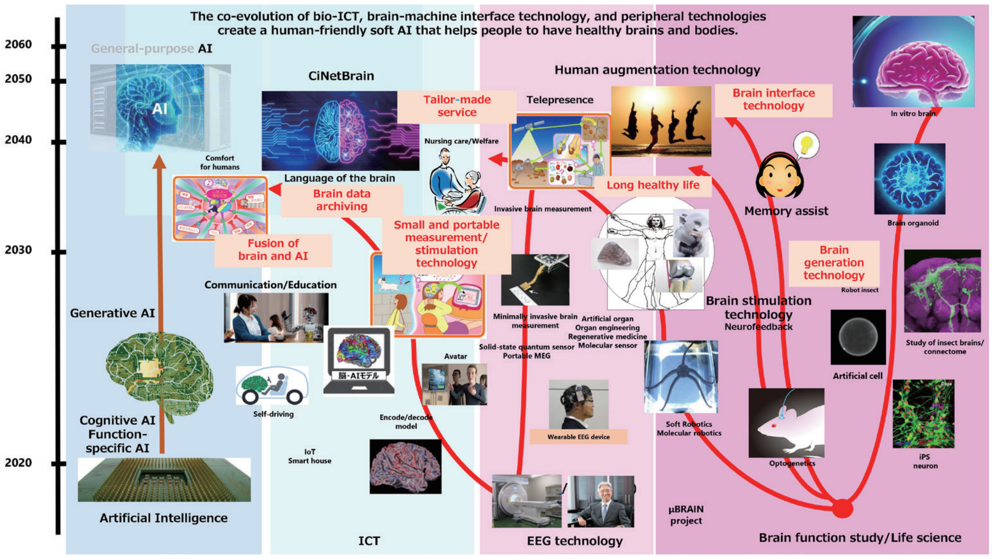


Fig. 2.8-3 Future Prospects of Bio ICT and Brain science for ICT

(1) Future Prospects in the Field of Information Communication & AI

In the next 10 years, the advancements in brain science for ICT in Neurotech/Brain-tech, and the development of Bio-ICT research are expected to achieve the following:

- Thanks to the deciphering of brain information and the clarification of information representation in the brain, techniques for efficiently transmitting optimal information to the brain and presenting information will be developed. In addition, bidirectional five-sensory communication utilizing biosensors capable of detecting trace substances will evolve. Access to effectors will become possible, and technologies utilizing non-verbal behavior changes, such as motor function improvement and training to prevent function decline utilizing brain characteristics, will advance.
- Next-generation AI technologies incorporating the brain functions of humans and insects, and brain-integrated AI will emerge. Next-generation energy-saving information processing technologies and next-generation pulse wireless communication technologies that imitate the brain and organisms will emerge. This is based on the pulse-based information communication of neuronal activity, and its use in IoT sensor networks is expected. Moreover, the practical application of molecular communication technology, which perceives chemical substances as information carriers, will begin.
- BMI technology by using brain waves and neurofeedback will become popular, causing learning promotion and concentration improvements by using brain waves to be widespread. Minimally invasive cortical brain wave BMI technology will become bidirectional, starting to shift from medical use to general use.

(2) Future Prospects in the Field of Life Science Research

In research using biological entities, cellular engineering using iPS cells is advancing, and various organs and tissues are being reconstructed. Even now, brain organoids [128] are being developed, and studies assessing the learning capabilities exhibited when these organoids are electrically stimulated are progressing. In the future, an in vitro brain could possibly be created. Moreover, with genome editing technology, it is possible to introduce any gene into a cell and express its protein, greatly expanding the possibilities of cellular engineering. The advancement of such cellular engineering technologies, including iPS cells, will eventually lead to medical applications like organ banks, extending healthy life expectancy, and challenging immortality through alternative organs. Also, bottom-up techniques for artificially creating cells are advancing, which will lead to the development of micro-robot-like cells capable of surviving in harsh environments.

In R&D of brain function measurement technology, the development of small, portable, and high-precision measurement devices is rapidly advancing. More precise EEG (electroencephalogram) devices will emerge. While non-invasive ones are mainstream now, low-invasive brain wave measurement devices will eventually be widely accepted and used. Moreover, the development of quantum magnetic sensors [129] is progressing, making portable MEG (magnetoencephalogram) measurements possible. The concept of functional assistance by stimulation devices will be added to the dominant practice of measuring brain functions. While techniques for improving body and brain functions by applying a weak current through electrodes attached to the scalp, like tDCS and tACS (Transcranial Direct Current Stimulation and Transcranial Alternating Current Stimulation), are starting to be used in addition to TMS (Transcranial Magnetic stimulation), applications of ultrasound stimulation technology and optogenetic methods will begin. As the molecular mechanisms of memory and learning are elucidated, therapies like memory assistance and memory recovery through localized neural stimulation will begin.

(3) Future Vision for 2050

The development of technology to safely access higher brain functions will be accepted and spread widely. In a super-aged society, the roles of Bio-ICT and brain interface communication fusion research become increasingly important when considering effective strategies for various phenomena associated with cognitive decline.

A type of AI that can understand meaning will be born as a brain-integrated AI, merging with human brain information. This will give birth to AI that can perform various tasks as if they were an extension of oneself. Moreover, the archiving of brain information will become possible, allowing individuals to upload their own brain information, memories, and motor skills for reference.

Brain function measurement devices will become smaller, more portable, and less invasive, deepening the system with the addition of stimulation devices. The portability of these devices will allow access to physicality, utilize sensory information obtained from essential movement for spatial cognition, accelerate motor assistance and function enhancement, and push up the level of AI integrated with the human brain. The possibility of humans and AI to connect seamlessly will increase significantly.

Health longevity will markedly extend due to iPS cell technology, cellular engineering technology, and artificial cell technology. The installation of artificial organs and organ banks will progress, suppressing physical aging. Correspondingly, there will be increased demand for the development of technologies to maintain healthy brains. As safety is confirmed, the general use of memory assistance and neurofeedback will progress. In the coming era where brain information can be uploaded to silicon memory or downloaded from an external memory device through access to and archiving of brain information, the storage medium could be a silicon device, organoid made of biological molecules, or reconstituted brain.

It should be noted that for such scientific and technological developments to harmoniously advance with the human mind, there is a need for wide-ranging discussions on ELSI (Ethical, Legal, and Social Issues) across different fields and initiatives for international collaborations are to be made early.

Chapter 3 Concluding Remarks

In this report, we introduced eight major technological trends: Cross-sectional foundation technology, Utilization of electromagnetic waves, Communication network infrastructure, ICT device technology, Cybersecurity, Quantum ICT, Universal communication, and Bio ICT and brain interface on the ongoing R&D in the ICT sector, which is expected to play a significant role in realizing a prosperous future social infrastructure, and its future prospects. Given the wide-ranging environment surrounding ICT and the diverse range of technological topics within the ICT sector, this categorization is for the 2023 edition and further evolution expected is in the future.

While this report primarily focuses on technological trends, the social proliferation of general AI tools like ChatGPT necessitates discussions from various perspectives not only on the technical aspects but also on ethical, legal, and social issues (ELSI). This is a point that must be addressed in future overview reports. In future ICT R&D projects, it will be crucial to consider ELSI in parallel with technological development.

Similarly, in terms of ICT's contribution towards a sustainable society, it is necessary to not only improve the energy efficiency of various social systems through the use of ICT but also to make the energy consumption of ICT itself carbon neutral. Therefore, further advancements towards promoting green ICT are expected.

This report was primarily written by researchers at NICT and compiled from as neutral a standpoint as possible. However, as this is a first attempt, there may be areas of insufficiency, and updates are planned for the future. We hope that the contents of this report will be utilized by policy makers in Japan's information and communications, economy, administration, education, and ICT research communities to contribute to the development of ICT and the realization of a safe and secure Society 5.0.

Terminology

Appendix A

Chapter 2

2.2 Utilization of Electromagnetic Waves

1. Non-Terrestrial Network (NTN): Communication system that connects all types of mobile entities across sea, air, and space, including not only communication satellites but also High Altitude Platform Stations (HAPS), drones, and ships, in a multi-layered configuration. It is expected to enable new use cases such as logistics and IoT, as well as the use of the Internet on airplanes and ships.

2.3 Communication Network Infrastructure

1. HAPS: Acronym for High-Altitude Platform Station, which refers to unmanned aerial vehicles that can fly non-stop in the stratosphere at an altitude of 20 km for several days to months.
2. Space-division multiplexed optical fiber communication: Communication technology used to transmit over 1,000 times more information (at petabit per second levels) than conventional systems using multi-core fibers in which multiple cores are placed in a single fiber, or multi-mode transmission for which separate paths are used by light distribution (mode).
3. HTS (High Throughput Satellite communication system): Satellite communication system that narrows the satellite beam and concentrates many antenna beams at once to increase capacity.
4. Space RAN: Radio access network (RAN) in space. It organizes communication data received from devices such as smartphones and interacts with the subsequent core network. It includes antenna equipment, base stations, and line control devices.

2.4 ICT Device Technology

1. UVC: A type of ultraviolet (UV) light. UV light is broadly divided into A, B, and C from longest to shortest wavelength. UVC refers to light in the wavelength range of 100-280 nm. It is emitted by the sun in nature but completely absorbed by the stratosphere and ozone, so it does not reach the Earth's surface.

2.6 Quantum ICT Field

1. Coherence Time: It represents the time until quantum information stored in a spin is lost. The loss of quantum information occurs when the phase relationship between the ground and an excited quantum state is disturbed by external disturbances.
2. Superconducting Quantum Bit: It is implemented by superimposing the ground state and the first excited state of an artificially created atom on a wafer using superconductivity.

2.7 Universal Communication

1. LiDAR (Light Detection and Ranging): Technology that measures the distance and shape of an object from the reflected light of the irradiated laser.
2. GAN (Generative Adversarial Network): Technology that can generate data such as high-resolution images by making two networks, generation and recognition, compete against each other.
3. REXR (Realistic and EXpressive 3D avataR): 3D avatar construction technology that can reproduce delicate expressions and bodily movements of the person in real time from just one camera image.
4. NeRF (Neural Radiance Fields): Technology that generates high-quality images of different viewpoints from images from multiple viewpoints.

2.8 Bio ICT and Brain Interface Fusion Research Inspired by Biological Functions

1. SwaP: Attempt to consider the trade-offs between computational ability, resources, and size, weight, and power (SWaP). The µBRAIN research aims to explore innovative basic research concepts for developing prototype computational models that can map appropriate hardware to emulate the remarkable functions of small insects' highly integrated sensory-neural systems. Nature forces these small insects to dramatic miniaturization and energy efficiency, and some have only a few hundred neurons in a compact form factor while maintaining basic functions. This research will enable systematic or entirely new ways of inference, prediction, generalization, and problem abstraction, helping to find solutions to pressing problems.
https://www.darpa.mil/program/microbrain
2. Neurotech-Braintech: Collective term for technologies that apply insights from neuroscience, such as technologies for monitoring brain activity, stimulating the brain for therapy or

improvement, and technologies to support them.

3. Neuromorphic computing: It aims to improve the performance of existing devices by analyzing and mimicking the superior performance of biological brains. It is guided by the principles of biological neural computation and achieves functions close to human cognition by using new algorithmic approaches to emulate how the human brain interacts with the world. From Intel's HP.
https://www.intel.com/content/www/us/en/research/neuromorphic-computing.html
4. Soft Robotics: Biological bodies are soft, and their form, structure, mechanism, and information processing mechanisms are fundamentally different from any artificial objects we can currently build. We aim for autonomous robots based on the biological systems that possess the characteristics of organisms, newly defining them as soft robots.
https://softrobot.jp/outline/
   - New academic field called Soft Robotics https://softrobot.jp/
   - Introduction to Soft Robotics: Basic Composition and Mathematics of Flexible Objects (Japanese version only), written by Yasuichi Suzumori, Kohei Nakajima, Tatsuya Shinoyama, and Ken Masuya, Ohmsha ISBN 978-4-274-22998-5
5. Molecular Communication: New communication paradigm that uses biological molecules as information transmission carriers. Biologically produced materials or artificially manufactured nanoscale biomachines are embedded in the body, and communication is achieved by inducing chemical reactions to propagate bio-molecules (information molecules) such as enzymes and proteins from the transmission nanomachine to the receiving nanomachine.
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Additional Information

Appendix C

C-1. Conditions in Europe (related to Chapter 1.2.2)

C-1-1. Forming Europe's Digital Future

'Digital Compass 2030' and 'Path to the Digital Decade' define the goals and governance frameworks for the formation of Europe's digital future by 2030.

Digital Compass 2030
https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/europe-fit-digital-age/europes-digital-decade-digital-targets-2030_en

Path to the Digital Decade
https://ec.europa.eu/commission/presscorner/detail/en/ip_21_4630

C-1-2. Geopolitical Trends in Europe's ICT sector

In March 2019, the European Commission and the EU High Representative for Foreign Affairs and Security Policy, in "EU-China: A Strategic Outlook," repositioned China from a "strategic partner" to a "technological hegemony-seeking economic competitor" and a partner for cooperation and negotiation, taking into account China's rapid growth not only economically and politically but also technologically.

https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52019JC0005

C-1-3. Smart Networks and Services Joint Undertaking

The first round of public recruitment began in January 2022. In the first round, 35 projects including R&D of 6G and development of experimental infrastructure were adopted, and these projects started in January 2023, when the second round of public recruitment also began.

https://digital-strategy.ec.europa.eu/en/news/europescales-6g-research-investments-and-selects-35-newprojects-worth-eu250-million

https://digital-strategy.ec.europa.eu/en/news/europelaunches-second-phase-its-6g-research-and-innovationprogramme

C-1-4. Research and Development in European Countries

The French government formulated an Acceleration Strategy for 5G and Future Communication Network Technologies in July 2021. As a part of this it is implementing B5G/6G projects.
https://www.entreprises.gouv.fr/fr/strategie5G

Also, the Spanish government is advancing R&D projects for Beyond 5G/6G.

https://portal.mineco.gob.es/es-es/comunicacion/Paginas/20220818-NdP--convocatoria-5G-+-y-6G.aspx

C-1-5. Examples of Collaboration within Europe

France and Germany have signed a collaborative declaration on AI, and since October 2020, have been advancing various joint R&D projects centered around Inria and DFKI.

https://www.enseignementsup-recherche.gouv.fr/fr/declaration-d-intention-conjointe-formalisant-les-liens-entre-les-reseaux-francais-et-allemands-en-49019

https://www.inria.fr/en/first-five-projects-inrias-partnership -dfki

C-1-6. Trends in the Green ICT field

In France, as a national initiative, a roadmap for Digital and Environment was announced in February 2021, promoting the reduction of the environmental footprint in the ICT sector.

https://www.ecologie.gouv.fr/nouvelle-etape-faire-converger-numerique-lexigence-environnementale-gouvernement-publie-feuille

C-1-7. Research and Development Trends in the Semiconductor Field

Specific R&D projects in the semiconductor field are being implemented under the Key Digital Technology Joint Undertaking (KDT JU), a public-private partnership.

https://www.kdt-ju.europa.eu/

C-2. Regarding ICT Device Technology (Related to Chapter 2.4)

C-2-1. Domestic and Overseas Research and Development Examples

Intel Corporation in the United States has developed a 150 GHz band wireless receiver chip that integrates a PLL and an ADC using a 22-nm FinFET, demonstrating a communication speed of 128 Gb/s. Also, in Japan, a group from the Tokyo Institute of Technology and NTT has developed a 300 GHz band wireless transceiver chip using a 65-nm Bulk CMOS process, and it has reported the development of a phased array radio system through packaging technology to arrange the mounted boards at half-wavelength intervals. NICT, together with the joint research institutions conducting the project, is advancing the development of RF front-end circuits, antennas, baseband circuits, and packaging technology, and they have demonstrated beam steering technology in 300-GHz band wireless communication. Currently, R&D are underway to enhance beamforming technology and to enable spatial multiplex transmission technology with multi-element modules. As for high-output GaN devices, Sumitomo Electric Industries holds the top share for GaN-HEMT as transistors for 5G base stations. NICT has also reported the highest maximum oscillation frequency fmax in Japan.

C-2-2. Research and Development Trends of Spatial Light Modulators (OPA)

For various methods of spatial light modulators, the Liquid Crystal on Silicon (LCOS) method has been put into practical use for relatively slow applications with a light scanning speed of up to 10 kHz. Si-OPA has been reported to control high deflection angle light beams and demonstrate the operation of LiDAR at a wavelength of 1.5 mm. However, the light beam scanning speed of Si-OPA is limited to around 100 kHz, and the power consumption is also large, over 5 mW per channel. On the other hand, EOP-OPA has reported more high-performance operational demonstrations with a light beam scanning speed of 2 MHz and power consumption of 0.38 mW at a wavelength of 1.5 mm. The table below compares the operating mechanisms, scanning speeds, power consumption, and wavelengths of each method.

Type	Device mechanism	Optical scanning	Power consumption	1.5-m wavelength/ Visible light
LCOS	Orientation change	~10 kHz	Low	○/○
Si-OPA	Thermo-optical effect	~100 kHz	High	○/×
EOP-POA	EO effect	~2 MHz	Low	○/○

C-2-3. Research and Development Trends of Transistors and Diodes

Regarding a vertical structure that is useful as a power device, steady progress can be seen particularly in the device performance of Schottky Barrier Diodes. However, their comprehensive device characteristics, represented by the power performance index [(breakdown voltage × breakdown voltage) / on-resistance], are tending towards saturation, and have not yet reached the theoretical limits of SiC and GaN. Lateral transistors are also being reported one after another, showing improvements in device characteristics represented by breakdown voltage. In addition, there has been a surge in the development of thin film crystal growth and devices corresponding to the metastable structure of α-Ga_2O_3. α-Ga_2O_3 is the most advanced in research among metastable structures because it is a crystal structure formed mainly through heteroepitaxial growth on sapphire substrates. FLOSFIA Inc. is advancing the development of Schottky Barrier Diodes and transistors using α-Ga_2O_3. And, it has started selling DC/DC buck converters using α-Ga_2O_3 SBDs.

C-3. Universal Communication (Related to Chapter 2.7)

C-3-1. Supplementary Information on Large-Scale Language Models

LLMs that follow the Transformer model can be broadly divided into discriminative and generative models. Notable discriminative models include BERT [109] suitable for tasks such as document classification and question answering, while generative models include the GPT series, PaLM [105], and LaMDA [130].

C-3-2. Additional Information on GPT-3

When GPT-3 was first announced, it attracted attention because it could deliver high accuracy in various tasks without fine-tuning with individual task-specific learning data, a method called zero/few shot. However, for ChatGPT, a model called GPT-3.5 was fine-tuned, and reinforcement learning was implemented to realize the system.

C-3-3. Supplementary Information on Conversational AI

In addition to ChatGPT, Meta has released BlenderBot 3, available only in the United States, released in August 2022 [131], and Galactica, released in November 15, 2022, as being able to generate scientific articles and explanatory text, but criticized for generating discriminatory expressions and inaccurate scientific knowledge, resulting in the suspension of its release just three days later [132]. Google announced LaMDA, Language Model for Dialogue Applications [130], in 2021 as a related technology and has launched it as a conversational AI service called Bard [133] utilizing LaMDA. Bard later was then modified to run with PaLM2, the successor to the LLM PaLM that formed the basis for LaMDA, and it was released with multilingual support, including Japanese. Elon Musk, famous for his startups Tesla and SpaceX, has also been reported to be exploring the development of a conversational AI similar to ChatGPT [134].

C-3-4. Issues on Conversational AI

ChatGPT, having met a certain standard, seems to have been accepted by society, as it reached 100 million active users within two months after its release. However, the standard seems to depend heavily on the nature of the operator of the conversational AI and the presentation, including the explanation of the purpose of the release. For instance, Google, which primarily conducts business through a search engine where accuracy of information is prioritized, experienced a commotion around its stock price, which fell by 9% after it was revealed that Bard's answer to a question was inaccurate upon the announcement of the AI [135].

With the advancement of conversational AI, new issues are arising that developers of conversational apps and others need to consider. For example, when developing a voice conversation system, if one uses the APIs of the same provider for both speech recognition and speech synthesis to configure the system, the inputs and outputs to the system will be controlled by that provider. This allows the API provider to collect a large amount of input and output data from the dialogue system, and by using conversational AI, they can easily build a similar service using the collected data as training data. It is also possible to construct services from the inputs and outputs of other dialogue systems, and to compose more advanced services by combining these dialogue services. Therefore, there is a risk that the conversational app one has built could be unknowingly imitated within a more advanced conversational service and offered as a service.

C-3-5. LLM Development at NICT

At NICT, in view of the issues with generative LLMs mentioned earlier, we have been working on R&D for the construction of discriminative LLMs and their applications from a practical perspective. We have constructed models such as Japanese BERT, which was trained with our own 350 GB web text, and a large-scale BERT that is 50 times larger. We have been conducting research and developing applications using the models. To support the efficient development of LLMs, we have developed RaNNC, an automatic parallelization deep learning middleware that makes parallel learning easy regardless of neural network architecture, and we have released it as open source.

C-3-6. Real-World Modeling & Image Generation Technology

Deep learning technology that models the 3D structure and surface properties of the real world to generate novel realistic images has made rapid progress in recent years. As a core technology for spatial computing that integrates the real and digital worlds, it is expected to be used in a wide range of fields, such as telecommunications (dialogue and collaboration in shared spaces), remote work using robots, simulation, remote medical care/caregiving, and experiential education/training.

The targets of real-world modeling can be divided into people and environments (indoor/outdoor artificial/natural objects). 3D sensor information such as motion capture, LiDAR, etc., and camera images (still images/videos) are used for the information acquisition. In the past, large-scale devices such as expensive sensors and multiple cameras were used, and enormous work was required for setting up the equipment and data processing, but the use of machine learning has made it possible to significantly reduce costs, shorten processing time, and improve reconstruction accuracy.

A variety of representations such as point cloud data, surface meshes, and volumetric models are used as 3D information of the reconstructed real environment, but image generation (image rendering according to lighting conditions, etc.) based on such 3D information is essential for making people feel the reality of the space. On the other hand, the development and application of GAN technology to generate novel high-quality images from a few images without explicitly reconstructing 3D information is also being advanced in many fields.

In the area of modeling technology for real people, there has been progress in the development of technology to construct a 3D avatar from the image of a single camera image based on deep learning, without using large-scale devices with multiple sensors and cameras. NICT's REXR technology, released in 2022 (Appendix Fig. C-1), succeeded in constructing a 3D avatar (surface mesh shape, surface texture, parameters such as joint positions, angle inside the body) from the image of a single webcam, and generating fine facial expressions and subtle body movements in real-time from arbitrary viewpoint [136].

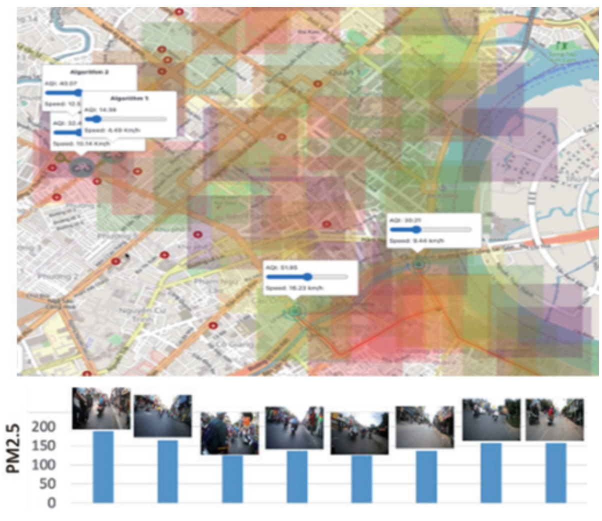
Appendix Fig. C-1 Construction of Expressive 3D Avatars using REXR

As for modeling real-world environments, there are also advances in the development of technologies to generate novel high-quality images from a small number of images. For instance, NeRF is a deep learning technique that generates images from arbitrary viewpoints with high accuracy solely from images taken from multiple viewpoints (without providing 3D object information during training). When the paper was published in arXiv, in March 2020, it attracted significant attention due to the high quality of its generated images [137]. In fact, the paper received a Best Paper Honorable Mention at the ECCV 2020 international conference and has been cited in over 1500 papers in less than two years. The main feature of NeRF is that it represents 3D scenes as volume densities (a continuum representing the opacity of an object) rather than surface meshes. On the other hand, challenges with NeRF include its limitation to static scenes and the substantial computational cost of learning and rendering, but various attempts and improvements are currently being made to overcome these challenges.

General future issues related to this technology include 1) improving the accuracy and robustness of modeling and image generation and 2) increasing the speed of learning, parameter estimation, and rendering for real-time processing. Since these are trade-offs, it will be necessary to develop individual technologies according to the purpose and application. In order to do this, it will be crucial to clarify the technical requirements required for each usage while revealing the human factors of the users. Furthermore, to avoid the misuse of this technology and ensure its safe and secure use, it will also be necessary to simultaneously create a scheme for reliable management and authentication of the real-world models and images generated by this technology.

C-3-7. Urban Digital Twins

Digital twins are virtual models of physical objects, which can capture physical state changes through IoT data and enable analysis, prediction, and optimization. In recent years, efforts have been made to use digital twins to collect, monitor, and manage urban data, promoting city planning, environmental management, traffic control, energy use management, and so on, aiming for smart and sustainable cities [138]. The introduction of digital twins has started in several cities, and they are being utilized for optimizing city planning through simulation and decision-making support (in Singapore), improving infrastructure and traffic, and assisting with mobility in emergency situations (in Rotterdam, the Netherlands).



Appendix Fig. C-2 Example of Route Guidance to Avoid Air Pollution Risk

The key technologies for urban digital twins include surveying and mapping technologies and Building Information Modeling (BIM) that form the foundation for managing urban assets and infrastructure, IoT and 5G technologies for collecting and feeding back dynamic data, AI technologies for understanding and predicting situations, and simulation technologies for assisting with planning and early warning [139]. Compared to traditional digital twins, urban digital twins integrate different types, domains, and spatiotemporal data from various sensors and information sources. By uncovering hidden patterns and unknown correlations, it can predict the future states and significant changes of physical objects, validate solutions through simulations, and optimize themselves. For urban digital twins, R&D are underway on the foundations of these systems [137]. For instance, real-time traffic data and machine learning on it can be used to effectively predict and prevent traffic accidents, track and monitor environmental data, track people's behavior during emergencies or disasters, predict potential risks, and support disaster prevention and mitigation actions (Appendix Fig. C-3). Furthermore, efforts are being made to improve the interoperability of diverse data and models and to standardize international measures [141].

As a new trend, the integration of edge computing and AI can enable physical objects to achieve high-performance, low-latency, and high-security recognition and prediction [142]. For instance, in intelligent traffic systems, data on the floating population, traffic flow, weather, and air quality can be collected by smart cars and other means, and traffic risks can be determined and predicted in real time on the spot, sharing the results (Appendix Fig. C-3). In edge environments, where computational resources and power supply are extremely limited, technologies such as data reduction, machine learning model lightening, distributed machine learning in cooperation with the cloud, and federated learning for privacy protection are needed.

The metaverse is a virtual digital space accessible via the network, allowing for highly immersive communication using AR and VR. In recent years, while the metaverse based on real cities has been progressing, the construction of digital twins using existing municipal data is also being promoted [143]. In the future, as the integration of urban digital twins and the metaverse progresses, it is expected to not only simulate and visualize cities but also to solve issues through cooperative work and behavioral changes across virtual and real boundaries, enabled by the interaction of virtual models and physical objects and interactive communication.

C-4. Quantum ICT (Related to Section 2.6)

C-4-1. Research and Development to Improve Quantum Computing Accuracy

Research is being conducted to improve the operational accuracy of quantum computation by using two-state quantum systems and quantum levels of the third state and higher to expand the Hilbert space and increase the degrees of flexibility in quantum computation.

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