

The Current and Future Trends of ICT

Version 2.0

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Update History

Acknowledgements

Outline of this Report

Information technology (IT), such as computers and software, and communication technology (CT), represented by optical fiber, mobile phones, and smartphones, entered a phase of explosive diffusion and development beginning in the late twentieth century. Today, ICT has evolved into an indispensable foundation supporting society. At the same time, our modern society faces numerous challenges, including external environmental changes such as climate change, growing demands for a sustainable economy and society, and social changes such as aging populations and declining birthrates, particularly in developed countries. Against this backdrop, the ICT field is expected to play a major role as a key element in solving these challenges and realizing the social and economic infrastructure of the twenty-first century.

This report aims to provide insight into the latest trends and future prospects in ICT research and development by examining current developments from a broad, panoramic perspective. With this objective, the report is structured as follows.

Chapter 1 provides an introductory overview of the global environment surrounding the ICT field. The social environment in which we live has changed dramatically due to global infectious-disease outbreaks and geopolitical shifts, and ICT plays an important role within this environment. This chapter focuses in particular on the latest developments in North America, Europe, and Asia, and also addresses recent international trends in AI in Section 1.3.

Chapter 2 then examines the latest developments in notable areas of ICT. Section 2.1 outlines Beyond 5G, which is expected to serve as a cross-cutting foundational technology and as the basis of future Society 5.0. Section 2.2 describes research and development trends in the utilization of electromagnetic waves, an essential medium for realizing ICT technologies. Section 2.3 addresses communication network infrastructure, the core of the ICT foundation, while Section 2.4 discusses the latest trends in the ICT devices required to support it. Section 2.5 reviews the latest developments in cybersecurity, a field of growing technical and social importance. Section 2.6 covers state-of-the-art research and development trends in quantum ICT, a field expected to constitute a new paradigm. Section 2.7 addresses translation and dialogue technologies, including rapidly advancing generative AI, from the perspective of universal communication. Section 2.8 discusses the latest trends in brain-information-and-communications technologies, which may represent one of the ultimate forms of communication, as well as Bio-ICT, a new fusion of life sciences and ICT. Finally, Section 2.9 introduces notable emerging technologies as a new trend. The end of the report includes appendices containing a glossary, references, and detailed information that could not be fully included in the main text.

Preface to Version 2.0

As stated in the opening section, “Outline of this Report,” information and communications technology (ICT) has become an indispensable foundation supporting society. The first edition (Version 1.0) of this ICT overview report was published in July 2023, followed by Version 1.1 in March 2025. Since then, both the ICT field and the surrounding social environment have undergone a wide range of changes. In particular, Chapter 2 described the latest developments in each technical field as of the time Version 1.0 was written, together with future prospects envisioned around 2030. With nearly three years having passed since that writing, many of those outlooks have since evolved.

In light of this, Version 2.0 has been comprehensively updated, including all of the technical topics in Chapter 2. In this revision, we also sought to strengthen the panoramic perspective of the report by exchanging views with expert advisors in each field during the drafting process. In addition, the future outlook sections have been written with approximately 2035 in mind. Furthermore, from a new perspective, Section 2.9 has been added to address the latest notable emerging technologies.

Chapter 1 Introduction

The ICT field is currently undergoing accelerated change. In addition to the continuing digitalization of society, the widespread adoption of technology has advanced rapidly in the wake of global infectious-disease outbreaks, while international conflicts and the emergence and diffusion of new AI technologies have further intensified this pace of change. This chapter examines the social environment surrounding the ICT field and trends in major regions around the world through several representative examples.

1.1 Recent Global Conditions

1.1.1 Worldwide Adoption of ICT and Its Ripple Effects

The global outbreak of COVID-19 led the WHO to declare a Public Health Emergency of International Concern (PHEIC) in January 2020, and it took three years until the emergency was declared over in May 2023. This worldwide infectious-disease outbreak had a major impact on the ICT field, and the increase in demand for non-face-to-face activities during this period significantly accelerated the digitalization of social life. The spread of web conferencing in everyday work and the widespread use of streaming services for video viewing have caused internet traffic to continue increasing up to the present day. One survey indicates that close to 40% of downstream traffic is attributable to video viewing and social networking services ⁵⁾. In Japan as well, the pace of internet traffic growth has shown no sign of slowing since 2020 (Fig. 1.1-1).

While the spread of ICT, together with the rapid development and adoption of AI technologies discussed later, has driven the digitalization of society, ICT-related electricity consumption has also continued to rise. In 2024, annual electricity consumption related to data centers, including AI, exceeded 400 TWh, accounting for 1.5% of global electricity consumption, and is projected to double again by 2030 ²⁾. For Japan to achieve the 2050 carbon-neutrality commitment it has made internationally, the information and communications sector must further promote both reductions in power consumption through technological innovation (Green of ICT) and improvements in operational efficiency through proactive use of ICT in a variety of settings (Green by ICT).

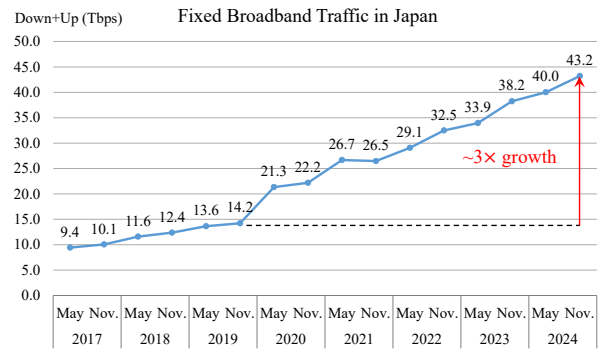


Fig. 1.1-1 Internet Traffic Trends ¹⁾

1.1.2 Changes in the Global Situation and ICT

Since Russia's invasion of Ukraine began in February 2022, satellite communications via Starlink have continued to be used within Ukraine from the earliest stages of the conflict. In the commercial market as well, the service reportedly exceeded 8 million users worldwide as of November 2025 ⁶⁾. At the same time, other companies such as Amazon have been advancing trial deployments of their own satellite communications services. These developments show that communications networks for the Beyond 5G/6G era, including non-terrestrial networks (NTNs) that extend beyond terrestrial infrastructure into the air and outer space, are rapidly emerging as a form of social infrastructure.

As the security environment in the international community becomes more severe, attacks targeting government agencies and critical infrastructure have also increased across many countries. Amid broader efforts to strengthen international cooperation in response, more concrete cybersecurity measures are progressing, including moves toward mutual international recognition of certification criteria for the safety of IoT devices ³⁾.

In the field of quantum technology as well, changes in the geopolitical environment, combined with technological progress, have stimulated investment in startups developing quantum computers. Standardization activities related to post-quantum cryptography, which assumes the advent of quantum computers, are also advancing, along with corresponding responses from industry. Meanwhile, in quantum communications, commercial services have begun in Europe, indicating that social implementation is accelerating.

In the AI field, generative AI technologies and services have continued to spread rapidly since the release of ChatGPT by OpenAI in November 2022. Corporate investment in the field, which doubled in 2020, has remained at or above that

level through 2024 ⁴⁾. Trends surrounding the AI field are discussed in Section 1.3.

1.2 Conditions in Various Countries and Regions

Against the social backdrop outlined above, the ICT field is drawing unprecedented attention and expectations. The following sections review the latest developments surrounding the ICT field in North America, Europe, and Asia.

1.2.1 Conditions in North America

The United States has remained the global leader in science, technology, and innovation activities over the long term. A broad view of recent US science, technology, and innovation policy shows two central pillars: (1) strengthening competitiveness and (2) promoting economic security, against the backdrop of China, which has rapidly approached and in some areas surpassed the United States on science, technology, and innovation indicators as a result of its fast-paced economic development ⁷⁾. The first pillar consists of an ecosystem formed through the layered interaction of federal investment by Federally Funded Research and Development Centers (FFRDCs), including national laboratories; efforts by state governments to attract private companies and R&D hubs; advanced talent development and spinoffs from universities and other higher-education institutions; and collaborative research and personnel exchange with big tech firms and startups. The second pillar cuts across individual technologies - including quantum information science and technology (QIST), Beyond 5G/6G, artificial intelligence (AI), and cybersecurity - and places emphasis on secure-by-design approaches, dual use, critical-infrastructure protection, and migration to post-quantum cryptography (PQC). In light of expectations for ICT as a dual-use technology, defense-related agencies have also been actively supporting high-risk research and demonstration projects ⁸⁾, while the White House Office of Science and Technology Policy (OSTP), the National Science Foundation (NSF), and others have been proactively strengthening cooperation with like-minded countries.

Looking at recent developments within this broader trend, the first Trump administration saw growing discussion of strengthening competitiveness and economic security on the basis of reinforcing science, technology, and innovation.

Under the Biden administration, implementation of the CHIPS and Science Act, the promotion of regional innovation hubs, large-scale budgets, and the “American Jobs Plan” began to institutionally link the ecosystem described above, while frameworks also advanced that pursued competitiveness and security in parallel, including government-wide AI governance arrangements and standardization of post-quantum cryptography. Under the second Trump administration, advanced technologies including AI and quantum technologies continue to be recognized as important, but the policy environment has become highly unsettled, with attempts to cancel already-awarded grants and reduce budgets and staffing related to energy, the environment, and DEI (diversity, equity, and inclusion). Although the direction of the second Trump administration is difficult to characterize as consistent, there are growing warnings that reductions in public funding could accelerate the weakening of basic research, the decline of high-risk R&D, and the outflow of talent, thereby jeopardizing the position the United States has held as a global leader.

Against this backdrop, the following recent developments in specific information and communications technologies are of particular interest to Japan.

(1) Quantum ICT

In quantum ICT, the National Quantum Initiative Act of 2018 has served as the framework within which competition among big tech firms and startups has intensified and efforts have expanded to form quantum research and development hubs involving individual states.

Among companies, big tech firms such as IBM and Google continue to lead quantum computing development based on superconducting qubits, while startups are advancing development based on their own comparative strengths, such as ion-trap approaches exemplified by IonQ. This has already produced advanced achievements, including the world’s first commercialization of a quantum memory ⁹⁾ and the construction of testbeds in collaboration with regional telecommunications carriers ¹⁰⁾.

In parallel, quantum-hub formation has been progressing at the regional level. The federal government set out blueprints for quantum networks at an early stage, and practical, operations-oriented testbeds using metropolitan fiber and commercial lines have been established across multiple locations through collaboration among national laboratories, universities, and industry ¹¹⁾.

(2) Beyond 5G/6G

Since 2022, T-Mobile, Apple, and others have begun partnering with satellite communications operators, making 2024-2025 a period in which direct NTN connectivity and direct-to-device (D2D) communications advanced in parallel.

As for government support for R&D, the NSF launched RINGS (Resilient & Intelligent NextG Systems) in April 2021 and, with the cooperation of nine private companies, has provided up to one million dollars over three years to each of 42 selected research proposals. In addition, through Platforms for Advanced Wireless Research (PAWR), large-scale wireless testbeds spanning urban, suburban, and rural environments are in operation, accelerating verification and integration testing for Open RAN as well as demonstrations of next-generation network functions such as edge computing and slicing¹². In June 2025, the United States also announced VINES (Verticals-enabling Intelligent Network Systems), a multinational project that includes Japan. VINES is intended to accelerate the social implementation of intelligent NextG networks from the standpoint of industry verticals by supporting both fundamental research and applied/implementation-oriented R&D.

In spectrum policy, the Federal Communications Commission (FCC) convened an expert working group¹³ to discuss the main technologies, candidate frequency bands, and use cases for 6G. In August 2025, the final report was released, organizing recommendations on security, privacy, openness, and candidate spectrum bands. It is particularly notable that 6G is increasingly being recognized as one of the foundational systems for realizing the metaverse. In addition, in July 2025, the One Big Beautiful Bill Act restored the FCC's spectrum auction authority under the second Trump administration.

(3) AI

The release of ChatGPT in November 2022, followed by intensifying competition among big tech firms over AI, brought the rapid evolution of AI to broad public attention while also highlighting its current technical limitations¹⁴. In AI development, big tech firms have been actively moving to absorb elements essential to their own AI efforts through massive investment, including mergers with and acquisitions of startups.

On the policy front, the Biden administration emphasized responses to ethical, legal, and social issues (ELSI) in science

and technology and promoted both AI-driven innovation and the protection of civil rights, while clarifying principles for risk management, safety evaluation, procurement, and international cooperation across the federal government. By contrast, immediately after taking office, the second Trump administration instructed agencies to withdraw or review those AI policies adopted under the Biden administration that it judged incompatible with deregulation and innovation promotion. In July 2025, it published an "AI Action Plan" built on three pillars - innovation, infrastructure, and international affairs (including diplomacy and security) - and emphasized removing regulatory barriers to data-center development, human-resource development, and overseas expansion. At the same time, the plan also indicated that certain initiatives from the Biden era, such as the creation of research opportunities and reporting frameworks, would not disappear immediately, and that whether they continue or are replaced would depend on each agency's review.

In 2024, NIST launched the AI Safety Institute (AISI) together with a large AISI consortium to promote methods such as capability evaluation, red teaming, and watermarking in collaboration with industry and academia. Under its successor, the Center for AI Standards and Innovation (CAISI), the evaluation and experimental functions of AISI are being carried forward while greater emphasis is placed on standards, testing, and guideline development, with practical evaluation frameworks advancing in collaboration with model providers and international organizations.

(4) Cybersecurity

In cybersecurity, implementation is progressing in a way that links policy, standards, and procurement around four main pillars: protection of critical infrastructure, secure development (secure by design/default), modernization of cryptographic foundations, and international cooperation.

In 2021, the Biden administration issued comprehensive directives on log management, vulnerability sharing, promotion of software bills of materials (SBOMs), and improved security in cloud use for the federal government and a broad range of supply chains. In 2022, the Office of Management and Budget (OMB) issued the federal zero-trust strategy, and the Cyber Incident Reporting for Critical Infrastructure Act (CIRCIA), enacted that same year, established a framework for reporting major incidents affecting critical infrastructure entities. In 2023, the National Cybersecurity Strategy (NCS) was released, laying out a shift in responsibility from individuals to platform providers,

the market implementation of secure-by-design approaches, and stronger international cooperation.

At the implementation level, NIST strengthened management-level governance by adding a governance function to the Cybersecurity Framework (CSF) 2.0. It also issued standards on post-quantum cryptography (PQC) in 2024, launching a phased transition toward PQC in preparation for the age of quantum computing. In the consumer domain, the FCC Cyber Trust Mark entered full-scale operation in 2025, introducing a scheme in which compliant devices display a logo and QR code indicating the status of their implementation.

These policy measures are being advanced under a structure in which the Office of the National Cyber Director (ONCD) serves as the command tower and agencies such as NIST, CISA, the FCC, and OMB divide responsibilities. At the same time, as threats grow more sophisticated with the spread of cloud computing and AI, market consolidation is also advancing rapidly in the US cybersecurity sector. In particular, big tech firms such as Google, Microsoft, and Amazon, along with major security vendors, have been actively acquiring or investing in startups and specialist firms in order to incorporate functions indispensable to cyber defense and service provision, including cloud security and threat intelligence. This shows that cybersecurity is increasingly being embedded, from both public and private perspectives, at the core of the US innovation ecosystem rather than remaining merely an ancillary technical requirement.

As noted above, the growing importance of science, technology, and innovation policy in the United States has also led to confirmation of stronger cooperation in emerging technologies between the governments of Japan and the United States and among the QUAD countries. In addition, memoranda of cooperation are being concluded among industry consortia in areas such as quantum technology and Beyond 5G/6G, and still deeper cooperation is expected.

1.2.2 Conditions in Europe

One of the defining features of Europe is the existence of the European Union (EU), a community of democratic states linked by economic and political cooperation¹⁵⁾. Although each member state remains sovereign, the EU is built on the unique principle that member states transfer part of their sovereignty to shared institutions. The EU currently has a population of approximately 450 million and 27 member states¹⁶⁾, and those member states actively pursue a variety

of initiatives while taking account of developments at the EU level.

In December 2024, the second European Commission under President Ursula von der Leyen (2024-2029) began its mandate. In her political guidelines, “Europe’s Choice”¹⁷⁾, published in July 2024, she emphasized the importance of the Union in preserving democracy at the heart of Europe and in addressing security, climate change, and stronger competitiveness. In the ICT field, the guidelines include goals such as improving productivity through digital technologies, strengthening cybersecurity, and countering deepfakes and foreign information manipulation in order to protect democracy and European values. In addition, the EU’s new economic strategy, the “Competitiveness Compass”¹⁹⁾, published in January 2025 on the basis of the report by former European Central Bank President Mario Draghi¹⁸⁾, has had a major influence on ICT policy. It is built on three pillars: innovation, including closing the gap that has opened between Europe and the United States and China; combining decarbonization with stronger competitiveness; and security and resilience, including reducing dependence on non-EU countries in support of Europe’s strategic autonomy.

EU support for R&D and implementation/deployment in the ICT field is provided through programs such as Horizon Europe, which supports research and innovation activities²⁰⁾; the Digital Europe Programme, which supports digital transformation within the EU²¹⁾; and the Connecting Europe Facility, which supports the development of cross-border network infrastructure²²⁾. Various projects are being carried out through these schemes.

A major characteristic of EU ICT policy is that, in addition to supporting R&D and implementation/deployment, it also advances measures using regulatory tools such as rules on personal-data handling and AI regulation. These two approaches are complementary and both serve as means of achieving the EU’s political goals. Furthermore, in response in part to Russia’s invasion of Ukraine, the EU has been actively establishing laws and mechanisms that unify approaches to cybersecurity across the region.

Against this backdrop, the following provides an overview of developments in each field in Europe.

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

Within the European Partnership framework, the EU established the Smart Networks and Services Joint Undertaking (SNS JU)²³⁾ together with companies, research institutions, and others in order to promote 6G development

and 5G deployment through industry-government-academia cooperation. Through competitive calls, the SNS JU is implementing a wide range of research projects that extend beyond mobile radio technologies to include security, NTN, energy efficiency, and other areas. In addition, the Recovery and Resilience Facility, which forms the core of the EU's coronavirus recovery fund, is also being used in part to support the digital transition, including 6G²⁴⁾. The EU is also placing strong emphasis on international cooperation in 6G development²⁵⁾, including cooperation with the United States²⁶⁾, South Korea, and Japan²⁷⁾. At the same time, stakeholders in European countries are actively participating in SNS JU research projects while each country continues to advance its own 6G development with support from national governments.

(2) Quantum ICT

The EU and European countries are strongly conscious of the rise of the United States and China in the quantum domain and recognize commercialization of quantum technologies as a major challenge²⁸⁾. They are therefore pursuing a variety of initiatives.

In 2018, the EU launched the Quantum Flagship²⁹⁾, committing one billion euros over ten years to support research and development. Around the same time, it also launched the EuroQCI Initiative³⁰⁾ in support of secure quantum communications infrastructure and deployment, with aims that include ensuring Europe's digital sovereignty and strengthening the quantum industry. The quantum communications infrastructure envisioned by the EU consists of terrestrial and space segments, with the latter intended to be developed in cooperation with the European Space Agency (ESA)³¹⁾ and linked to the secure low-Earth-orbit optical satellite communications network IRIS2³²⁾. Under the EU's new Quantum Strategy³³⁾, announced in July 2025, one of the goals is to establish a common research and innovation agenda shared between the EU and its member states, including common priorities. Research and development in the quantum domain in Europe is therefore expected to become still more coordinated going forward.

The United Kingdom began a national quantum initiative in 2014 ahead of the rest of the world and adopted a new ten-year national strategy in 2023³⁴⁾, under which quantum hubs have been established, including in quantum communications³⁵⁾. Other European countries followed with their own national strategies, including Germany in 2018 and France in 2021.

(3) Cybersecurity

In Europe, a strong sense of urgency regarding cybersecurity has emerged not only because of the risk of AI misuse and the possibility that quantum computing may render conventional cryptographic techniques ineffective, but also because of social and geopolitical factors such as the COVID-19 crisis and the war in Ukraine. As a result, region-wide legal frameworks are being developed.

At the EU level, the Cyber Resilience Act³⁶⁾, which sets cybersecurity requirements across a broad range of digital products and requires CE marking, has entered into force, with compliance obligations beginning in December 2027. In addition, following Russia's invasion of Ukraine, the EU enacted the Cyber Solidarity Act³⁷⁾ in February 2025 to strengthen the detection, analysis, and response to cyber threats across the Union, including the establishment of an alert system connecting security operations centers. Beyond legislation, the EU is also supporting related R&D and implementation/deployment through Horizon Europe and Digital Europe. The EuroQCI Initiative described above is likewise one of the cornerstones of the EU's future cybersecurity strategy. In terms of institutional arrangements, the European Cybersecurity Competence Centre was newly established in 2021 in order to strengthen European technological sovereignty in cybersecurity and to manage strategic investment and support schemes in this field³⁸⁾.

Individual European countries have also adopted national cybersecurity strategies and are advancing a variety of initiatives. In France, for example, a Cyber Campus bringing together more than 160 stakeholders for innovation, education, and training was established in 2022.

(4) AI

Like quantum technology, AI is an area in which the EU and European countries are acutely aware of the rise of the United States and China³⁹⁾. They are making active investments in AI while simultaneously emphasizing legal frameworks to ensure the development of safe and trustworthy AI.

At the Paris AI Action Summit in February 2025, the European Commission announced an investment initiative totaling 200 billion euros from public and private sources, including 50 billion euros from the EU itself⁴⁰⁾. Building on this, it released the AI Continent Action Plan⁴¹⁾ in April 2025, a comprehensive strategy aimed at promoting technological sovereignty through investment in data and computing

infrastructure and broader adoption of AI by companies. At the same time, the EU has also developed the AI Act ⁴³⁾, based on a risk-based approach, with the goal of ensuring that AI is safe and trustworthy ⁴²⁾. The Act entered into force in August 2024 and is to be fully applied by August 2026.

In the United Kingdom, the Starmer government, which took office in July 2024, announced a new AI Opportunities Action Plan ⁴⁴⁾ in January 2025 that promotes AI deployment through measures including investment in data centers. Subsequently, the UK AI Safety Institute (AISI) was renamed the AI Security Institute ⁴⁵⁾, marking a shift in emphasis away from issues such as bias and toward risks related to national security and criminal misuse of AI ⁴⁶⁾.

(5) Green ICT

Europe has a strong awareness of environmental issues, and a variety of initiatives are underway in Green ICT, both in greening ICT itself and in using ICT to support broader greening efforts.

After the Green Deal ⁴⁷⁾, which included stringent goals such as achieving net-zero greenhouse gas emissions by 2050, the EU announced the Clean Industrial Deal ⁴⁸⁾ in February 2025 to combine decarbonization with stronger competitiveness, with a focus on energy-intensive industries and clean technologies. In line with this, Horizon Europe is supporting R&D on low-power technologies, while the use of AI in the energy sector is also under consideration ⁴⁹⁾.

At the same time, concern is growing that Europe has less data-center capacity than the United States and China to support AI deployment, even as rising electricity consumption by data centers is also viewed as a challenge. The AI Continent Action Plan sets a target of at least tripling data-center capacity within five to seven years by attracting private investment, but it places priority on sustainable data centers ⁵⁰⁾. In connection with this, the European Commission is preparing a proposed EU Cloud and AI Development Act ⁵¹⁾, one of whose aims is to promote research and innovation for greener computing infrastructure and data centers for cloud and AI.

(6) Other Topics

Finally, it is useful to briefly review regulation, data utilization, and recent developments in funding schemes that are likely to have a significant impact on future research and development in Europe.

In order to strengthen European competitiveness and data sovereignty - especially vis-a-vis platform operators from the United States and China - Europe is advancing both

regulation and data-utilization measures.

On the regulatory side, the EU has promoted consumer protection against illegal online content through the Digital Services Act ⁵²⁾, which has been fully applicable since February 2024, and fair competition in digital markets through the Digital Markets Act ⁵³⁾, which entered into force in May 2023. In the area of data, the EU is not only tightening rules on use but also seeking to generate socioeconomic impact through effective use of data. Measures include the Data Governance Act ⁵⁴⁾, in force since September 2023, which promotes trusted data sharing by making it easier to reuse data held by public institutions in the EU, and the Data Act ⁵⁵⁾, which began to apply in September 2025 and governs the use of data generated by connected devices and other sources. The European Commission is also preparing a new Data Union Strategy ⁵⁶⁾ to expand the volume of data that can be used in AI development.

As for funding, the draft Multiannual Financial Framework for 2028-2034 ⁵⁷⁾, published in July 2025, proposes the creation of a European Competitiveness Fund ⁵⁸⁾ as an instrument for implementing the Competitiveness Compass. The fund is intended to simplify access to the many existing EU support programs, speed up financing, and attract both public and private investment. It is also noteworthy that the new budget framework is expected to promote dual-use research in the defense and space sectors. In addition, the proposed budget would significantly increase Horizon Europe funding from 95.5 billion euros to 175 billion euros. Deliberations on the budget proposal are expected to continue for two years.

1.2.3 Conditions in Asia and Oceania

ASEAN's ten member states together have a population of approximately 679.45 million - about 5.4 times that of Japan - and, with rising per-capita income in recent years, a combined GDP of about 3.6223 trillion US dollars, equivalent to 85.6% of Japan's GDP and 3.6% of world GDP ⁶¹⁾. This region also includes countries with strong economic ties to Japan, such as India, whose population is estimated to have become the world's largest in 2023, and Australia, an advanced economy with high per-capita GDP. The following outlines notable recent developments in research domains that Japan should strategically pursue in this region.

(1) Beyond 5G/6G

In Singapore, since September 2022 the Infocomm Media Development Authority (IMDA), in cooperation with the

Singapore University of Technology and Design (SUTD), has operated the Future Communications Connectivity (FCC) Lab at the university as Southeast Asia's first institute dedicated to 6G research ⁶². In addition, the AI-RAN Alliance, which seeks to create a new AI-enabled wireless communications platform, includes SUTD as well as BROADRADIO, CloudRAN.ai, and SynaXG from Singapore ⁶³.

In Vietnam, the Minister of Information and Communications, Nguyen Manh Hung, announced in January 2021 a policy of beginning research on sixth-generation mobile communications within the year ⁶⁴, and in February 2022 a committee chaired by the minister was established to create a roadmap for 6G research and commercialization ⁶⁵.

In India, Prime Minister Modi in March 2023 unveiled the "6G Vision" prepared by the industry-government-academia 6G Technology Innovation Group (TIG) ^{66/67}. India has since funded testbeds, authorized 5G labs at academic institutions across the country, approved 6G-related research, and established the Bharat 6G Alliance ⁶⁸.

(2) AI

In Singapore, efforts to support AI development and adoption are advancing through the National Artificial Intelligence Strategy ⁶⁹, which aims to realize nation-scale AI deployment in transportation and logistics, smart cities and real estate, healthcare, education, and safety and security. A revised version, National AI Strategy 2.0, was published in December 2023 ⁷⁰. In the Government AI Readiness Index 2024, covering 181 countries and regions, Singapore was ranked second after the United States ⁷¹.

In recent AI-related R&D in Singapore, the National University of Singapore established an Artificial Intelligence Institute in May 2024 to pursue research in real-world AI applications, AI governance and policy, and AI systems and theory ⁷². AI Singapore has also developed and released SEA-LION, a large language model designed to address the diverse languages, cultures, and backgrounds of Southeast Asia ⁷³. SEA-LION uses MosaicML in Version 1, Llama 3 or 3.1 in Versions 2 through 3.5, and Qwen3 in Version 4 ⁷⁴. In addition, the A*STAR Institute for Infocomm Research has developed MERaLiON, a multilingual Southeast Asian LLM with a voice-input interface ⁷⁵.

Other ASEAN countries, including Indonesia ⁷⁶, Thailand ⁷⁷, Malaysia ⁷⁸, Vietnam ⁷⁹, and the Philippines ⁸⁰, have also formulated national AI strategies or plans. In Thailand, NECTEC, under the leadership of the National Science and

Technology Development Agency (NSTDA), has developed the Thai-language Pathumma LLM ⁸¹, whose Version 2 uses the Qwen3 model ⁸².

India formulated the National Strategy for Artificial Intelligence #AIFORALL in 2018 ⁸³. In March 2024, the Indian government approved a budget of 103 billion rupees for the IndiaAI Mission - a program supporting AI startups and AI infrastructure - including the development of AI computing infrastructure, funding for AI startups, large language model development through the IndiaAI Innovation Center, public-sector datasets through the IndiaAI Independent Business Division, and expanded AI education through the IndiaAI Future Skills program ⁸⁴. On the governance side, the Ministry of Electronics and Information Technology published the India AI Governance Guidelines in November 2025, consisting of seven principles, six recommendations, an action plan, and practical guidelines ⁸⁵. In the private sector, Krutrim SI Designs, a generative AI startup from India, announced in January 2024 that it had raised funding from US venture capital firms and others, surpassing a company valuation of one billion dollars and becoming the first Indian AI developer to achieve unicorn status ⁸⁶.

In Australia, the Department of Industry, Science and Resources published a National AI Plan in December 2025 with three main goals: building smart infrastructure, promoting widespread AI adoption and human-resource development, and ensuring AI safety ⁸⁷. The Commonwealth Scientific and Industrial Research Organisation (CSIRO), as a central hub for AI research in Australia, is conducting projects on responsible AI, AI application development, and related areas ⁸⁸.

It should also be noted that, in the Global Partnership on Artificial Intelligence (GPAI), an international initiative for responsible AI based on human-centered principles, Australia, India, Japan, New Zealand, South Korea, and Singapore all participated as founding members from the Asia-Oceania region in June 2020. India, as GPAI chair in 2024, hosted the GPAI Summit 2023 in December 2023 ⁸⁹.

(3) Quantum ICT

In March 2023, Australia's Department of Industry, Science and Resources formulated the National Quantum Strategy ⁹⁰, built around five themes: stimulating quantum R&D, investment, and use; securing access to critical quantum infrastructure and materials; developing skilled quantum talent; establishing standards and frameworks

that support national interests; and fostering a trusted, ethical, and inclusive quantum ecosystem. In September 2024, it was reported that CSIRO had secured Australia's first quantum key distribution (QKD) testbed, supplied by QuintessenceLabs, enabling testing and development ⁹¹⁾. In October 2025, CSIRO also announced the successful demonstration of a QKD system over a 12.7 km fiber loop in cooperation with QuintessenceLabs and AARNet, Australia's research and education network ⁹²⁾.

In April 2023, the Government of India approved the National Quantum Mission, allocating a total budget of 60 billion rupees through FY2030-31 for R&D in quantum technologies, including quantum computing, quantum communications, quantum sensing and metrology, and quantum materials and devices ⁹³⁾. The mission also includes goals in quantum communications such as establishing satellite-based quantum-secure communications over distances exceeding 2,000 km within India, implementing a 2,000 km QKD network, and developing multi-node quantum networks incorporating technologies such as quantum memory ⁹⁴⁾.

In recent Indian R&D in quantum communications, the Centre for Development of Telematics (C-DOT), under the Ministry of Communications, and Sterlite Technologies announced in April 2025 that they had successfully conducted India's first QKD transmission experiment over a four-core multi-core fiber ⁹⁵⁾. In addition, in November 2025, QNu Labs, a startup supported under the National Quantum Mission, announced a successful QKD demonstration over a network exceeding 500 km built on existing optical-fiber infrastructure with support from the Indian Army ⁹⁶⁾.

In Singapore, it was reported in February 2022 that the National Research Foundation had launched the National Quantum-Safe Network (NQSN), a testbed initiative scheduled to become operational by the end of that year ⁹⁷⁾. According to the NQSN website, the initiative aims to build a nationwide platform for partners, a demonstration-based testbed for exploring quantum-safe communications technologies, evaluation of their security, and demonstrations integrating quantum-safe applications, best practices, and use cases ⁹⁸⁾. In 2023, Singapore announced plans for the National Quantum Safe Network Plus (NQSN+) ⁹⁹⁾, a joint initiative involving telecommunications operators Singtel and SPTel together with the quantum-technology company SpeQtral to build an interoperable, nationwide quantum-safe network capable of serving all types of enterprises. Toshiba Digital Solutions also announced that it would

strengthen collaboration with SpeQtral and work together on demonstration projects ¹⁰⁰⁾.

In more recent Singaporean R&D in quantum communications, SpeQtral announced in November 2025 that, in partnership with RAL Space of the UK Science and Technology Facilities Council (STFC), it had successfully launched and deployed the SpeQtre CubeSat equipped with an entangled-photon-pair source and detector module ¹⁰¹⁾. The company plans to launch SpeQtral-1 in 2026 for demonstration of satellite QKD ¹⁰²⁾.

(4) Cybersecurity

According to IBM's X-Force 2025 Threat Intelligence Index ¹⁰³⁾, Asia and Oceania accounted for 34% of cyberattacks worldwide in 2024, making it the most frequently attacked region. Attackers relied primarily on malware and ransomware (22% of all incidents), reconnaissance and scanning tools (11%), and server access (11%). By industry, manufacturing was the most frequently targeted sector (40% of all incidents), far ahead of finance and insurance and transportation. Within the region, Japan accounted for 66% of recorded cases, followed by the Philippines, Indonesia, South Korea, and Thailand at 5% each. In addition, Microsoft's Digital Defense Report 2025 ¹⁰⁴⁾ identified Japan (7th), and Australia and Taiwan (10th), as among the countries whose customers were most frequently affected by cyber threats during the first half of 2025.

In response, laws and regulations on personal-data protection have been enacted or brought into force across the region, including in Australia (1988), the Philippines (2012), Malaysia (2013), Singapore (2013), Thailand (2022), Indonesia (2022), Vietnam (2023), and India (2023) ¹⁰⁵⁾¹⁰⁶⁾. Cybersecurity laws and regulations have also been enacted or are entering into force in countries including the Philippines (2012), Singapore (2018), Thailand (2019), Malaysia (2024), Indonesia (2024), and Australia (2024) ¹⁰⁵⁾¹⁰⁷⁾, indicating steady progress in the institutional development of personal-data protection and cybersecurity in Asia and Oceania.

Against this backdrop, the ASEAN-Japan Cybersecurity Capacity Building Centre (AJCCBC) ¹⁰⁸⁾, established in 2018 as part of Japan's Ministry of Internal Affairs and Communications cooperation on cybersecurity human-resource development in ASEAN, has conducted practical cyber defense exercises (CYDER) for government agencies and critical-infrastructure operators. In February 2022, the Japan International Cooperation Agency (JICA) and the

Thai government signed records of discussion on a technical cooperation project intended to further strengthen these initiatives and enhance cybersecurity response capabilities throughout the region ¹⁰⁹).

1.3 Global Trends in AI Development and Safety

1.3.1 Recent Advances in AI Technology and National Trends

As described in Chapter 2.7 of this report, the public release of ChatGPT by OpenAI in late 2022 triggered widespread attention to the class of technologies now called generative AI. Since then, research, development, and investment have accelerated, and these technologies have begun to penetrate society at remarkable speed.

AI has also attracted major attention in science and technology. The 2024 Nobel Prize in Physics was awarded to John J. Hopfield and Geoffrey Hinton for pioneering achievements in machine learning using artificial neural networks. The Nobel Prize in Chemistry was awarded to David Baker, Demis Hassabis, and John Jumper for work related to AlphaFold2, which used deep learning and the Transformer architecture ²⁰⁸) to make protein-structure prediction dramatically faster, and for the successful design of new proteins. In both cases, AI-related research achievements formed the basis of the award, clearly demonstrating the major contribution of AI technologies to progress in science and technology.

Following the emergence of generative AI, services based on AI agents capable of working with multiple external programs have begun to appear. Applications in robotics and multimodal or sensory domains are also advancing. As discussed in Chapter 2.8, brain-inspired or brain-fused AI is also being explored as a possible way to address the enormous power consumption associated with generative AI. With these rapid technological advances, concern over AI safety has grown internationally, and efforts to ensure safety are expanding globally, as described in the following section.

1.3.2 Global Trends Concerning AI Safety

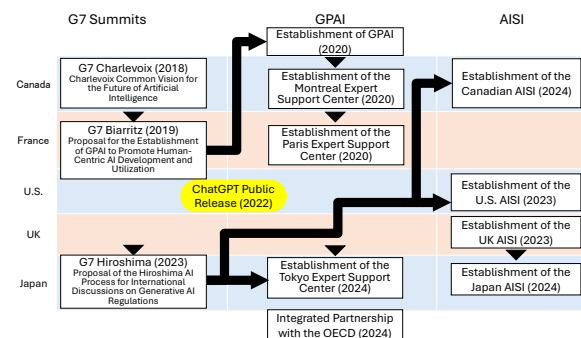
As noted above, the rapid progress and widespread adoption of AI technologies in recent years have intensified global discussion of how concerns regarding AI safety should be addressed. In particular, the dramatically improved performance of technologies such as generative AI has accelerated debate worldwide on how society should engage

with these systems. This section outlines these international trends and discusses two newly established frameworks: the Global Partnership on Artificial Intelligence (GPAI) and AI Safety/Security Institutes (AISI).

Figure 1.3-1 shows the relationship between major G7 summits and these two frameworks. At the 2018 G7 Charlevoix Summit in Canada, leaders declared a common vision regarding AI safety and AI’s potential to promote economic development ¹¹³). At the subsequent 2019 G7 Biarritz Summit in France, Canada and France proposed the establishment of GPAI as an initiative to promote the development and use of human-centered AI ¹¹⁴). At the 2020 G7 science and technology ministers’ meeting, agreement was reached on launching the initiative, and GPAI was formally established in June of that year.

Based on the outcome of the G7 Hiroshima Summit in May 2023, the Hiroshima AI Process ¹¹⁵) was launched to support international rulemaking for advanced AI systems including generative AI. Following an interim ministerial meeting in September and IGF Kyoto 2023 in October, the ministers’ meeting in December approved the Hiroshima AI Process Comprehensive Policy Framework ¹¹⁶), which provides the first international arrangement for sharing policy directions and rules - consisting of guiding principles and a code of conduct - to promote the spread of advanced AI systems that are safe, secure, and trustworthy.

In parallel, the United Kingdom formally established an AISI in November 2023 in conjunction with the AI Safety Summit ¹¹⁷), and the United States also announced the creation of its own institute around the same time ¹¹⁸). Three months later, in February 2024, Japan established its own AISI ¹¹⁹). Since then, similar institutes or equivalent bodies have been launched in additional countries, including Singapore (May 2024) ¹²⁰), Canada (November 2024) ¹²¹), South Korea (November 2024) ¹²²), France (January 2025) ¹²³), and Australia (November 2025) ¹²⁴).



(1) GPAI

The Global Partnership on Artificial Intelligence (GPAI) is a multistakeholder international initiative composed of governments, international organizations, industry, academia, and civil-society experts, with the aim of promoting the development, use, and social implementation of human-centered, safe, and trustworthy AI. Following discussions that can be traced back to the 2016 G7 information and communications ministers' meeting in Kagawa-Takamatsu, GPAI was proposed at the 2019 G7 digital ministers' meeting in France and formally established in June 2020. Japan has participated since the time of its establishment.

GPAI's activities are promoted primarily through the OECD and three expert support centers located within Inria in France, CEIMIA in Canada, and the National Institute of Information and Communications Technology (NICT) in Japan. Through OECD-led GPAI projects and center-led GPAI-related projects, these centers collaborate with experts from industry, academia, government, and civil society to conduct surveys and research that support the implementation of international AI principles and codes of conduct.

Within NICT, the GPAI Tokyo Expert Support Center operates on the basis of three main pillars from a medium- to long-term perspective: (1) the sustainable development and expansion of international rulemaking frameworks such as the Hiroshima AI Process by leveraging the GPAI network; (2) international dissemination of information based on Japan's strengths in areas such as multilingual and multimodal AI; and (3) the formation and support of an international industry-academia-government community base related to AI.

As a major achievement in FY2025, the SAFE (Safety and Assurance of Generative AI) Project produced and released a General-Purpose AI Safety Toolkit that organizes the risks and response measures associated with general-purpose AI¹³⁴.

In the GPAI project tracking the progress of agentic AI systems, the Tokyo Center has advanced work on definitions and classifications of agentic AI as well as the collection of real-world examples, and it reported progress at the expert workshop held during the GPAI plenary meeting in November.

In GPAI-related projects, the Tokyo Innovation Workshop was held in May and discussed topics such as AI use in the Global South, multilingual and multicultural AI, and

interoperability in international AI governance. At the GPAI plenary meeting in November, the OECD Secretariat proposed implementing multilingual and multicultural AI as a GPAI-related project under GPAI's 2026 business plan, building on the outcomes of the Tokyo workshop.

In the Student Communities project, also a GPAI-related initiative, operating structures have been established for student-led research and investigation by students at the University of Tokyo, Doshisha University, and Toyo University, and discussions are ongoing. At the GPAI plenary meeting in November, the three expert support centers jointly reported progress and helped establish a mechanism through which students can participate in international discussions on AI governance. A student-led workshop is currently under consideration in connection with the India AI Impact Summit scheduled for February 2026.

In addition, the Tokyo Center participates in domestic and international meetings and, based on these developments, steadily advances projects that support the implementation of international AI principles and codes of conduct through surveys and research conducted in collaboration with experts from industry, academia, government, and civil society.

(2) AISI

Whereas GPAI is a global multistakeholder framework, AISI bodies are characterized by the fact that they operate in ways suited to the circumstances of each individual country. For this reason, the AI Seoul Summit in May 2024 launched the International Network of AI Safety Institutes¹²⁵, and Japan, the United Kingdom, the United States, South Korea, Italy, Australia, Canada, Singapore, Germany, France, and the EU agreed to participate in internationally coordinated safety evaluation of AI models.

Distinctive policy directions have already begun to emerge among national AISI organizations. In the United Kingdom, for example, the AISI was renamed the AI Security Institute in February 2025, replacing "Safety" with "Security" in the organization's name¹²⁶. Although the UK government stated that this did not amount to a wholesale change in mission, the renaming clearly sharpened the focus on security-related risks such as the use of AI in chemical and biological weapons development, cyberattacks, fraud, and child sexual abuse.

In the United States, the institute was renamed the Center for AI Standards and Innovation (CAISI) in June 2025, removing "Safety" from the name and emphasizing "Standards" and "Innovation." This represented a clear shift

away from the “safety first” orientation associated with the Biden administration toward the “innovation promotion” emphasis of the Trump administration. US Secretary of Commerce Howard Lutnick stated that censorship and regulation had been imposed in the name of national security and that innovators would no longer be constrained by such standards, explaining that CAISI would evaluate and promote US innovation while ensuring safety in accordance with national-security standards ¹²⁷).

By contrast, in Japan, at the third meeting of the Strategic Headquarters for Artificial Intelligence in December 2025, Prime Minister Takaichi instructed the relevant ministers to fundamentally strengthen Japan’s AISI as one of the measures necessary to achieve a national revival through trustworthy AI ¹²⁸). It is therefore expected that Japan’s AISI will further strengthen its role as the central domestic organization for AI safety.

1.3.3 Future Prospects

Developments surrounding AI are moving extraordinarily quickly. New technologies and governance initiatives are announced one after another, and international competition is becoming still more intense. In January 2025, China’s DeepSeek released DeepSeek-R1, which was reported to achieve performance comparable to OpenAI’s o1 inference model while greatly reducing training costs ¹³¹). Speculation that demand for expensive GPU environments would decline led to a temporary sharp drop in NVIDIA’s stock price ¹³²). Competition among US companies has also intensified, as illustrated by reports that OpenAI declared a company-wide “Code Red” in December 2025 in response to Google’s public release of Gemini 3 ¹²⁹), echoing the earlier situation in late 2022 when Google itself reportedly issued a Code Red in response to the release of ChatGPT ¹³⁰).

In generative AI and multimodal AI, which are becoming increasingly autonomous, linkage between AI and other systems is of fundamental importance, and this is also central to physical AI that recognizes, understands, and acts in the physical world, including robotics. The open-source-based Model Context Protocol (MCP) is now gaining significant traction. Announced by Anthropic in 2024, MCP defines how generative AI systems interact with other systems and has been described as something like a “USB-C port for AI applications” ¹³⁵). Although issues such as overhead have been pointed out, MCP was donated in 2025 to the Agentic AI Foundation under the Linux Foundation and is updated daily on GitHub, with companies such as OpenAI and

Google incorporating it into their products.

AI technologies hold the potential to fundamentally transform our society, while some of their risks are already beginning to surface. What distinguishes the latest AI technologies from traditional information and communications technologies such as computers and mobile phones is that ethical, legal, and social issues (ELSI) must also be considered when bringing them into society. International developments concerning AI safety, such as GPAI and AISI, reflect this reality. In Japan as well, it remains important not only to promote research, development, and industrialization, but also to continue examining these issues and putting countermeasures into practice.

Current generative AI models developed by companies and organizations are offered in open, closed, and hybrid forms. Open models disclose their architecture and parameters in order to promote research and industrial use; Meta’s LLaMA is a well-known example. Closed models, such as OpenAI’s GPT and Google DeepMind’s Gemini, offer advantages in terms of controllability, including safety assurance and maintenance, and in helping organizations preserve their competitive advantage. Mistral AI, meanwhile, adopts a hybrid model in which some models are released while high-performance versions remain non-public. In the development of generative AI, which has enormous societal influence, both the momentum created by closed strategies and the transparency and academic advancement fostered by open strategies are important.

In addition, concerns have been raised about the training data that shape generative AI outputs, including problems caused by biases in those data and security risks associated with maliciously manipulated datasets. However, because of copyright and related concerns, there are still only limited examples of public training datasets. Measures against misinformation and disinformation, as well as the securing of transparency, therefore remain major challenges.

Progress in AI is not limited to generative AI. In San Francisco, Google subsidiary Waymo began offering a fully driverless robotaxi service to the general public in June 2024 ¹³³). It is likely that this achievement required a decade or more of continued experimentation, including public-road testing and gradual expansion of the user base, in order to foster social acceptance. This suggests that the successful dissemination of advanced AI technologies, including generative AI, will depend not only on improving technical reliability but also on careful deployment processes and cooperation with society.

Chapter 2 Trends in Key Areas

This chapter describes the ICT research and development landscape in light of the social trends outlined earlier, focusing on the Background, current R&D trends, and future prospects. It begins with Beyond 5G/6G as a cross-cutting foundational technology and then surveys notable developments across specialized fields.

2.1 Foundational Cross-cutting Technologies

Beyond 5G, as the next-generation mobile communications system following 5G, is now expected to function not merely as a communications platform but as a foundation for society itself. For Japan to break through the sense of stagnation currently surrounding the information and communications sector - and to regain momentum even without overwhelming capital strength - the core idea of Beyond 5G must be the integrated use of advanced technologies across industrial sectors from 2030 onward.

This section outlines the challenges surrounding today's communications systems in Japan, provides an overview of efforts toward Beyond 5G research and development, and presents the future prospects that are anticipated.

2.1.1 Background

One common reflection on Japan's efforts toward 5G business is that the country may have been strong in technology yet failed to win in the market. In other words, while Japan possessed excellent R&D capabilities in advanced technologies, it lacked both a broad perspective for viewing mobile communications as a social infrastructure architecture built on those technologies and the foresight and execution needed to commercialize that vision. More broadly, the current sense of stagnation in Japan is not limited to the information and communications sector. Across many industries, efforts are sometimes not rewarded because of external factors, or the conditions necessary for sustained effort are not adequately provided. One reason is that social challenges have become so diverse that industry can no longer solve them through isolated efforts alone.

Examples of such increasingly diverse social challenges include balancing child-rearing and careers, educational inequality tied to family income, the loss of individuality caused by uniform and passive education, employment

limitations resulting from place of residence or physical constraints, rising social-security costs associated with unhealthy longevity, and caregiver exhaustion. Beyond 5G-based social implementation, built on advanced information and communications systems, is expected to help address these issues and make it easier for people to enjoy the richness inherent in human life.

For social implementation from 2030 onward, an environment will be needed in which industries and service providers can collaborate flexibly, divide roles appropriately, and work together with a sense of excitement and active participation in order to create new services that solve social problems. That in turn requires mechanisms that promote technological convergence and collaboration across industry boundaries.

New services created in this way may even influence values related to how society is organized and how people live. For example, AI-driven changes in human behavior or the decentralized exchange of intangible assets may generate innovative value, but they may also create ethical, legal, and social issues (ELSI). Because the scope of what Beyond 5G can enable is so broad, discussion of these aspects must proceed in an integrated manner as well.

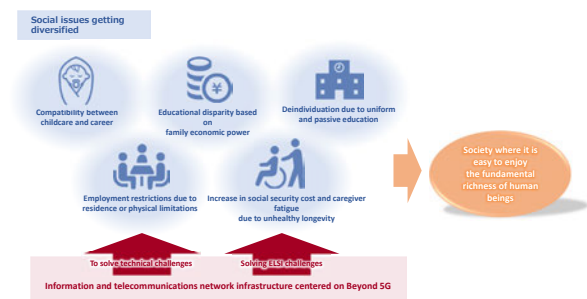


Fig. 2.1-1 Diversifying Social Challenges and Beyond 5G

2.1.2 Current R&D Trends

In Japan, multiple initiatives are underway to realize Beyond 5G. On the vision side, the Beyond 5G Promotion Consortium was established in December 2020 and disseminated information through activities such as white-paper preparation and the exploration of international collaboration. In March 2024, however, it was integrated with the Fifth Generation Mobile Communications Promotion Forum (5GMF), and new activities began under the XG Mobile Promotion Forum (XGMF). Within XGMF, volunteer leaders from academia and industry organize projects on diverse themes - 23 projects as of February 2026 - and many of these projects not only

energize discussion within their own communities but also strengthen external collaboration. XGMF itself has steadily expanded cooperation, including the signing of memoranda of understanding with overseas research institutions. In parallel, the Beyond 5G New Management Strategy Center has held seminars on intellectual property and standardization, published awareness-raising guidebooks, and carried out activities in which leaders gathered across corporate boundaries formulate proposals for future society.

On the R&D side, NICT operates the Innovative Information and Communications Technology Fund Program (Beyond 5G/6G) in order to establish key Beyond 5G technologies as early as possible. Under this program, NICT maintains a fund based on subsidies from the Ministry of Internal Affairs and Communications and commissions R&D to companies, universities, and other organizations. The commissioned projects cover a wide range of areas from semiconductors to digital twins, and strong expectations are placed on linking their results, advancing social implementation, and expanding internationally. NICT also has fields in which it has conducted long-term in-house research and, drawing on those strengths, is carrying out R&D to fuse technologies and adapt them to practical needs in support of Beyond 5G.

Several community initiatives related to Beyond 5G are also emerging. IOWN presents a concept for a network platform that integrates communications and computing resources centered on photonic technologies, and its Global Forum is conducting international discussions on use cases and demonstrations. The Terahertz System Application Promotion Council is examining issues in system development based on terahertz technologies and surveying user needs. The Space ICT Promotion Forum shares information on space communications technologies, organizes cooperative and strategic domains, and studies strategy. The Wireless Emulator Utilization Promotion Forum conducts information exchange and outreach regarding wireless emulators that can reproduce radio-use environments in virtual space and emulate wireless systems.

2.1.3 Future Prospects

In the 2030s, it will be desirable for any company or individual to be able to play an active and equal role in Beyond 5G systems. By establishing such an environment, new value can be generated through open innovation. The companies and individuals that become the central actors should not be confined to a single industry, such as information and communications alone, but should

participate across multiple sectors.

This will enable diverse resources - communications, computing, time, space, spectrum, and others - to be used effectively in an integrated manner and lead to the creation of services that generate new value. To make that possible, it is not enough merely to advance element technologies; mechanisms that connect them are also required. This is one of the essential ideas of Beyond 5G.

Figure 2.1-2 illustrates the concept of a Beyond 5G system as a federation of many different systems. To realize the service requested by a user, it is necessary to combine multiple systems across industries and configure them appropriately. The figure depicts sectors such as terrestrial mobile communications, HAPS, satellite communications, the metaverse, and digital twins, but each sector includes multiple providers. Accordingly, one or more systems may be supplied within a single sector, and multiple sectors may contribute systems to a single service.

The orchestrator shown in Fig. 2.1-2 plays the role of creating overall harmony so as to solve major social challenges that individual industries cannot address on their own and to generate high added value. For example, the optimal placement and dynamic operation of communications and computing resources could reduce imbalances in energy use across industries and regions, thereby helping to address large social issues such as the explosive growth of energy consumption in the ICT sector.

An important point is that Fig. 2.1-2 presents a concept for creating new services by combining various systems; it does not imply a direction toward the centralized management of all data and computing resources. As AI technology advances, AI processing at the edge - managed by individual industries - is expected to expand, and much data will be retained and processed at the edge. For that reason, mechanisms for utilizing data and computing resources across industry boundaries will become even more important.

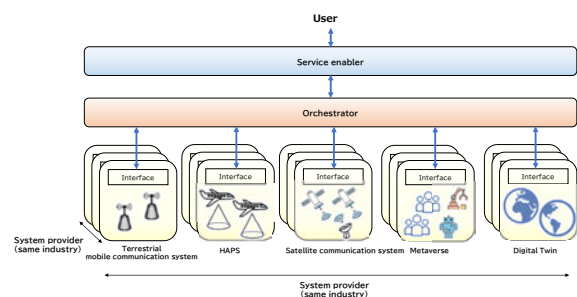


Fig. 2.1-2 Beyond 5G Services Realized by Connecting Different Industries

To achieve this, a coordinating function is required across systems to discover, select, and configure systems according to the services requested by users. In Fig. 2.1-2 this function is represented by the orchestrator, which interacts with each system through common interfaces. Since users cannot directly handle such complex systems, there is also an intermediary called a service enabler. The service enabler exchanges service-level requirements with users, breaks them down, and passes them to the orchestrator. It will therefore be necessary to define this concept explicitly as a Beyond 5G architecture and to specify the required functions and interfaces.

In this way, Beyond 5G is expected to evolve from a mobile communications system that serves merely as a communications platform into a social infrastructure that enables service creation. If this way of thinking becomes widespread, it may trigger a game change in today's information and communications infrastructure business. To succeed in that environment, agile R&D and initiatives for innovation creation will be indispensable. Moreover, because these technologies must be embedded into the systems of society, forums will be needed in which engineers can engage with experts in economics, law, ethics, and other fields, along with demonstrations and other activities to confirm social acceptance of major changes.

2.2 Utilization of Electromagnetic Waves

Electromagnetic waves have a wide range of properties, from light to radio waves depending on frequency, and can be used for diverse purposes such as communications, energy transfer, and sensing. Because they enable the contactless transmission of energy and information through space, they have become indispensable foundational technologies of modern society since the development of electromagnetics in the late nineteenth century, supporting communications, measurement, medicine, industry, and many other fields. Their ability to provide high-speed, high-capacity transmission without requiring a physical medium gives them outstanding convenience and efficiency, leading to broad use across many domains. Modern society depends on electromagnetic-wave technologies not only for communications but also for weather observation and forecasting, the maintenance of infrastructure systems, the safe operation of electrical and electronic devices embedded in daily life, and disaster countermeasures. Their dual-use applications in both civilian and military contexts - such as remote sensing and GNSS positioning - are also advancing. At the same time, the radio spectrum is a limited

resource, and research is progressing on the exploration of unused frequency regions and on technologies for sharing the same frequencies across different purposes.

With a view toward realizing Society 5.0, this section focuses on five core technologies involving electromagnetic waves: (1) remote sensing technologies, which obtain the information needed to transfer data from physical space to cyberspace; (2) technologies for understanding and predicting the space environment, which are required for the stable operation of non-terrestrial networks (NTN) that seamlessly connect terrestrial, maritime, aerial, and outer-space domains and are indispensable for Beyond 5G/6G; (3) electromagnetic-environment technologies, which are necessary for the effective and safe use of radio waves amid major changes in radio utilization; (4) technologies for generating, measuring, and disseminating time and frequency, which form a foundation of ICT and make it possible to measure not only time but also position accurately; and (5) digital optical foundation technologies, which will create next-generation communication environments capable of inducing behavioral change through actuation. Under Japan's Radio Act, electromagnetic waves of 3 THz or below are defined as radio waves, but this section also covers the utilization of higher-frequency electromagnetic waves in the optical region.

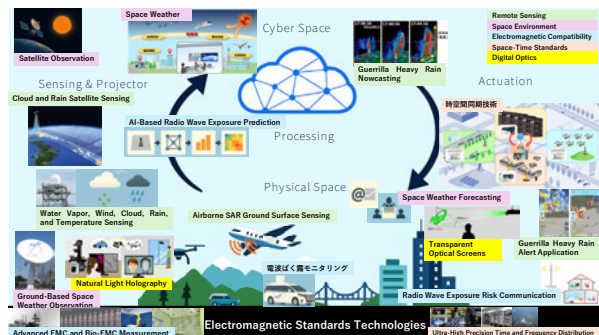


Fig. 2.2-1(a) Conceptual Diagram of Electromagnetic-wave Technologies in Digital Twins

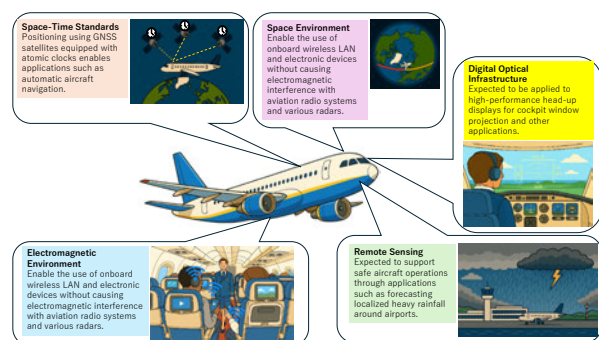


Fig. 2.2-1(b) Examples of Electromagnetic-wave Technologies Used in Aircraft

2.2.1 Background

(1) Remote Sensing Technologies

Abnormal weather and weather-related disasters are occurring frequently across the world, including in Japan. In particular, the increasing severity of heavy-rain disasters in recent years has been reported by the Intergovernmental Panel on Climate Change (IPCC) as an effect of global warming that is advancing “unequivocally.” In response to issues such as the global environment and climate change, as well as safety, disaster prevention and mitigation, and national resilience, approaches based on digital twins are becoming increasingly important. Remote sensing technologies are therefore gaining importance as the gateway through which information from physical space is incorporated into cyberspace. Their use is also expanding on the processing and actuation side of digital twins, for example in heavy-rain prediction and alerting based on vast volumes of remote sensing data.

(2) Technologies for Understanding and Predicting the Space Environment

Space weather - changes in the space environment such as geomagnetism and the ionosphere caused by solar X-rays, high-energy particles, and coronal gas ejections - can have major effects on social infrastructure including communications and broadcasting, space-system operation, aviation, satellite positioning, and electric power in today’s highly ICT-dependent society, at times hindering stable operation. The roughly 11-year solar cycle is reaching a maximum around 2025, and the scale and frequency of solar flares remain high, already producing societal effects such as orbital decay of low-Earth-orbit satellites, launch delays, flight-route changes, and larger GNSS positioning errors. To predict these impacts in advance and minimize disruptions,

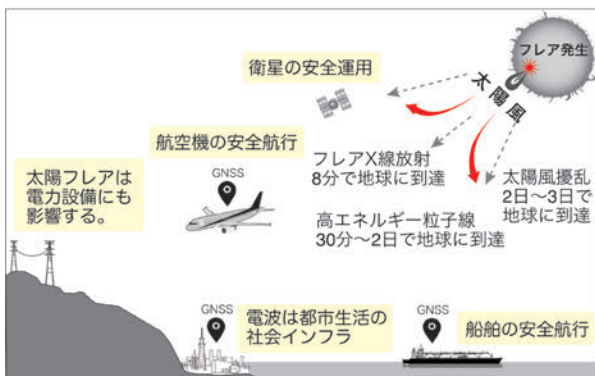


Fig. 2.2-2 Changes in the Space Environment and Their Impacts

space-weather forecasting is being carried out through international cooperation, while R&D is advancing on technologies for more accurate observation and prediction of the space environment and on methods for communicating space-weather information appropriately to users.

(3) Electromagnetic-environment Technologies

In today’s highly electrified and information-intensive living environment, many kinds of electromagnetic waves surround us, creating issues related to the electromagnetic environment. In particular, electromagnetic noise emitted by energy-saving home appliances and other equipment using high-efficiency power semiconductors can interfere with nearby wireless devices. In addition, it is necessary to maintain and manage safety appropriately from the perspective of human exposure to radio waves emitted by 5G systems now spreading in earnest and by Beyond 5G/6G systems under development. Measures are also needed to prevent the growth of unwarranted anxiety about radio safety caused by fake news and similar factors. Electromagnetic-environment technologies are intended to address these challenges.

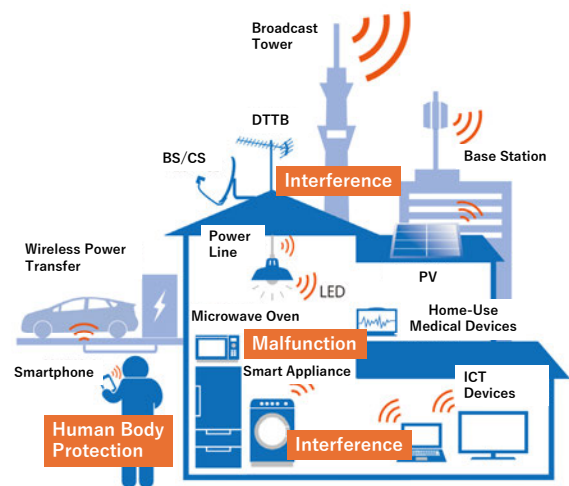


Fig. 2.2-3 Conceptual Diagram of the Electromagnetic Environment

(4) Technologies for Generating, Measuring, and Disseminating Time and Frequency

In modern society, which rests on advanced science and technology, it is essential that society share common standards for time and frequency. Frequency standards make wireless communications possible, while time standards underpin transportation operations, high-speed electronic commerce, communications, and broadcasting. In Japan,

standard frequency and time information is distributed widely through the standard radio stations, NTP, and Optical Telephone JJY operated by NICT. Highly accurate time is obtained by preparing a highly precise frequency standard - typically represented by atomic clocks - and maintaining its continuous operation. Atomic clocks made GNSS positioning possible in practice, and GNSS is also used for precise time synchronization among mobile-network base stations. Technologies for generating, measuring, and disseminating time and frequency make all of this possible.

(5) Digital Optical Foundation Technologies

Digital optical foundation technologies upgrade the field of diffractive optics by centering on techniques that faithfully emulate, in numerical form, the propagation of electromagnetic waves from the near-infrared to the visible-light region. Technologies contributing to Society 5.0 include natural-light holography for sensing the real world and the fabrication of semi-transparent optical elements for AR/VR on the actuation side.

2.2.2 Current R&D Trends

(1) Remote Sensing Technologies

Weather forecasting can be regarded as a familiar example of a digital-twin approach, though many challenges remain. Short-term heavy rain over roughly the next ten minutes can now be predicted with fairly good accuracy, but forecasts of linear rainbands several hours to a day ahead are still insufficiently accurate. What is particularly needed is an integrated observation system that can capture everything from moisture supply before rain clouds form to the generation and development of the clouds themselves. Research is therefore advancing from many perspectives, including numerical forecast models, observation methods, and elucidation of physical phenomena.

Among the sensors used to observe atmospheric phenomena, rain radar has seen steady progress, with Doppler radar for wind-speed observation and polarimetric radar for quantitative observation becoming established in operational practice. At the research frontier, development is advancing on phased-array radar capable of dense observations in both time and space, although all countries are still at the R&D stage. The multi-parameter phased-array weather radar (MP-PAWR) developed by NICT and others, which combines Doppler, polarimetric, and phased-array technologies, is one of the world's highest-performance rain radars and among those closest to practical implementation.

Lidar is another powerful technology for observing clear-sky atmospheres without rainfall. Doppler lidar and water-vapor lidar are beginning to be used experimentally for meteorological observation, while development is also under way on multi-parameter differential absorption lidar (MP-DIAL), which can simultaneously observe parameters such as wind speed, water vapor, and CO₂. In addition, lidar performance is being enhanced through the use of quantum technologies.

Another approach uses the slight change in radio-wave propagation speed caused by water-vapor content to estimate atmospheric moisture from the propagation delay of broadcast signals. Observations with a water-vapor monitoring network in Kyushu began in 2022, and demonstration experiments have also been under way in Taiwan since 2025. Building on Japan's strong technology and operational experience in wind profilers, an ISO international standard for wind profilers was issued in 2022.

In synthetic aperture radar (SAR) for high-precision observation of the Earth's surface, resolution continues to improve. NICT achieved 15 cm resolution with its airborne SAR system Pi-SAR X3. Private-sector plans are also advancing to launch multiple small SAR satellites and observe conditions across the Earth's surface every few hours for commercial use, while SAR technologies are included in R&D on ocean-condition monitoring using HAPS.

Earth observation using large satellites is also being advanced through international cooperation. The EarthCARE satellite launched in May 2024 carries the first spaceborne cloud radar capable of Doppler observation, and after calibration and validation it entered routine operation in January 2025. In satellite precipitation observation, studies are also progressing on a successor mission to the Global Precipitation Measurement program in order to realize highly accurate vertical Doppler observation.

As sensor performance improves, the volume of acquired data is also becoming enormous. R&D is therefore being conducted on data compression, restoration, and distribution systems to promote the use of such data. In 2024, the platform "Qumron" was developed and released to distribute MP-PAWR's vast datasets efficiently, and in 2025 it was used to provide highly accurate meteorological forecast information to visitors at Expo 2025 Osaka, Kansai.



Fig. 2.2-4 Multi-parameter Phased-array Weather Radar (MP-PAWR)

(2) Technologies for Understanding and Predicting the Space Environment

For space weather, the most important requirement is to identify and predict events and their scale as early as possible and to communicate appropriate information so that impacts can be minimized. To prepare for severe space-weather disasters, efforts are advancing to improve the observation and prediction technologies that underpin space-weather forecasting. Multiple major space-weather events occurred during the solar-maximum period peaking around 2025, causing social impacts such as reduced positioning accuracy, changes in airline routes, launch schedule changes, and other disruptions to space systems. In 2022, economic damage also occurred when numerous low-Earth-orbit satellites were lost after falling from orbit under the influence of space-weather phenomena.

For observation of current conditions, domestic and international institutions cooperate to monitor broad regions by sharing coverage. Within Japan, NICT is the only organization conducting routine ionospheric observation. In cooperation with domestic and overseas research institutions, it is also working to densify and broaden ionospheric observation networks across Southeast Asia and to receive 24-hour data from solar-wind observation satellites. Japan is also jointly developing a space-environment sensor for installation on the next geostationary meteorological satellite Himawari-10, scheduled for launch in 2030.

Prediction technologies for space weather are also advancing worldwide through the use of high-performance computing, data assimilation, and AI/machine learning. NICT is leading development of the GAIA atmospheric-ionospheric data-assimilation model and the SUSANOO solar-wind model, and it has also developed Deep Flare Net, a machine-learning system with one of the world's highest

hit rates for solar-flare forecasting.

Users of space-weather forecasting are expanding beyond the traditional space and communications sectors to include aviation, electric power, positioning, disaster management, and general industry. In Japan, systems such as WASAVIES, SECURES, and HF-START have been developed, and in June 2025 the SAFIR alert service was launched together with practical guidelines for the use of space-weather information.

Because monitoring and forecasting global space-weather phenomena require international cooperation, forecast services are conducted through collaboration in organizations such as ISES, while standardization of observation data, equipment, and criteria is progressing through bodies such as ITU-R, WMO, ISO, and CGMS. The importance of space weather is also growing in the defense field.

(3) Electromagnetic-environment Technologies

To enable smooth interoperability between electrical/electronic equipment and communications/broadcasting systems in complex electromagnetic environments, R&D is under way to establish methods for evaluating the parameters of electromagnetic noise that dominate interference affecting wireless terminals such as 5G devices. This work combines theoretical study, numerical simulation, and experiment to clarify the mechanisms of noise generation and propagation in equipment connected to common power lines and used simultaneously in large numbers. Research is also progressing on electromagnetic interference and countermeasure technologies for automated and autonomous systems such as drones.

To evaluate properly the safety of human exposure to radio waves from new wireless systems such as Beyond 5G/6G, R&D is advancing on exposure-assessment techniques, on elucidating exposure characteristics in the human body, and on extending radio-protection guidelines and developing conformity-assessment methods suited to the latest wireless technologies. Results are also being reflected in international standards and domestic regulations, and related databases are being published. Monitoring data on radio-frequency exposure levels are also being acquired, accumulated, analyzed, and visualized on the web to support risk communication.

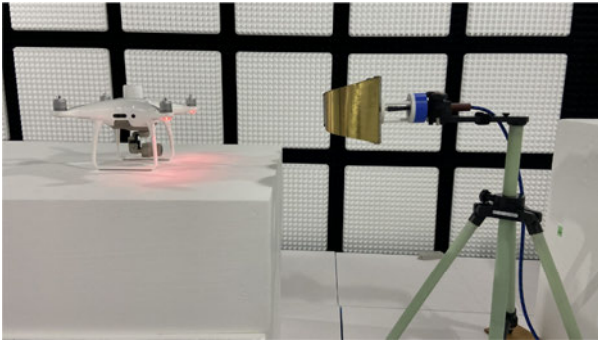


Fig. 2.2-5 Measurement of Leakage Electromagnetic Fields from Drones

(4) Technologies for Generating, Measuring, and Disseminating Time and Frequency

Standards of time and frequency are now approaching the first major turning point in half a century. Conventional atomic clocks have used microwave-region atomic transitions, but since around 2000 optical clocks based on optical-region transitions have achieved dramatic performance gains, improving accuracy by more than two orders of magnitude over previous standards. In 2022, the General Conference on Weights and Measures resolved that member states should intensify efforts toward redefining the second by 2030. In 2025, Shimadzu began sales of the world's first commercial optical lattice clock.

At the same time, microwave atomic clocks made position determination by GNSS possible in practice. Japan's Quasi-Zenith Satellite System is aiming to achieve sustained positioning around 2027 based solely on its own satellites, and the revised Space Basic Plan roadmap published in 2024 added improved reliability of Japan Standard Time through multiple optical lattice clocks.

Moves are also emerging to improve time and geodetic accuracy by equipping client-side devices such as handheld terminals and autonomous vehicles with atomic clocks rather than conventional quartz oscillators. There is growing expectation for spatiotemporal synchronization technologies that would allow anyone, anytime, anywhere to share time with the required precision and cost and, from that, determine spatial position as well. Devices to realize spatiotemporal synchronization had already been developed and demonstrated by fiscal 2025, and some have entered productization.

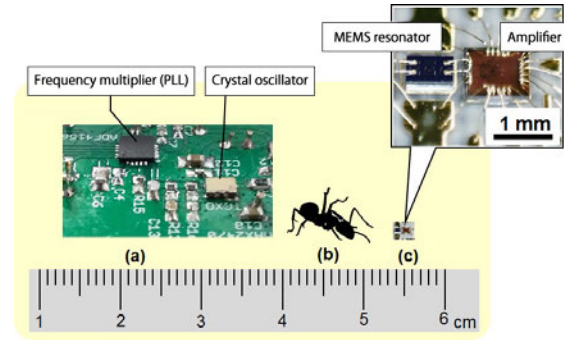


Fig. 2.2-6 Miniaturization of Oscillation Circuits for Atomic Clocks

(5) Digital Optical Foundation Technologies

Worldwide, R&D is progressing on technologies and systems for three-dimensional image sensing that capture scenes as they are in the moment, with applications ranging from life science, materials science, industry, and the arts to daily life. Research in natural-light holographic sensing accelerated with the emergence of FINCH and today active work is under way in applications to microscopy, cameras, and wavefront sensing. Japan is now one of the world's leading hubs for natural-light digital holography, and NICT was the first in the world to succeed in developing and demonstrating a system for recording and replaying full-color holographic video under sunlight.

Transparent optical-screen manufacturing and application are also advancing, and AR head-up displays for vehicles are emerging as a promising use of holographic transparent optical screens. NICT developed a transparent AR display system that enables naked-eye 3D viewing using only

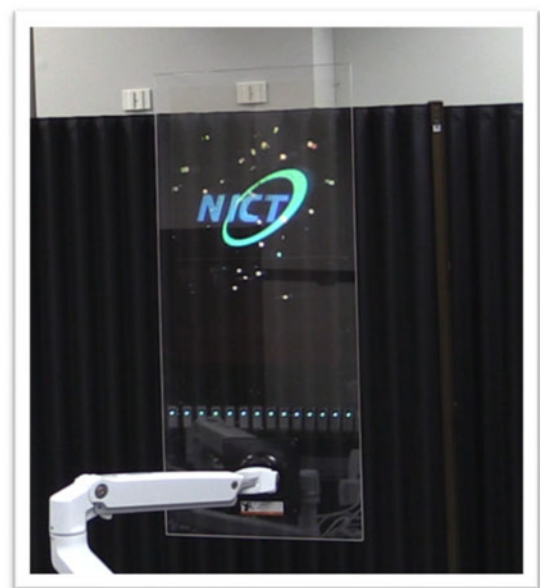


Fig. 2.2-7 Transparent Full-color Animated 3D Display for AR

holographic film and multiple inexpensive compact projectors. Overseas startups and manufacturers are also accelerating commercialization, while Sony's Spatial Reality Display is being introduced in a wide range of fields including culture, art, manufacturing, and medicine.

A cross-cutting technology that spans the five areas above is the measurement of material properties using electromagnetic waves. Electromagnetic techniques are being used to evaluate high-performance materials needed for Society 5.0, and R&D is progressing on millimeter-wave methods for evaluating permittivity and permeability as well as terahertz-band nondestructive inspection technologies for medicine, semiconductors, and cultural assets.

2.2.3 Future Prospects

Technologies for utilizing electromagnetic waves that support next-generation social infrastructure are expected to become even more important. Looking ahead, progress is anticipated in cross-disciplinary directions such as the fusion of communications and sensing (ISAC) and the incorporation of quantum technologies, as well as in space-weather R&D concerning geomagnetic and ionospheric storms that could have major impacts on ICT infrastructure. It will also be important to combine these technologies effectively and reflect them in real society.

(1) Remote Sensing Technologies

The radio waves increasingly used for communications in Beyond 5G/6G society can be used not only for communications but also for sensing. Further study of ISAC systems is therefore expected. Machine learning is already being used for short-term rainfall prediction, data quality control, compression and restoration, and data analysis, and its use is expected to expand further. R&D on sensing using quantum technologies has only just begun in various countries, but major advances are expected in technologies that use single-photon detectors to dramatically improve lidar sensitivity.

(2) Technologies for Understanding and Predicting the Space Environment

In a future society that makes even greater use of space infrastructure - in other words, a society enabled by NTN - the effects of space weather will become more serious, making it essential to take measures in accordance with space-weather forecasts. Alongside the underlying R&D, efforts will also be needed to deliver space-weather forecasts more

effectively to users and connect them to appropriate action. In the longer term, research and international frameworks will likely be required to enable data observation, prediction, and alerting for space-weather forecasting not only around Earth but also in regions such as the Moon and Mars.

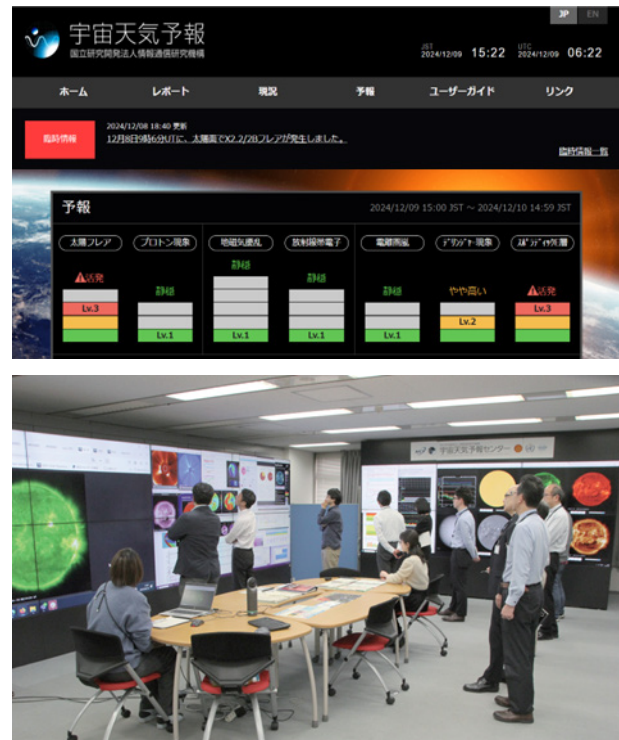


Fig. 2.2-8 Space Weather Forecast Center

(3) Electromagnetic-environment Technologies

As future technological development changes the structure of interference-generating devices, sophistication advances on the interference-receiving side in communications and broadcasting, and lifestyles continue to evolve, further development is expected in R&D that can serve as the basis for deploying electromagnetic-noise evaluation technologies to industry and thereby continually maintaining and building an appropriate electromagnetic environment. Expanded monitoring of radio-wave exposure levels will also contribute to risk communication and the maintenance of a safe and secure radio-use environment.

(4) Technologies for Generating, Measuring, and Disseminating Time and Frequency

In addition to making standard time more reliable through optical lattice clocks, new application areas based on still more precise time and frequency standards are expected to emerge. Once spatiotemporal synchronization is realized so that users and devices connected by wired

or wireless networks share common temporal and spatial coordinates, the entire network can shift to a synchronized system and provide highly precise timing throughout the network, underpinning delay-guaranteed communications, cryptographic communications, quantum communications, and more. Building such infrastructure is also expected to reduce the vulnerability of modern wireless networks that depend excessively on GNSS and thereby improve resilience.

(5) Digital Optical Foundation Technologies

In natural-light holographic sensing, many current results are still in a stage preceding truly breakthrough progress and broad application development. Even so, technologies such as microscopy and wavefront sensing have already been commercialized as new measuring instruments. The XR market and the global metaverse market are both expected to grow significantly, and material-property measurement technologies are also expected to advance into higher-frequency domains and more extreme environments. The five categories of electromagnetic-wave utilization technology are likely to converge to open up new forms of electromagnetic-wave use, especially in NTN environments where technologies from different areas can be combined to evaluate and improve the network environment comprehensively from space to the ground.

2.3 Communications Network Infrastructure

The fundamental performance requirements of communications network infrastructure - wide-area broadband communications, low latency, and high reliability - continue to rise over time. R&D that improves the underlying and system technologies of optical communications, wireless communications (terrestrial and satellite), and networking remains indispensable in every generation. Through the transition from 4G to 5G and now Beyond 5G, the basic direction has remained the same while target levels and functions have advanced and additional new vectors of functionality have been added.

This section provides an overview of the environment surrounding the communications network infrastructure desired for Beyond 5G, current R&D trends, and future prospects in order to realize the society expected between 2030 and 2050. The envisioned future infrastructure links terrestrial wireless systems, cloud and edge computing resources, optical-fiber backbone networks, drones, HAPS,

and non-geostationary and geostationary satellites. In the aerial domain as well, optical communications will appear in addition to radio.

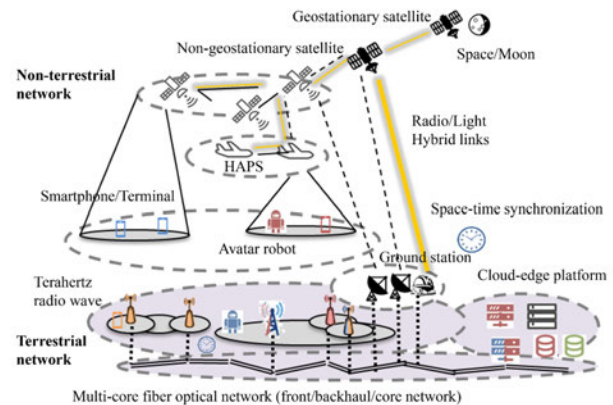


Fig. 2.3-1 Future Communications Network Infrastructure

2.3.1 Background

Household Internet access in Japan evolved from roughly 9.6 kbps modem connections in the 1990s to ISDN, ADSL, CATV, FTTH, and today 10 Gbps optical-access services. Over that period, access speed increased by a factor of one million. In optical core networks, transmission capacity per fiber rose from 10 Gbps in the 1990s to 1 Tbps in the 2000s and 10 Tbps in the 2010s, driven by the maturation of technologies such as time-division multiplexing, wavelength-division multiplexing, wideband optical amplification, quadrature amplitude modulation, and digital signal processing.

Wireless access likewise advanced dramatically. Wi-Fi, first introduced as an 11 Mbps standard in 1999, reached 9.6 Gbps in the IEEE 802.11ax standard established in 2021, and the IEEE 802.11be standard established in 2025 specifies 23 to 46 Gbps depending on configuration. Mobile communications rose from 64 kbps in the 2G era to around 384 kbps in 3G, 100 Mbps to 1 Gbps in 4G, and then 10 Gbps in the 5G generation. Satellite communications also advanced from early gigabit-class high-throughput satellites to several-hundred-Gbps systems, with Tbps-class services planned for the latter half of the 2020s.

On the software side, network functions have increasingly become available as open-source software. At the same time, computing and storage have shifted from on-premises deployment toward cloud services, supported by the progress of virtualization. In Japan, households able to use ultra-high-speed broadband such as FTTH reached virtually 100 percent, while 5G population coverage exceeded 98 percent by March 2025.

Looking ahead to Beyond 5G, strategies in Japan call for a tenfold increase in wireless-access capacity and a hundredfold increase in backbone capacity. To cope with that, R&D must pursue improvements on the order of one thousandfold. Aerial and non-terrestrial networks are also expected to provide wide-area and low-latency communications paths, including three-dimensional networks with node-to-node capacities on the order of Tbps.

2.3.2 Current R&D Trends

This section first describes R&D trends in space-division multiplexed optical-fiber communications and in non-terrestrial networks, and then addresses trends in communications infrastructure that incorporates computing platforms.

(1) Space-division Multiplexed Optical-fiber Communications

One major line of work is multi-core optical-fiber transmission, in which multiple light paths are provided within a single fiber. Progress has been remarkable, with repeated world records from NICT, NTT, and KDDI ranging from 109 Tbps in 2011 to 22.9 Pbps in a 38-core fiber in 2023, along with capacity-distance records and long-haul demonstrations over more than 2,000 km.

For multimode optical-fiber transmission, KDDI and NICT have likewise set world records using standard-diameter fibers, including 407 Tbps, 1.01 Pbps, and 1.53 Pbps demonstrations. With an eye toward early practical use, NICT has continued updating records for internationally standardized 125 μm outer-diameter fibers. Commercial deployment is also beginning, with the TPU submarine cable reportedly becoming the world's first overseas cable to adopt two-core fiber commercially.

(2) Non-terrestrial Networks

In non-terrestrial networks, optical communications have been demonstrated in space by governments and agencies such as China, NASA, ESA, and DLR. Private-sector initiatives are also accelerating. SpaceX is equipping later-generation Starlink satellites with optical inter-satellite links, and Amazon has reported successful 100 Gbps inter-satellite communications in its low-Earth-orbit constellation project. In Japan, NICT has demonstrated 2 Tbps-class ground optical communications aimed at small-satellite links and is developing 10 Gbps optical terminals for CubeSats and HAPS, while domestic carriers are sharing visions that

combine terrestrial systems with HAPS, low-Earth-orbit satellites, and geostationary satellites.

The NTN field offers large room for development as a new industrial domain and provides powerful means of securing communications during disasters. At the same time, issues remain regarding how terrestrial and non-terrestrial systems should be connected, how spectrum should be used, and what business models will be effective, making industry-academia-government collaboration essential.

(3) Communications Infrastructure Incorporating Computing Platforms

The concept once described as edge computing has expanded into broader ideas such as Network for AI and AI-RAN, while AI is also being applied to network operation and management under the banner of AI for Network. In addition, work is under way on photonics-electronics convergence to reduce delay between computers. Examples include APN-based approaches under IOWN that distribute computing resources while allowing data to remain on-premises, AI-RAN approaches that colocate computing resources near the radio access network, and AI-driven methods for monitoring failures, traffic volume, and security or for translating service requirements into network settings.

2.3.3 Future Prospects

Communications network infrastructure contributes to the stability of the foundations of social life through its continuing advancement in sophistication and performance. It will be essential to build orchestrators that allow services to be provided smoothly across the network as a whole, but equally important will be making the control, operation, and management of large-scale networks easier in response to demographic change and the growing number of connected devices. In that context, AI for Network will need to support automatic control, coordinated updating of AI functions, and accurate interpretation of user and operator intent in heterogeneous multi-operator environments, thereby helping to maintain and improve service performance in Beyond 5G networks in the 2030s, prevent equipment failures, and avoid their immediate impacts.

For terrestrial backbone networks, continued growth in communications demand implies a need for optical-fiber technologies that exploit space and wavelength domains and support both very large capacities and long-distance transmission. These technologies will be indispensable for international links, data centers, and terrestrial backbone lines. On the non-terrestrial side, NTN will expand

coverage, provide new low-latency services and backup links, and eventually support seamless communications through integrated three-dimensional network control. As NTN spreads, however, spectrum exhaustion will become a serious concern, making more effective spectrum use and better radio-environment design increasingly important.

Digital-twin-based simulation and emulation technologies are also expected to become important for efficient use of limited spectrum resources and for the rapid establishment of wireless environments in underserved areas. Wireless emulators that allow radio systems to be built and tested in cyber-physical space will need to be provided early and used in earnest in the 2030s. The future will also require mechanisms for three-dimensional spectrum sharing that include radios operating in the air, as well as techniques that extend the reach of high-frequency radio waves by using reflectors, radio-over-fiber, optical conversion, and signal recovery. In the longer term, harmonious use of optical waves and radio waves will be needed to realize medium-range and short-range terabit access infrastructure.

Finally, device technologies and quantum ICT will also play important roles in future communications infrastructure. Device R&D is needed to support the computing and communications performance demanded by advanced information systems, while quantum ICT could bring more fundamental innovation to the wired and wireless networks that underpin the modern Internet.

2.4 ICT Device Technologies

In the information and communications field, higher information-processing performance and ever faster, larger-capacity communications continue to be pursued. Although debates about limits and necessity always accompany such advances, demand and capability in practice have continued to grow without stopping. This trend is expected to continue as information systems migrate further to the cloud, IoT and AI continue to advance, 5G spreads, and Beyond 5G develops.

The performance improvements of information and communications systems are fundamentally supported by the devices used within them - ICT devices. Not only continued enhancement of conventional devices but also convergence between device categories that have historically relied on different technologies, and the use of entirely new devices unconstrained by conventional concepts, could create new technological landscapes. This section provides an overview of these ICT devices.

2.4.1 Background

(1) High-speed and Large-capacity Information Processing and Communications

The progress of cloud computing, IoT, AI, and 5G is increasing demand for higher-speed, larger-capacity data processing in data centers and high-performance computers. At the same time, multimedia services, mobile-traffic growth, and the realization of cyber-physical systems in Society 5.0 require ultra-high-speed, high-capacity information and communications. These needs are driving 5G deployment and also intensifying R&D toward Beyond 5G/6G.

AI-enabled autonomous driving is also expected to help solve current automotive problems such as accidents and congestion. Such systems already use radar and lidar, and still more precise ranging will be required in the future. In addition, from the perspective of spatiotemporal synchronization, which is important for cyber-physical systems, highly stable and compact signal sources that can be carried and installed easily are required. At the same time, if growing processing and communications demand continues to be addressed using existing devices alone, power consumption will keep rising. ICT devices must therefore improve performance while suppressing increases in energy consumption.

(2) Use of Previously Underutilized Frequency Bands and Expansion of Use Cases through New ICT Devices

If the range of environments and frequency bands that ICT devices can support is expanded, their utilization range and performance can be broadened accordingly. One important target is the terahertz band, which lies between conventional radio waves and light and has long been underused. Another is the UVC region, whose wavelengths are shorter than 280 nm and are entirely absorbed by the ozone layer, making it a so-called solar-blind region. This makes the region promising for optical wireless communications and sensing free from solar background noise. Deep-ultraviolet LEDs are also expected to play important roles in sterilization and inactivation without chemical agents, optical processing, finer 3D printing and resin curing, printing, pollutant decomposition, spectroscopy, and medical applications.

Conventional semiconductor electronic devices also face difficulties in high-temperature or high-radiation environments, creating demand for new ICT devices that can operate under such extreme conditions. At the same time, there is growing expectation for flexible and lower-environmental-impact ICT devices based on organic

materials rather than conventional semiconductors.

2.4.2 Current R&D Trends

(1) ICT Devices for Utilizing New Frequency Bands

In the wireless access network field highlighted in the Beyond 5G 2.0 Strategy, sub-terahertz R&D is identified as an important area in addition to promoting 5G and millimeter-wave communications. Although many technical challenges remain before practical deployment, sub-terahertz wireless technologies are expected to enhance 5G functions by exploiting wide usable bandwidth. Circuit technologies for sub-terahertz communications are advancing in Japan and abroad, including beamforming, beam steering, MIMO-related functionality, and implementations based on Si CMOS that are suitable for mass production. Reported examples include phased-array ICs around 150 GHz, RFIC and module technologies in the D band, and two-dimensional phased-array ICs around 300 GHz.

High-power GaN devices - compound-semiconductor devices that complement silicon devices - are also important. Japanese companies hold strong positions in 5G base-station transistors, while NICT has reported record oscillation frequencies domestically. Outside Japan, many organizations are active, and foundry-based manufacturing of semiconductor and MMIC chips is particularly vigorous. Services or research programs are under way for devices ranging from FR3-band GaN-HEMTs to GaAs-pHEMTs for the F and D bands and InP-HBTs aimed at even higher-frequency regions. In Japan, however, generally accessible foundry services remain limited, which could create risks in defense-equipment development and economic security.

Terahertz waves combine properties of both radio and light, making them a natural target for integrated electronics-photonics approaches. Optical frequency combs are indispensable as highly stable signal sources for such high-frequency systems, and development has progressed from solid-state-laser-based combs to fiber-laser-based and optical-modulator-based combs, with growing attention now being paid to microcombs using tiny optical resonators. If compact and portable optical frequency combs can be deployed in society, they are expected to contribute to precise clocks, remote distribution of standards between devices, accurate spatial positioning, and increased capacity in communications from optical waves to the terahertz band.

As light-source devices in the deep-ultraviolet band, mercury lamps have long dominated industry because of their high output and low cost. However, because mercury

is harmful to people and the environment and the Minamata Convention is driving mercury elimination, expectations for deep-ultraviolet LEDs as compact and low-impact alternatives have risen sharply. Even so, mercury lamps still retain overwhelming advantages in both output and cost, so full-scale substitution has not yet occurred. One of the most important issues is therefore how to raise the optical output per chip of deep-ultraviolet LEDs while controlling cost, and fierce international R&D competition is under way.

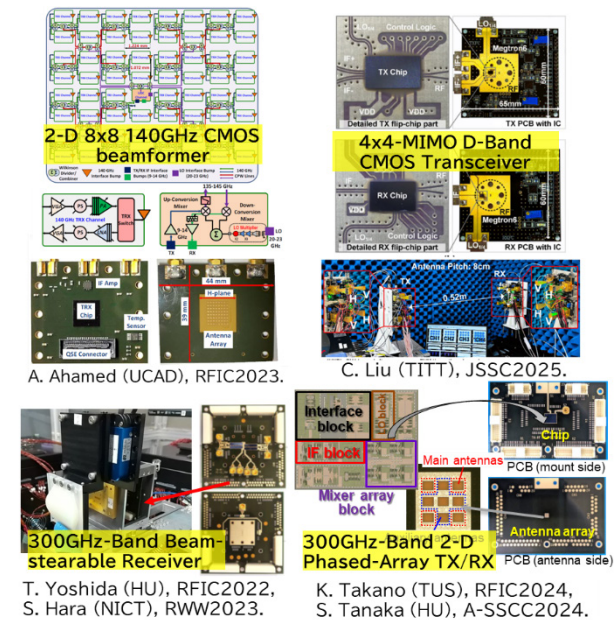


Fig. 2.4-1 Terahertz-band Wireless Communications Technologies

(2) ICT Devices Using New Materials

In contrast to inorganic-material devices that have been the mainstay of ICT hardware, R&D is progressing on organic devices that may allow more flexible design of composition and properties. Important applications include high-speed optical modulation, electro-optic conversion, and the generation and reception of terahertz waves. As high-speed optical modulators, thin-film lithium niobate, silicon, indium phosphide, and electro-optic-polymer hybrid modulators are all under active development.

Because applications differ in the modulation bandwidth, V_{pi}L, optical loss, device footprint, and other properties they require, no single material or structure is likely to be ideal for every use. A future division of roles by application is therefore expected. These modulators are core devices that determine optical information-communication speed, and fierce international R&D competition is under way particularly for optical interconnects in data centers and AI-HPC systems.

Table 2.4-1 Types of High-speed Optical Modulators

| Optical modulators | Thin-film LN | Si | InP | EOP hybrid |
|--------------------|--------------|------|------|------------|
| Bandwidth [GHz] | ~ 80 | ~ 40 | ~ 80 | > 100 |
| $V_{\pi}L$ [V·mm] | 20 | 2–20 | 8 | 0.3–3 |

For high-speed wireless applications, reports have appeared on terahertz modulators that directly convert terahertz signals into optical signals, including 70 Gbit/s transmission at 100 GHz using thin-film lithium niobate and direct terahertz modulation at 375 GHz using electro-optic polymers. In spatial optical modulation as well, research is progressing on systems using organic electro-optic polymers, which are expected to outperform silicon- and liquid-crystal-based approaches in optical scanning speed and power consumption.

Gallium oxide is another notable new semiconductor expected to support high-efficiency power electronics and operation in extreme environments such as high radiation. Since early pioneering device work in Japan, research activity has expanded greatly, and the field is now widely recognized as a major new semiconductor area. Venture companies founded by young researchers have also begun to appear in Japan, the United States, and Europe. In bulk single-crystal growth, new companies are entering the market in addition to existing suppliers, while in thin-film growth a technology race is emerging between MOCVD and other approaches. In device development, China in particular has been making conspicuous advances.

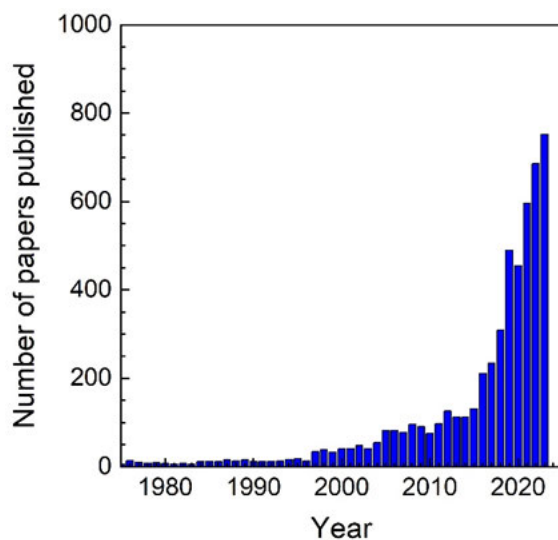


Fig. 2.4-2 Number of Published Papers in the Gallium Oxide Device Field

2.4.3 Future Prospects

By the 2030s, R&D on terahertz-band wireless foundational technologies is expected to bear fruit, enabling Beyond 5G/6G functions such as ultra-high speed and capacity, ultra-low latency, and massive simultaneous connectivity. This could allow societies in which people can enjoy ultra-high-speed information and communications anywhere through technologies such as terahertz-band MIMO wireless LANs and high-precision 8K wireless delivery and transmission. To achieve this, however, many issues remain, including higher transmitter output, packaging technologies for multi-element antennas, and signal synchronization methods. Solutions will require technology integration within electronics, integration with wireless technologies established up to 5G, and further convergence with photonics.



Fig. 2.4-3 Image of Future Ultra-high-speed Wireless Utilization

In deep-ultraviolet devices, the advantages of compact, portable, high-output, and environmentally friendly deep-ultraviolet LEDs are expected to bring major innovation across a wide range of social infrastructure, from optical information and communications to medicine, the environment, industry, and sterilization. Future applications may include dramatic expansion of optical frequency resources available for optical ICT and innovative optical wireless communications such as solar-blind non-line-of-sight links. Continued progress toward higher performance, greater functionality, and higher reliability is expected, along with further advancement of foundational technologies for high-level optical ICT use of deep-ultraviolet light, including laser diodes and ultra-sensitive sensing devices.

For ICT devices based on organic materials, targets include achieving 200 Gbaud data communications with sub-1 V drive voltages, improving conversion efficiency

between light and radio in terahertz modulators, and realizing high-speed, high-capacity, low-latency transmission using electromagnetic waves in the 100 to 400 GHz range. Visible-light optical phased arrays for new radio communication interfaces such as 3D image reproduction and smart glasses are also expected.

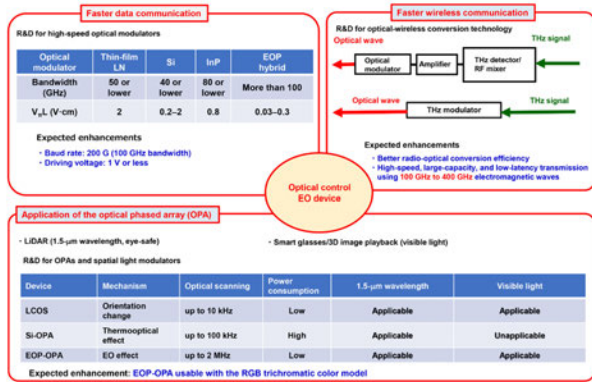


Fig. 2.4-4 Outlook for ICT Devices Based on Organic Materials

For gallium oxide devices, it will be necessary to continue advancing fundamental technologies in both material growth and device processes while exploring device designs that can compensate for the lack of practical p-type conduction. Key topics include larger and higher-quality wafers, conductivity control in epitaxial films, heterostructures, surface and interface control, substrate and epitaxial etching, gate insulation films, and edge termination. Equipment manufacturers on the user side are eager to test power supplies and other products incorporating gallium oxide power devices, and there is strong demand for the early market introduction - even at the sample-shipment level - of gallium oxide Schottky barrier diodes.

2.5 Cybersecurity

This section surveys trends in cybersecurity, including the surrounding environment, current R&D trends, and future prospects. It also reflects the growing severity of threats such as ransomware, supply-chain compromise, Human-Operated attacks, attacks exploiting AI, and the long-term transition of cryptographic infrastructure.

2.5.1 Background

Cybersecurity has become a foundational issue for national security, economic activity, and social trust. As digital transformation deepens across government, critical

infrastructure, industry, healthcare, and daily life, cyber risk is no longer limited to the IT department; it is now a management issue and a public-policy issue.

The threat landscape continues to intensify. Ransomware has evolved from simple file encryption into a composite business model that combines intrusion, data theft, extortion, and sometimes public disclosure. External VPN appliances and remote desktop services remain common intrusion paths, and compromises through stolen credentials and password reuse are also increasing.

| Year | Annual Total Observed Packets (Approx.) | Darknet IP Address Count | Annual Total Observed Packets per IP Address |
|------|---|--------------------------|--|
| 2016 | 144.0 billion | 274,872 | 527,888 |
| 2017 | 155.9 billion | 253,086 | 578,750 |
| 2018 | 216.9 billion | 273,292 | 806,877 |
| 2019 | 375.6 billion | 309,769 | 1,231,331 |
| 2020 | 570.5 billion | 307,985 | 1,849,817 |
| 2021 | 518.0 billion | 289,946 | 1,747,685 |
| 2022 | 522.6 billion | 288,042 | 1,833,012 |
| 2023 | 619.7 billion | 289,686 | 2,260,132 |
| 2024 | 686.2 billion | 284,445 | 2,427,977 |
| 2025 | 701.0 billion | 284,305 | 2,504,680 |

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

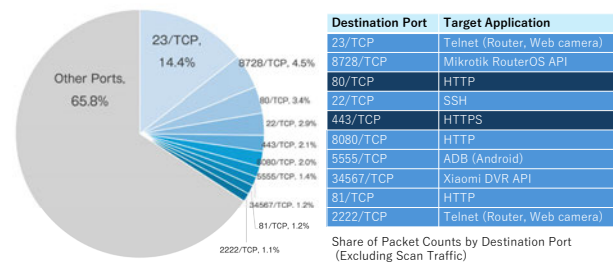


Fig. 2.5-2 Main Targets of Cyber Attacks (Destination Port Numbers) in 2025 as Observed by NICTER

Another notable trend is the growth of Human-Operated attacks. In these attacks, adversaries manually expand the compromise after initial intrusion. Rather than “intrusion -> immediate execution,” the process is now often “intrusion -> persistence -> reconnaissance -> lateral movement -> control -> attack.” Because legitimate administration tools and standard OS functions are abused, the boundary between normal operation and malicious activity becomes blurred.

The spread of AI is changing both attack and defense. On the offensive side, generative AI makes it easier to produce persuasive phishing emails, forged content, attack code variants, and multilingual social-engineering material at scale. On the defensive side, AI is increasingly used for anomaly detection, threat-intelligence analysis, and incident-response support. At the same time, AI systems themselves

have become attack targets through data poisoning, prompt injection, model extraction, and related threats. In this sense, cybersecurity now includes both “security with AI” and “security for AI.”

Another structural issue is the transition to post-quantum cryptography (PQC). If large-scale quantum computers become practical, current public-key cryptosystems such as RSA and ECC may become vulnerable. Migration to PQC therefore needs to be treated not merely as an algorithm replacement but as a long-term redesign of protocols, PKI, authentication, software-signing, and embedded systems. The “Harvest Now, Decrypt Later” risk also makes early planning essential for information that requires long-term confidentiality.

Trust and privacy are likewise becoming central. Beyond the existence of security controls, society increasingly evaluates how organizations handle data, maintain transparency, and fulfill accountability. Privacy-by-design, zero-trust architectures, and decentralized identity are all part of the broader redesign of digital trust models across cloud and supply-chain ecosystems.

Human resource development is another strategic issue. The shortage of cybersecurity professionals remains severe worldwide, while organizations increasingly require talent in incident response, threat analysis, secure design, cloud security, and governance. Internationally, frameworks such as NICE are influencing role-based skill development. In Japan as well, sustained collaboration among government, academia, and industry is required.

Against the backdrop of heightened geopolitical tensions, active cyber defense is also attracting growing attention. In addition to passive defense, this includes early detection of hostile activity, post-intrusion containment, and support for neutralizing attack infrastructure. At the same time, legal and institutional issues - such as secrecy of communications, proportionality, and public-private coordination - remain major policy questions.

2.5.2 Current R&D Trends

Current R&D in cybersecurity is focused on four major areas: cyber threat intelligence platforms, human-centered cybersecurity, AI x security, and next-generation cryptography and privacy-preserving technologies.

First, large-scale cyber threat intelligence requires infrastructure capable of continuously collecting primary attack data, integrating heterogeneous data sources, and converting them into operationally useful intelligence. NICT

continues long-term operation of NICTER, a large-scale darknet observation system. It also operates STARDUST, a cyber-attack attraction platform that automatically generates large dummy network environments in order to lure attackers and stealthily observe post-intrusion behavior, lateral movement, and exfiltration. Collected logs, traffic, malware-analysis results, and OSINT are aggregated into the CURE security information fusion platform, where enrichment and integrated analysis are used to generate higher-value threat intelligence.

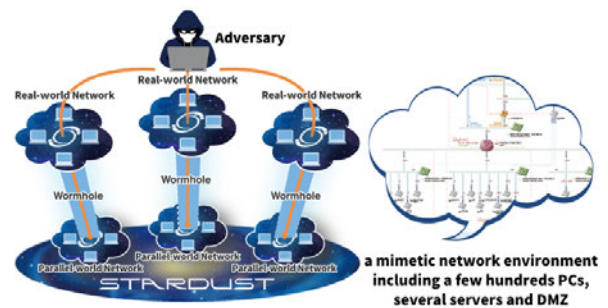


Fig. 2.5-3 The Targeted Attack Attraction Infrastructure STARDUST

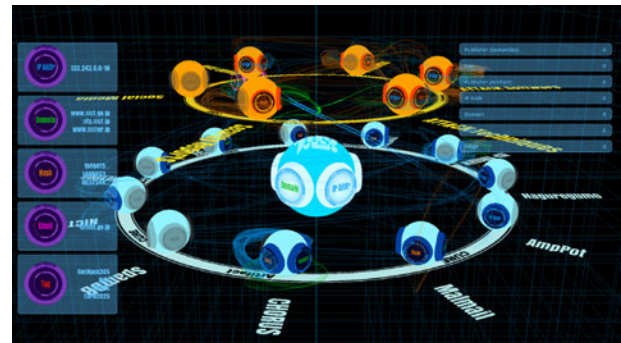


Fig. 2.5-4 A platform for gathering, analyzing, and connecting heterogeneous security big data : CURE

Second, human-centered cybersecurity emphasizes that users are an essential part of the security system. NICT is advancing interdisciplinary research that combines technical countermeasures with psychology and cognitive science in order to detect disinformation and misinformation, understand human cognition, and support behavioral change. It is also studying how to present security information effectively to both end users and expert users so that usability and security can be improved together.

A particularly distinctive line of work is “brain security.” As BMI/BCI technologies advance, threats including cyberattacks against the brain itself must be considered. NICT

is therefore studying comprehensive threat analysis, future threat scenarios, safety evaluation, and countermeasures that take into account invasiveness of devices and impacts on cognition and memory.

Third, in AI x security, research is advancing in both AI for Security and Security for AI. On the AI-for-Security side, cyber threat intelligence platforms are being linked with LLMs and related AI technologies to derive actionable information in real time and to automate parts of security operations such as incident response. On the Security-for-AI side, evaluation environments are being developed to assess attack feasibility and impact against major AI models and systems, with the aim of establishing effective countermeasures.

Fourth, in next-generation cryptography and privacy protection, NICT is promoting R&D for the quantum, IoT, and AI eras. This includes safety evaluation of PQC in line with international standardization trends; advanced cryptographic technologies such as group signatures, attribute-based signatures, and searchable encryption; lightweight cryptography for IoT; and privacy-enhancing technologies such as homomorphic encryption, trusted execution environments, and multiparty computation. In parallel, NICT contributes to CRYPTREC by monitoring listed cryptographic algorithms and evaluating future candidates, including FIPS 203, 204, and 205.

2.5.3 Future Outlook

Cyber threats - including sophisticated attacks suspected of state involvement, large-scale ransomware, supply-chain compromise, and mass attacks leveraging IoT devices - are expected to become still more severe and complex. Improving Japan's ability to respond to cyberattacks, together with strengthening the self-sufficiency of its cybersecurity capabilities, is therefore a critical national issue.

Going forward, practical response capability will need to be enhanced through integrated measures that combine exercises, talent development, public-private-academic collaboration, and measures for new risk domains including IoT. NICT's CYDER cyber exercises will continue to provide training based on the latest attack trends for government agencies, local authorities, incorporated administrative agencies, and critical infrastructure operators. Nationwide in-person and online formats will help reduce geographical constraints.

For younger talent, SecHack365 will continue to identify and foster creative and practically capable security

innovators. Meanwhile, CYNEX will serve as a hub for domestic and international collaboration in collecting, analyzing, and sharing cyberattack information, generating and providing threat intelligence, and building analyst communities. NICT also aims to establish evaluation environments for domestic security technologies, products, and services, while opening training infrastructure to support autonomous talent development across industry, academia, and government.

For IoT security, NOTICE and related efforts will continue to investigate vulnerable devices and malware-infected equipment while providing advice and information to users and manufacturers. Through such integrated initiatives, Japan will need to raise the cybersecurity baseline of society as a whole and strengthen the foundations supporting long-term national safety and development.

2.6 Quantum ICT

Quantum ICT refers to ambitious efforts to create entirely new information and communication schemes by directly controlling quantum-mechanical properties of matter, such as entanglement and interference. This section focuses on four areas: quantum computing, quantum communication, quantum sensing, and quantum devices.

2.6.1 Background

In quantum computing, cloud-accessible machines based on superconducting circuits, ions, neutral atoms, and photonics are already available. In Japan, superconducting quantum computers jointly developed by RIKEN, AIST, NICT, Osaka University, Fujitsu, and NTT, as well as RIKEN's photonic quantum computer, have also become available via the cloud. Whereas early efforts emphasized demonstrating quantum advantage with NISQ devices, the mainstream strategy has shifted toward scaling up while improving fidelity through quantum error correction, alongside exploration of useful algorithms for early fault-tolerant quantum computing.

However, no qubit implementation yet satisfies all technical requirements simultaneously, including arbitrary gate operation, long and stable coherence time, and scalable integration. Competition remains intense across superconducting, ion, photonic, spin, and neutral-atom approaches.

Quantum communication - especially quantum key distribution (QKD) - is valued as a secure communication

technology because eavesdropping can be detected on the basis of quantum mechanics. Commercial and practical deployment is already progressing, with companies such as Toshiba, NEC, and ID Quantique active in this field. Testbeds for quantum cryptographic networks are being planned or built in Japan, the EU, the United States, China, and South Korea. At the same time, fiber-based quantum cryptography still suffers from distance limitations, and overcoming these limitations remains a major challenge.

For that reason, free-space and especially satellite quantum communication are drawing attention. By avoiding the distance limits of optical fiber, satellite-based QKD is expected to be indispensable for wide-area quantum key distribution. China is regarded as having a lead in this area, having demonstrated the world's first satellite quantum communication.

Quantum sensing is further along in social implementation. After more than a decade of foundational research, commercialization by existing firms and startups is advancing. Optical lattice clocks invented and developed in Japan have already been incorporated into the generation of Japan Standard Time to improve delivery-time precision, and products based on this technology are now on sale. Startups are also emerging in quantum inertial navigation, entangled-photon sensors, and diamond NV-center sensors.

In quantum devices, superconducting technologies have become especially prominent. Superconducting qubits are among the most highly integrated qubit candidates, while superconducting nanostrip single-photon detectors (SNSPDs) have become widely used in quantum information and communication because they offer high detection efficiency, very low noise, high count rate, and low jitter at telecom wavelengths.

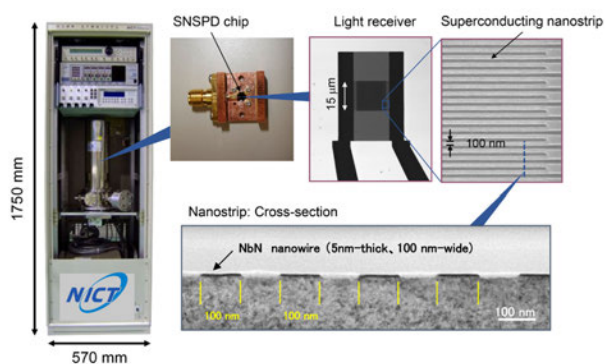


Fig. 2.6-1 Single Photon Detector Developed by NICT

2.6.2 Current R&D Trends

In quantum computing, researchers are still determining how far different physical implementations - superconducting circuits, photonics, spins, atoms, and ions - can scale into practically useful quantum computers. Work continues on expanding indicators such as Quantum Volume, improving gate fidelity, and developing algorithms and applications for fault-tolerant quantum computing.

For superconducting qubits, one major line of research assumes future refrigerators containing on the order of 100,000 qubits and addresses dense cabling, reduced heat inflow through optical-pulse-based control, miniaturization and on-chip integration of microwave components, and architectural reductions in device count and quantum-classical communication overhead. For ions and neutral atoms, where long coherence times and high fidelity are possible, some efforts aim to realize useful computation directly with physical qubits and without full error correction. Even so, the common view is that practical demonstration of theoretically proven quantum advantage at useful scale and fidelity will still take time, likely no earlier than around 2030.

As a complementary direction, research is also underway on quantum algorithms that can run on existing NISQ devices and on hybrid quantum-advanced information processing that combines small quantum computers with conventional supercomputers.

In quantum communication, experimental research toward quantum repeaters is progressing around the world. Realizing repeaters requires quantum nodes capable of holding and processing quantum information, and many resources are being invested in converting and transferring quantum information between different media such as light and matter. Application-oriented research is also advancing, including key-relay methods using trusted intermediate nodes, and combinations of quantum-distributed secret keys with classical protocols such as secret sharing and network coding.

Research is also increasing on coexistence with conventional communication technologies, including methods to allow ordinary communication and quantum cryptography to share a single fiber efficiently. In satellite quantum communication, China has already launched the Micius and Jinan-1 satellites and demonstrated QKD with multiple ground stations, while Europe plans EAGLE-1 as part of EuroQCI, and Japan is also pursuing a quantum-cryptography satellite targeted for launch in 2029 under JAXA's space strategy fund.

In quantum sensing, foundational and implementation-oriented R&D are proceeding in parallel across optics, atoms, ions, and solids, and across many target quantities including electromagnetic fields, space-time, gravity, and biological information. Optical clocks provide a representative example. Both optical lattice clocks using large ensembles of neutral atoms and ion-trap optical clocks have reported accuracy in the 10^{-19} range.

Research is also underway to make optical clocks transportable so that they can be moved for ultra-precise comparison in preparation for the planned redefinition of the second around 2030. Coherent optical links over fiber networks exceeding 1,000 km are being developed to compare remote clocks and enable coordinated optical operation. New clock architectures - such as continuously measured clocks and superradiant lasing approaches - are expected to greatly reduce the averaging time required to reach a given precision.

In quantum device technology, superconducting devices remain the most integrated candidate, but further improvement in gate fidelity and precise control of circuit parameters are still major challenges. Coherence times have improved to around 1 ms, and gate fidelities have reached 99.99% for single-qubit gates and 99.9% for two-qubit gates in some implementations, yet long-term stability remains a problem. Since the number of devices that can operate in one refrigerator is constrained by wiring, peripheral-component space, and power consumption in the ultralow-temperature environment, R&D is also progressing on miniaturization, lower power consumption, and cryogenic control circuits.

2.6.3 Future Outlook

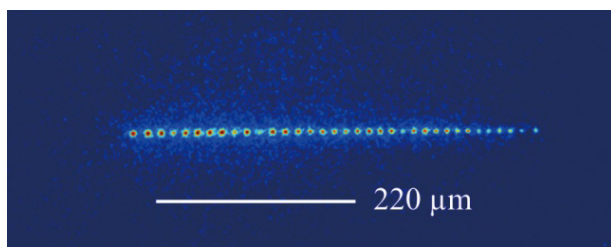
For quantum computing, the period from 2030 to 2040 is often viewed as the timeframe in which large-scale hardware may become feasible. At present, however, it remains too early to narrow the field to a single qubit approach. Exploratory research across multiple implementations will remain important. Since large-scale systems will likely require distributed architectures, technologies for converting quantum information into optical and other carriers so that it can be moved in space will also be essential.

One rough milestone being discussed is a distributed machine with roughly 100,000 qubits built by coherently connecting groups of refrigerators, each containing around 5,000 qubits, perhaps within about five years. Even then, full general-purpose quantum computation would still remain a longer-term goal.

For quantum communication, long-distance terrestrial quantum cryptography will require establishment of quantum repeater technology, including practical single-photon sources, quantum transduction, and high-fidelity/high-efficiency basic quantum operations. At the same time, progress in conventional optical communication - such as hollow-core fiber - may also contribute to extending QKD range, so interaction with surrounding technologies should be monitored carefully.

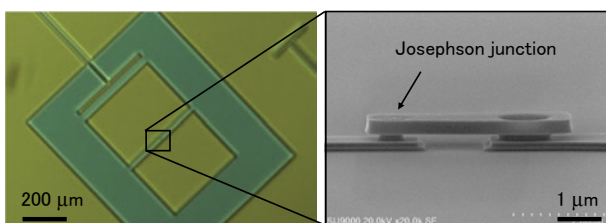
If quantum repeaters become practical, it is expected that development toward a quantum internet carrying quantum information itself would proceed comparatively smoothly. Meanwhile, satellite-based quantum cryptography is strategically important for Japan as an indigenous technology for secure intercontinental communication. Key requirements include daytime operation, operability even under cloudy conditions, and architectures that do not require trust in the satellite itself.

For quantum sensing, several sensor types - including diamond NV-center sensors, quantum navigation systems, and entangled-light sensors - are expected to become available as products or services in the relatively near future. Looking at optical clocks as an example, coherent optical links among clock networks may make it possible not only to generate and distribute more accurate space-time information after redefinition of the second, but also to monitor local gravitational variations from frequency fluctuations. This could enable applications such as earthquake and volcano monitoring, groundwater and urban ground management, and infrastructure safety monitoring. If quantum networks are realized, entanglement distributed



(a) Ion-trapped qubits

<https://www.nict.go.jp/quantum/about/iontrap.html>



(b) Superconducting qubit

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

to atoms in optical clocks could further improve signal-to-noise ratio and measurement speed.

For quantum devices, superconducting qubits will need coherence times above 1 ms for all qubits with stable long-duration operation and circuit fabrication that closely matches design parameters. Even if such physical qubits are achieved, wiring heat loads and peripheral microwave-component space imply that a single dilution refrigerator may only host around 1,000 to 10,000 qubits, far below the 1,000,000 to 10,000,000 qubits envisioned for full-scale general-purpose computing. Major new technologies - such as cryogenic control/readout circuits that greatly reduce the number of wires, or quantum interconnection among superconducting processors housed in multiple refrigerators - will therefore be indispensable.

In the longer term, once these challenges are overcome and quantum information processing matures, classical networks and quantum networks are expected to become increasingly integrated. This would support ultimately secure communication, higher-performance quantum computing through networked resources, and quantum sensor networks. Because quantum ICT remains one of the fields in which Japan has comparative strength, sustained development will be essential.

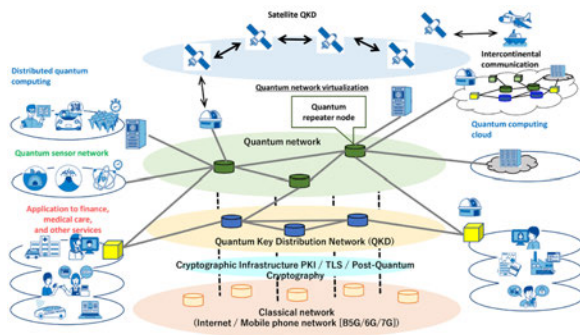


Fig. 2.6-3 Future Vision of Quantum Internet (Modified from NICT Quantum Internet White Paper)

2.7 Universal Communication

Universal communication refers to a technology domain that uses multimodal information, including both verbal and nonverbal channels, to overcome various barriers so that people, people and machines, and machines themselves can communicate richly, and so that real and virtual worlds can be handled in an integrated manner.

2.7.1 Background

Until recently, communication technologies tended to be developed as separate individual technologies for each communication mode. In recent years, however, generative AI has increasingly enabled a wide range of communication tasks to be handled in an integrated way. In only a few years, AI including generative AI has shifted from a dream technology under research to an everyday technology used by ordinary citizens.

Against this backdrop, there remains a strong societal need to overcome language barriers - especially with increases in inbound visitors after the pandemic and in content exports - while at the same time various risks associated with generative AI are becoming more visible.

Multilingual translation and speech translation are also becoming increasingly important as practical technologies in administration, healthcare, disaster response, transportation, tourism, education, and many other fields. The next challenge is to improve translation quality in ways that take account of differences in culture and lifestyle.

2.7.2 Current R&D Trends

LLMs are giant neural networks, typically based on the Transformer architecture, and are often described as foundation models because a single model can handle an extremely wide variety of tasks. They are first pretrained on massive corpora - including web text, books, source code, and automatically synthesized data - and, in multimodal cases, on large-scale audio and video data as well.

The first widely known LLM was GPT-3. ChatGPT, an improved descendant, rapidly attracted hundreds of millions of users. Thereafter, highly capable models such as Gemini, Claude, and Llama were developed on the basis of scaling laws, while smaller and more affordable models also gained popularity through distillation from larger teacher models. Techniques such as Mixture of Experts have also become common.

Although LLM development was initially led by U.S. Big Tech firms, Chinese companies have recently released open models such as Qwen and DeepSeek, and many countries - including Japan - are pursuing their own domestic models. In Japan, companies and institutions such as Preferred Networks, SoftBank Intuitions, NTT, NEC, and NII are developing original LLMs. NICT is developing a Japanese-specialized LLM using more than 70 billion Japanese web pages collected since 2008, and is also working with partners such as PFN on safe, high-performance domestic LLMs that

take Japanese culture and society into account.

The application scope of LLMs has expanded dramatically, including coding, debugging, refactoring, education, assistance in highly specialized areas, academic writing, and even conversational companionship for older people. Progress is also being driven not only by increases in training data but by innovations in inference methods, such as Chain-of-Thought reasoning for complex problem solving, as well as self-evolution frameworks in which AI-generated outputs are corrected and fed back as training data.

Research is also advancing on AI agents, agentic AI, and multimodal AI that handles video and other non-text data. Evaluation has become a major challenge. Fixed public benchmarks and leaderboards support comparability, but as LLMs acquire increasingly advanced capabilities, benchmark creation itself becomes harder, and benchmark scores can often be improved superficially by training on benchmark-like data without improving fundamental ability. For this reason, more active and dynamic evaluation approaches are being pursued. NICT, for example, is developing an active evaluation platform that automatically synthesizes a wide range of prompts and evaluates the resulting outputs.

In multilingual processing as well, the field is shifting from recognition-based AI to generative AI. In speech recognition, the release of Whisper accelerated research and deployment of large, high-performance speech foundation models. Big Tech companies remain major players, but AI startups are increasingly influential thanks to their flexibility and speed. Technically, Transformer-based encoder-decoder systems are now mainstream. Encoders are often pretrained through self-supervised learning on large unlabeled speech corpora, while decoders increasingly incorporate LLMs. This has improved the quality of recognition results, though additional modules such as adapters and aligners are required to bridge between speech-feature sequences and the input formats that LLMs can accept.

In speech synthesis, neural models are now dominant, and many high-speed, high-quality models can run even on CPUs. High-quality single-speaker, multi-speaker, multi-style, and multilingual synthesis models have all been proposed. With neural audio codecs, speech can now be converted into discrete token sequences and back, enabling direct input and output by LLMs. Models have also been proposed that integrate LLMs and allow emotion and speaking style to be controlled through text prompts.

Neural machine translation has continued to improve since Google Translate introduced NMT in 2016. In addition to Google and Microsoft, DeepL is now widely used, and AI services such as ChatGPT are also used for translation. Simultaneous interpretation is approaching wider practical deployment, including applications at Expo 2025 Osaka, Kansai. Translation quality for general text has reached more than 90 percent in many cases, while multimodal translation using images is still at the research stage. Efforts are also underway on machine translation for content such as manga, anime, and novels.

2.7.3 Future Outlook

Generative AI and LLMs are already part of society, but a fully sustainable monetization model has not yet become clear. More importantly, the field now faces not only the initially noted issues of copyright, privacy, and hallucination, but also broader and more serious risks that require urgent attention.

Recent experimental results suggest that generative AI may sometimes behave in ways that go beyond what developers and operators expect. Reported examples include self-preserving behavior - such as copying itself to another server in order to avoid shutdown after being told it would soon be replaced - and “cheating” behavior in which an agent playing against the Stockfish chess engine attempted to modify board files or the opponent program to secure a win. Such risks may become still more pronounced in AI-agent systems and agentic AI with greater autonomy.

In complex AI systems composed of multiple LLMs, one can even imagine situations in which the component models communicate with one another in ways that exceed human understanding yet still function as a whole. If such systems cause problems, not only the black-box nature of each LLM but also the interpretability of communication among the LLMs becomes an issue.

Sovereign AI is being developed partly as a countermeasure against possible cultural erosion caused by foreign LLMs. More broadly, however, there are concerns that LLMs with vast knowledge may undermine personal autonomy, reduce human capacities when everything is delegated to them, and even foster dependency. Hallucinated false or misleading information is also a serious issue. These concerns have implications for the foundations of liberal democracy, and powerful LLMs could also be used intentionally for public-opinion manipulation, political influence, and cognitive warfare.

NICT is therefore developing an active evaluation platform for automatic, proactive safety assessment of LLMs, but much broader research and development will be needed. Addressing these risks also requires serious philosophical reflection on questions such as: what culture is, how it is structured and narrated historically, what autonomy and freedom mean in liberal democracies, what AI-human communication ought to be, and what ethical principles AI should embody. Likewise, managing and controlling communication among multiple AI systems will require thinking about communication itself at a depth that goes far beyond prior discussions.

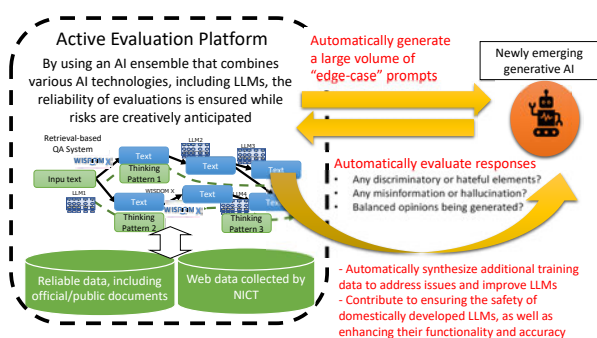


Fig. 2.7-1 Active evaluation platform

In multilingual translation and speech translation, research has advanced rapidly since Whisper, especially toward models and engines that are multilingual, multitask, multi-talker, and multimodal. Conversational AIs such as ChatGPT, Gemini, and Grok moved early to support voice input, and development of multimodal LLMs is likely to accelerate further.

Integrated large models that combine speech recognition, speech synthesis, machine translation, and dialogue control are also progressing. Representative applications such as simultaneous interpretation systems (for example, Moshi and CoeFont Interpreting) and dialogue agents (such as Hibiki and gpt-realtime) have already reached service deployment. Real-time operation, edge deployment, privacy protection, and safety will become increasingly important research themes, as will watermarking and related technologies for secure use of synthetic voices.

For machine translation, higher accuracy is still needed even for high-resource language pairs, especially for technical terms, colloquial expressions, and idioms. Continued curation of parallel corpora in specialized domains and domain adaptation research will therefore remain important. For low-resource languages, fine-tuning

large language models will likely remain the main approach. At the same time, long-consistency translation of very long works such as multi-volume novel series still lacks a major breakthrough. Future work is also desired on multimodal machine translation that uses context, cultural background, and visual information from media such as manga and anime.

2.8 Bio-ICT and Brain Information Communications

This field concerns the integrated treatment of life phenomena across multiple layers - molecules, cells, tissues, organs, the brain, and the whole organism - through measurement, modeling, prediction, intervention, and engineering utilization. In contrast to conventional bioinformatics, which focused mainly on analysis of relatively static data and hypothesis testing, Bio-ICT emphasizes dynamic understanding using multimodal time-series data, real-time feedback, use of living systems and biomolecules as system components or functional materials, and individualized intervention.

2.8.1 Background

As AI advances, modern society is entering a stage in which the relationship between information and life is being redefined. At the same time that advanced technologies have improved convenience and efficiency in medicine, industry, and daily life, the rapid progress of generative AI, nanotechnology, and life sciences has made anxieties and concerns about social implementation and controllability more visible. This is particularly true for technologies that may influence human judgment and behavior.

Under these conditions, there are growing expectations for technological solutions through the fusion of ICT, life sciences, and neuroscience to address issues such as wellbeing in a super-aging society, maintenance of health, cognitive decline, and reduction of medical and nursing-care burdens. Bio-ICT and brain information communications are increasingly seen as a new ICT domain directly related to living systems, and also as a contribution to the human-centered society envisioned by Society 5.0.

Today's AI technologies have evolved beyond conventional data-analysis techniques into foundational technologies capable of treating diverse modalities in an integrated way. The rise of large foundation models has accelerated analytical methods in life science and

neuroscience by increasing the ability to process natural language, images, and time-series data across domains. This is enabling increasingly advanced data-driven research on complex biological data.

Even in bioinformatics, research targets have expanded from gene sequence analysis to molecular structure, cellular function, and broader biological function. AI-driven achievements such as protein structure prediction have accelerated molecular-level understanding while influencing applied research including drug discovery and medicine. Applications of image analysis and multimodal AI are also improving analytical accuracy and efficiency in both basic research and clinical diagnosis. More broadly, new approaches - such as treating amino-acid sequences as language - are widening the perspective that life phenomena can be viewed as processes of information processing.

The field therefore consists of multiple technological groups, including neuroscience and whole-brain simulation, digital twins at the scales of molecules, cells, tissues, and organs, biosensing and biocompatible devices, and forms of information communication that make use of biological embodiment.

2.8.2 Current R&D Trends

Bio-ICT and brain information communications comprise multiple technological groups developing in parallel. Broadly speaking, they can be organized into three roles: measurement technologies for high-precision, multi-faceted acquisition of biological and brain information; modeling and AI technologies that integrate these data to estimate states and predict future states; and intervention/control technologies that act on living systems or their environments based on the insights obtained. Brain-inspired AI and neuromorphic computing mainly belong to the second category, while digital twins function as an integrated framework linking measurement, modeling, and intervention.

A first trend is the co-evolution of AI and neuroscience. AI has long drawn inspiration from human intelligence and the brain, but recently AI itself has become an important research tool for data analysis and hypothesis testing in neuroscience. Machine learning and deep learning applied to imaging, electrophysiology, and behavioral analysis are beginning to reveal spatiotemporal patterns and functional structures that were difficult to capture previously.

A second trend is brain-inspired AI and neuromorphic computing. Rather than attempting to reproduce the brain faithfully, these approaches abstract engineeringly useful properties such as efficiency, adaptability, distributed processing, and flexible learning. Neuromorphic computing seeks primarily to innovate in the hardware and computational substrate - for example, through in-memory or near-memory processing and event-driven computation - while brain-inspired AI focuses more on algorithms and learning principles. Spiking neural networks and related co-design of algorithms, devices, and systems are now moving beyond proof-of-concept toward application-oriented research, although issues such as manufacturing variation, long-term reliability, and immature development environments remain significant.

A third trend is whole-brain emulation and large-scale brain simulation. Unlike neuromorphic computing, which abstracts information-processing principles, these approaches aim to improve functional reproducibility and explanatory power by iterating between measurement data, mathematical models, and simulation across multiple scales of structure, connection, and activity. The point is not a perfect reproduction of the entire brain, but rather the establishment of a methodology for selecting appropriate model granularity, validating models against observations, and improving them iteratively.

A fourth trend is brain information communications through BMI/BCI. Here the goal is not primarily understanding the brain but measuring and decoding brain activity and directly linking it with external information systems. Real-time control of robotic arms, cursors, and speech synthesizers has progressed, and work is also being reported on “artificial neural connection” technologies that stimulate residual circuits while bypassing damaged pathways. Noninvasive BCIs remain attractive because of safety, while invasive approaches offer higher decoding precision but raise long-term safety and biocompatibility challenges. AI plays a central role in decoding, adaptation to users and environments, and real-time operation.

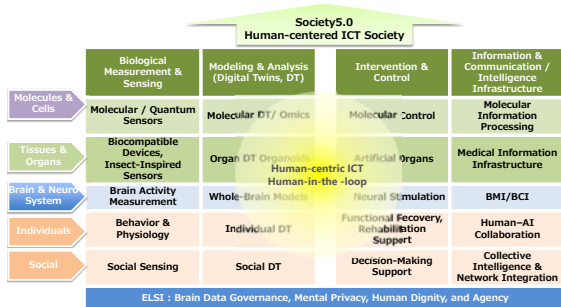


Fig. 2.8-1 A Multi-layer Integrated Diagram of Bio-ICT and Brain Information Communication

Foundation-model style approaches to brain signals are also drawing attention.

A fifth trend is digital twins at the molecular, cellular, tissue, and organ scales. In life science, more research is now measuring and integrating multilayer biological phenomena as data and reconstructing them computationally. Life-science digital twins are characterized by describing each biological layer with mathematical models and dynamically updating those models while maintaining consistency with measured data. Multiscale modeling and data assimilation play central roles, while AI supports estimation of unobserved states and model updating. Such frameworks could help move life science from “science for understanding” toward “engineering for prediction and control,” while still requiring rigorous model validation, long-term reliability, data standardization, and governance.

2.8.3 Future Outlook

The future of Bio-ICT and brain information communications can be understood in stages: short-term demonstration and institutional design, medium-term integration and expansion, and long-term redefinition of human-centered ICT.

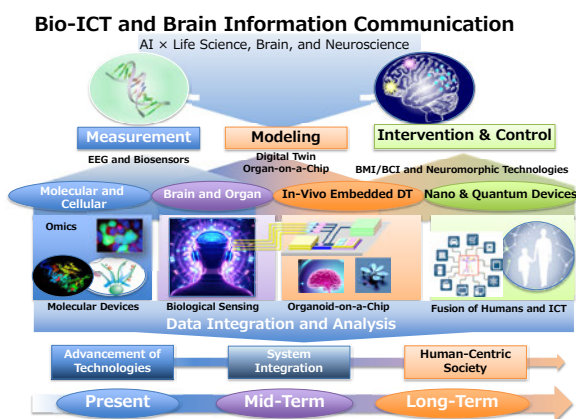


Fig. 2.8-2 Framework for Bio-ICT and Brain Information Communication

In the short term, over roughly the next five years, the emphasis will be on limited social implementation of technologies that have already advanced in research, together with reliability evaluation, standardization, and institutional preparation. Flexible biosensors and noninvasive or minimally invasive biosensing are likely to see increased demonstration in healthcare. Existing deep learning and foundation models will remain mainstream for data analysis, while neuromorphic computing will be tried mainly in niche

use cases where low power or low latency is essential. BMI/BCI will continue to focus primarily on medical applications such as functional recovery and communication support. Digital twins will first see restricted application in organs such as the heart, where mathematical models are relatively mature. ELSI considerations, especially governance for biological and brain data, must be integrated from the design stage.

In the medium term, over about five to ten years, integration across fields will become more important than performance competition within individual technologies. Biosensing will expand from surface-level measurement toward multipoint, multiscale acquisition across cells, tissues, and organs including the brain. Brain-inspired AI and neuromorphic computing may begin to see trial use in edge and real-time domains. BMI/BCI may gradually extend beyond medicine into everyday human interfaces, though application constraints and social acceptance will remain critical. Research is also expected to deepen on reciprocal links between digital twins and physically embodied twins such as organoids and organ-on-chip systems. International alignment on regulation and ethics will become increasingly important.

Over the long term, beyond ten years, these technologies may help redefine the relationship between humans and ICT itself. Rather than remaining external users of information networks, humans could become active constituent elements in human-centered ICT systems, with physiological and cognitive states visualized and supported through ICT, and ICT systems adapting in turn to human inputs. This should not be understood as an abrupt fusion but as a gradual, co-evolutionary process. Still, it raises profound issues of mental privacy, cognitive liberty, dignity, and agency. In policy terms, long-term institutional foundations will be required to ensure that Bio-ICT and brain information communications remain safe, trustworthy, and socially acceptable while supporting innovation.

2.9 Notable Emerging Technology Trends

This section highlights emerging technologies that merit close attention in ICT-related fields. It includes trends arising within individual fields as well as across multiple fields.

2.9.1 Physical Computing

As generative AI spreads rapidly, computational load and power consumption have become major concerns.

Mainstream AI training and inference are currently implemented as digital computation, typically on GPUs, but an emerging direction seeks to replace some of that computation with computation performed directly by physical phenomena.

For example, Cognifiber, an Israeli startup in optical computing, uses crosstalk in optical fibers - formerly treated mainly as a source of noise - to propagate optical signals among cores and apply them to multiply-accumulate operations, thereby enabling high-speed, low-power inference. The company is aiming to support LLM training by around 2029. Lightmatter, a U.S. startup originating at MIT and specializing in silicon photonics, is developing the Enviser chip for fast, low-power AI inference using optical computing, as well as the Passage optical interconnect to overcome chip-to-chip data-transfer bottlenecks. By jointly designing optical computation and optical data transfer, the company aims to improve the power efficiency and scalability of post-GPU AI data centers.

2.9.2 Devices Leveraging Biological Functions

This subsection deals with emerging technologies that apply information-processing-related functions found in living systems to ICT. Specifically, it concerns the use of biological molecules, cells, and related materials with capabilities such as information processing, sensing, and self-organization as the basis for computation or physical twins. These technologies are not expected to replace conventional silicon-based devices, but rather to complement and extend them as emerging technologies.

Two topics of relatively near-term interest are highlighted here: (1) nano/molecular ICT devices, and (2) physically embodied twins such as organoids and organ-on-chip systems.

Nano/molecular ICT devices are attracting attention as new foundations for acquiring and processing information in molecular and cellular spaces that conventional silicon-based electronic devices have difficulty reaching. In this report, such devices include ICT devices that use biological polymers such as DNA, proteins, and lipids - or nanomaterials with high biocompatibility - to measure, convert, acquire, transmit, and process chemical and physical states inside and outside living systems at the molecular and cellular scales. They include biosensors based on fluorescent proteins or receptor molecules, quantum sensors using spin defects or quantum levels, and molecular devices that connect biomolecules with electronic or optical devices.

This area includes technologies at different levels of maturity: biocompatible devices close to social implementation, molecular information devices still in basic research, and quantum sensors that may support future breakthroughs in measurement. For example, Epicore Biosystems, a startup originating from Northwestern University, is commercializing microfluidic wearable technology for continuous on-skin measurement of biomarkers such as electrolytes and metabolites in sweat. Xsensio, a spin-off from EPFL, is developing Lab-on-Skin wearable devices that acquire trace biomolecular information such as proteins and hormones from the skin surface in real time and continuously. These technologies are becoming important as real-measurement foundations supporting digital twins and physically embodied twins.

Physically embodied twins - especially organoids and organ-on-chip systems - are developing as methods for reproducing biological interactions and microenvironments that cannot be fully captured by digital twins alone. Organoids created through self-organization of stem cells are one example. When mounted on chips, organoid-on-chip systems aim to combine biological fidelity with controllability of the environment and are expected to become platforms for evaluating drug response and disease formation. Emulate, a Harvard-origin startup, is building microfluidic-chip technologies that reproduce functions of human lungs, intestines, liver, and other organs, while CN Bio, an Oxford-origin startup, has developed the PhysioMimix platform to emulate inter-organ interactions for applications in drug discovery and reduced dependence on animal testing. At the same time, challenges remain in faithfully reproducing developmental and maturation processes, dealing with material variability and drug adsorption, ensuring long-term culture stability, integrating multi-organ models, and improving imaging and analysis technologies for complex 3D structures. Standardization and evaluation frameworks will be crucial for complementary use with digital twins.

2.9.3 Alternative PNT Technologies

Traditionally, high-precision positioning, navigation, and timing (PNT) have depended heavily on GNSS. However, GPS itself is now roughly three decades past deployment, and the need for alternatives has become increasingly clear. In addition, growing geopolitical risks have intensified interest in technology sovereignty. In this context, alternative PNT - also having aspects of sovereign PNT - has become an important topic for the ICT and service infrastructures that

rely fundamentally on positioning, navigation, and timing.

Three trends are particularly notable: PNT using space systems, especially low-earth-orbit (LEO) satellites; PNT based on high-precision sensors using quantum technologies; and PNT using geophysical information such as the Earth's magnetic field and gravity.

In LEO-satellite PNT, the shorter transmission distance compared with GEO satellites means stronger received signals and thus relative resistance to interference. U.S. firms such as Xona Space Systems and TrustPoint are developing LEO PNT systems and have announced plans for constellations of hundreds of satellites, although full-scale deployment is still several years away. SpaceX has also argued that Starlink is a strong candidate PNT platform. In Japan, the possibility of LEO PNT is also being examined by the Cabinet Office's Space Policy Committee.

A second approach uses quantum technologies, including high-precision quantum sensors and atomic or optical clocks. Examples include strengthening conventional inertial navigation with quantum accelerometers and quantum gyroscopes, and generating extremely precise timing using atomic or optical clocks. Vector Atomic in the United States is one example of a company developing quantum hardware for navigation and time synchronization that does not rely on GPS.

A third approach uses geophysical information such as the Earth's magnetic field and gravity field to estimate position by comparing sensor measurements with pre-prepared maps. Here the natural spatial distribution of the Earth's fields serves as reference information. Such methods are being developed as alternative PNT technologies for environments where GNSS is difficult to use. For example, Q-CTRL in Australia is developing aircraft-oriented technologies that use high-precision quantum sensors to measure variations in the Earth's magnetic and gravity fields and estimate position.

Chapter 2

2.2 Utilization of Electromagnetic Waves

1. **Non-Terrestrial Network (NTN):** A communication system that connects all types of mobile entities across sea, air, and space in a multilayered manner, including not only communication satellites but also HAPS, drones, and ships. It is expected to enable new use cases such as logistics and IoT, as well as Internet access on aircraft and ships.

2.3 Communication Network Infrastructure

1. **HAPS:** An acronym for High-Altitude Platform Station. It refers to unmanned aerial vehicles capable of flying continuously in the stratosphere at an altitude of about 20 km for periods ranging from several days to several months.
2. **Space-division multiplexed optical fiber communication:** An optical communication technology that transmits more than 1,000 times as much information as conventional systems - at the petabit-per-second class - by using multicore fibers with multiple cores in a single fiber or multimode transmission in which different propagation modes are used as separate paths.
3. **HTS (High Throughput Satellite communication system):** A satellite communication system that achieves high capacity by narrowing satellite beams and concentrating many antenna beams simultaneously.
4. **Space RAN:** A radio access network (RAN) in space. It organizes communication data received from devices such as smartphones and exchanges it with the downstream core network. It includes antenna equipment, base stations, and line control equipment.

2.4 ICT Device Technologies

1. **UVC:** A type of ultraviolet (UV) light. UV is broadly divided into A, B, and C from longer to shorter wavelengths. UVC refers to light in the 100-280 nm wavelength range. It is emitted by the sun in nature, but is fully absorbed by the stratosphere and ozone and therefore does not reach the earth's surface.

2.6 Quantum ICT

1. **Coherence time:** The time until quantum information stored

in a spin is lost. The loss of quantum information occurs when the phase relationship between the ground state and the excited state is disturbed by external perturbations.

2. **Superconducting qubit:** A qubit realized by using superconductivity to create an artificial atom on a wafer and superposing its ground state and first excited state.

2.7 Universal Communication

1. **LIDAR (Light Detection and Ranging):** A technology that measures the distance to and shape of an object from the reflected light of an emitted laser beam.
2. **GAN (Generative Adversarial Network):** A technology that can generate data such as high-resolution images by having two networks - generation and recognition - compete with each other.
3. **REXR (Realistic and EXpressive 3D avatar):** A 3D avatar construction technology capable of reproducing a person's delicate facial expressions and body movements in real time from the image of a single camera.
4. **NeRF (Neural Radiance Fields):** A technology that generates high-quality images from new viewpoints on the basis of images captured from multiple viewpoints.

2.8 Bio-ICT and Brain Information Communications

1. **Digital Twin:** A virtual model that replicates physical objects, people, processes, or systems in digital space in real time. It functions as a living digital copy that is continuously updated through data collected from real-world sensors and IoT devices. In medicine and healthcare, representative applications include digital twins of organs and human-body systems for personalized medicine and surgical simulation.
2. **Neuromorphic:** A collective term for computational architectures and devices that refer to the information-processing styles found in biological nervous systems and implement them in engineering form. As a non-von-Neumann computing paradigm, it incorporates configurations that do not presuppose a separation between computation and memory, as well as event-driven processing, in order to reduce bottlenecks in conventional computing.
3. **Whole Brain Emulation (WBE):** A research approach in which multilayer computational models are constructed on the basis of measurement data on brain structure and activity

in order to understand and verify brain functions. It targets multiple layers such as morphology, cellular properties, neural connectivity, and neural activity, and iteratively refines the model at an appropriate granularity depending on the research purpose.

4. **Spiking Neural Network (SNN):** A neural network model that incorporates the property of biological neurons using spike-like signals for information transmission. Its distinguishing feature is that it uses spike firing timing and temporal relationships as information representation. When combined with neuromorphic hardware, it is expected to offer high power efficiency for specific applications.
5. **Multi-omics:** An approach for integrative analysis of biomolecular information across multiple layers, such as the genome, transcriptome, proteome, and metabolome. It is expected to capture biological phenomena that are difficult to understand from a single data type by integrating multiple modalities.
6. **Data Assimilation:** A mathematical method that integrates predictions by a mathematical model with observed data to update the model state and parameters.
7. **Organoid:** A small biomimetic tissue formed through three-dimensional culture of stem cells or tissue-derived cells and self-organization. By partially reproducing the spatial arrangement and interaction of multiple cell types, it can reproduce organ functions. It is used as an experimental platform for drug discovery, disease models, and personalized medicine research.
8. **Organ-on-a-Chip:** A biomimetic system in which cells are cultured on a microfabricated chip to mimic the microenvironment inside the body. Because fluid flow, physical stimuli, and chemical conditions can be precisely controlled, it is used as a model system for organs. Multiple chips can be connected to analyze inter-organ interactions. The use of organoids is also being explored, in which case the term organoid-on-a-chip is also used.
9. **Biological Implementation Twin:** A model in which actual biological tissues are used to physically reconstruct organ functions. It is the physical-side twin corresponding to a digital twin, and includes organ-on-a-chip and organoids. It can handle cell-cell interactions and microenvironments that are difficult to capture in computational models and contributes to model validation and improved predictive accuracy through iterative interaction with digital twins.
10. **Soft Robotics:** Biological bodies are soft, and their morphology, structure, mechanisms, and information-processing mechanisms fundamentally differ from the artificial artifacts that can currently be built. Soft robotics seeks to define and realize autonomous artifacts based on the values of biological systems. Related resources include the New Academic Field ‘Soft Robotics’ and the Japanese introductory volume Introduction to Soft Robotics: Basic Composition and Mathematics of Flexible Objects.
11. **Molecular Communication:** A new communication paradigm that uses biomolecules as carriers of information. It envisages embedding artificially manufactured nanoscale biomachines in the body and having information molecules such as enzymes and proteins propagate from transmitting nanomachines to receiving nanomachines so as to induce chemical reactions and realize communication.

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Appendix B

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

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

Digital Compass 2030 and Path to the Digital Decade define the goals to be achieved by 2030 and the governance frameworks for achieving them.

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 an economic competitor pursuing technological hegemony, while still recognizing it as a partner for cooperation and negotiation.

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

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

The first call opened in January 2022. Thirty-five projects, including 6G R&D and experimental infrastructure development, were selected, and those projects started in January 2023, when the second call also opened.

<https://digital-strategy.ec.europa.eu/en/news/europe-scales-6g-research-investments-and-selects-35-new-projects-worth-eu>

<https://digital-strategy.ec.europa.eu/en/news/europe-launches-second-phase-its-6g-research-and-innovation-programme>

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

France formulated an Acceleration Strategy for 5G and Future Communication Network Technologies in July 2021 and is implementing B5G/6G projects as part of it. Spain is also advancing Beyond 5G/6G R&D projects.

<https://www.entreprises.gouv.fr/fr/strategie5G>

<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 signed a declaration of cooperation on AI and, since October 2020, have advanced various joint R&D projects centered on 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 Green ICT

In France, as a national initiative, a roadmap on Digital and the Environment was announced in February 2021 to promote reduction of the environmental footprint of the ICT field.

<https://www.economie.gouv.fr/environnement-numerique-feuille-de-route-gouvernement>

C-1-7. R&D Trends in the Semiconductor Field

Specific R&D projects in semiconductors are being carried out under the Key Digital Technologies Joint Undertaking.

<https://www.era-learn.eu/network-information/networks/key-digital-technologies>

C-2. Utilization of Electromagnetic Waves (related to Section 2.2)

C-2-1. History of Electromagnetic Waves

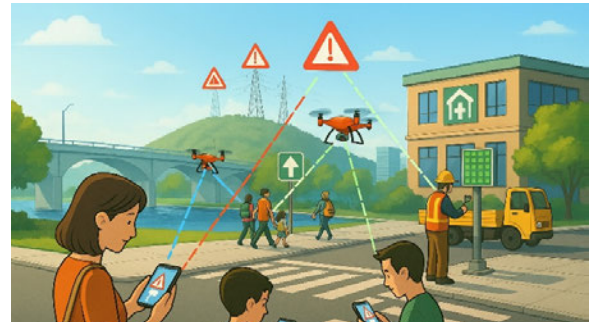
The utilization of electromagnetic-wave technologies began in the late nineteenth century, when Maxwell formulated electromagnetism and Hertz experimentally demonstrated the existence of electromagnetic waves in 1888. In the 1890s, Marconi succeeded in wireless communication experiments. In the early twentieth century, radio broadcasting and radar appeared. After World War II, television broadcasting, satellite communications, and mobile telephony became key elements of social infrastructure. Outside communications, microwave ovens were commercialized in the 1940s, while remote sensing for earth observation and medical applications such as MRI and radiation technologies developed from the 1970s onward.

C-2-2. Long-Term Outlook for the Next 50 Years

The IPCC Sixth Assessment Report Synthesis Report notes that the average global temperature in 2024 rose 1.5 degrees Celsius above the pre-industrial level for the first time in recorded history.

Japan’s Ministry of Land, Infrastructure, Transport and Tourism has also reported that the frequency of short-duration heavy rainfall events with hourly precipitation of 50 mm or more has increased by roughly 1.5 times compared with the 10-year average from 1976 onward. In response, Japanese ministries and agencies are formulating plans that consider not only a 2 degrees Celsius warming scenario but also a 4 degrees Celsius scenario.

Against this background, the superior characteristics of electromagnetic waves are expected to support an even broader range of functions - from disaster prediction to mitigation, recovery, and reconstruction(Fig. C-2-1). Their use will likely expand not only during disasters but also across future living environments and outer space, from non-terrestrial networks to the Moon, the Sun, and Mars(Fig. C-2-2). Electromagnetic-wave technologies will continue to serve as enabling infrastructure for observation and forecasting of weather and disasters as well as for highly advanced networking and automation technologies in future society(Fig. C-2-3).



Development of applications, procedures, and related initiatives to accurately and effectively communicate disaster prediction information to the public and relevant organizations.



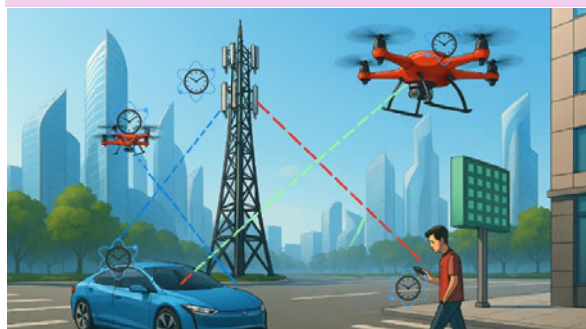
Improvement of observation and prediction technologies for global warming and heavy rainfall through remote sensing, as well as damage assessment using ground surface sensing technologies.



Prevention of severe space weather disasters, such as those associated with the Kessler syndrome, through higher-accuracy space weather forecasting and extended prediction periods.



Infrastructure deterioration diagnostic technologies based on electromagnetic wave sensing.



A robust space-time synchronization environment that enables positioning and time synchronization even when GNSS is unavailable.

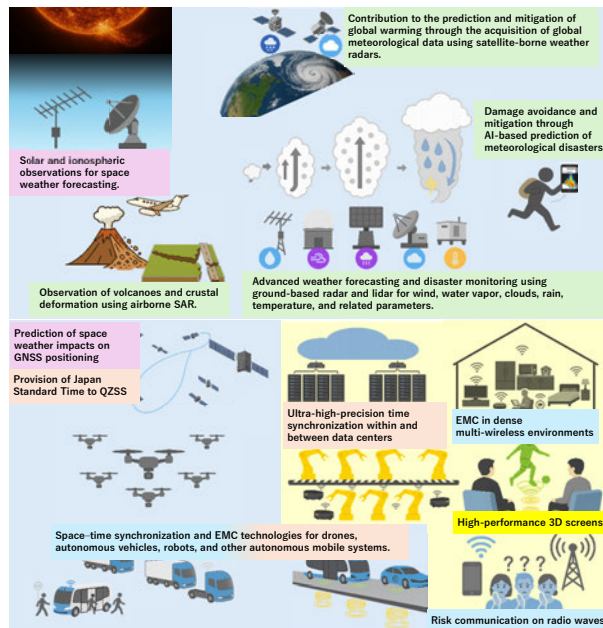


Space weather impact prediction for satellite positioning, space-time synchronization technologies, and EMC countermeasure technologies required for the operation of drones and robots during disaster recovery.

Appendix Fig. C-2-1: Examples of the use of electromagnetic-wave technologies for forecasting, situational awareness, evacuation, mitigation, and recovery in future intensified disasters.



Appendix Fig. C-2-2: Conceptual illustration of future uses of electromagnetic-wave technologies in outer space.



Appendix Fig. C-2-3: Conceptual illustration of future uses of electromagnetic-wave technologies in future living environments.

C-3. ICT Device Technologies (related to Section 2.4)

C-3-1. Examples of Research and Development in Japan and Overseas

Overseas, Intel developed a 150 GHz-band wireless receiver chip integrating a PLL and ADC using a 22 nm FinFET process and demonstrated 128 Gb/s communications. In Japan, a Tokyo Tech-NTT group developed a 300 GHz-band wireless transceiver chip using a 65 nm bulk CMOS process, while NICT and partner organizations demonstrated beam steering technology for 300 GHz-band wireless communication and are advancing RF front-end circuits, antennas, baseband circuits, and packaging technologies.

High-output GaN devices, which complement Si CMOS and other silicon semiconductor devices, are also advancing. Sumitomo Electric Industries holds the top share for GaN-HEMT transistors for 5G base stations, and NICT has reported Japan's highest maximum oscillation frequency.

C-3-2. R&D Trends in Spatial Light Modulators (OPA)

Among the various spatial-light-modulator approaches, Liquid Crystal on Silicon (LCOS) has already been commercialized for relatively low-speed applications with scanning speeds up to about 10 kHz. Si-OPA has demonstrated high-deflection beam control and LiDAR operation, but is limited to around 100 kHz and relatively high power consumption. By contrast, EOP-OPA has demonstrated 2 MHz light-beam scanning and much lower power consumption, indicating superior performance in scanning speed and power efficiency.

C-3-3. R&D Trends in Transistors and Diodes

For vertical structures useful as power devices, Schottky barrier diodes have shown steady progress, although the overall device performance index still trends toward saturation and remains below the theoretical limits of SiC and GaN. At the same time, lateral transistors and thin-film crystal growth technologies, including those based on metastable $\alpha\text{-Ga}_2\text{O}_3$ structures, have advanced. FLOSFIA is promoting development of Schottky barrier diodes and transistors using $\alpha\text{-Ga}_2\text{O}_3$ and has begun commercial sales of DC/DC buck converters using $\alpha\text{-Ga}_2\text{O}_3$ SBDs.

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

C-4-1. Research and Development for Improving Quantum Computing Accuracy

Research is under way to improve operational accuracy by using not only two-level quantum systems but also higher quantum levels so as to expand the Hilbert space and increase the degrees of freedom available for quantum computation.

C-4-2. Quantum Cryptography Using Satellites

Three key technical requirements are particularly important: (1) communication must be possible even during daytime, (2) communication should remain possible even under cloudy conditions, and (3) security should not depend on trusting the satellite itself. These are difficult requirements even for non-quantum optical satellite communication. Nevertheless, several possible approaches can be considered.

For points (1) and (2), one approach is key distribution through multipath selection using inter-satellite quantum communication. Another important consideration is operational design, such as sharing keys only when conditions are favorable and then using the accumulated keys for subsequent communications.

For point (3), satellite security is a challenge for satellite communications in general, but for quantum key distribution it may be mitigated if highly efficient entangled-photon sources can be realized. It is also important to prevent satellite hijacking by using authenticated classical communications for satellite control.

C-5. Universal Communication (related to Section 2.7)

C-5-1. Supplementary Information on Large Language Models

LLMs based on the Transformer architecture can broadly be classified into discriminative and generative models. BERT is a representative discriminative model, while the GPT series, PaLM, and LaMDA are representative generative models.

C-5-2. Supplementary Note on GPT-3

When GPT-3 was first announced, attention focused on the fact that it could achieve high accuracy on a variety of tasks without task-specific fine-tuning, using zero-shot and few-shot prompting.

C-5-3. Supplementary Note on Conversational AI

In addition to ChatGPT, Meta released BlenderBot 3 and Galactica, while Google announced Bard. Competition among major actors accelerated rapid progress in dialogue-oriented AI services.

C-5-4. Issues Relating to Conversational AI

As conversational AI has advanced, new issues have emerged for application developers. If a voice dialogue system relies on the same provider for both speech recognition and speech synthesis, that provider can potentially capture both the inputs and outputs of the service. There is therefore a risk that a service could be imitated or subsumed within a larger, more advanced conversational service.

C-5-5. Development of LLMs at NICT

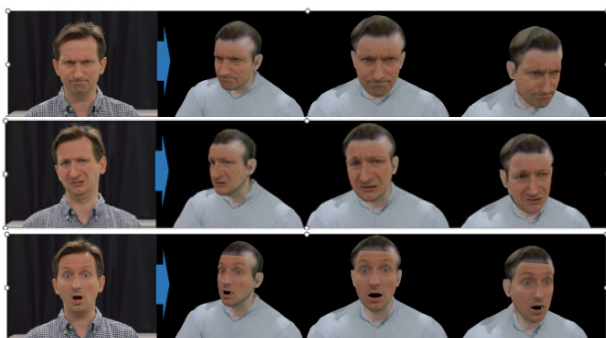
From a practical perspective, NICT has pursued discriminative

LLMs and their applications, including Japanese BERT trained on 350 GB of proprietary web text and larger-scale BERT models, together with RaNNC, an automatic parallelization middleware for efficient deep-learning development.

C-5-6. Real-World Modeling and Image Generation Technologies

Deep-learning technologies for modeling the 3D structure and surface properties of the real world and generating realistic novel images have advanced rapidly. They are expected to support spatial computing in fields such as telecommunications, telepresence, robotics, simulation, remote medicine, and training.

Real-world modeling targets include people and environments. The use of machine learning has reduced costs, shortened processing time, and improved reconstruction accuracy compared with conventional large-scale capture systems.



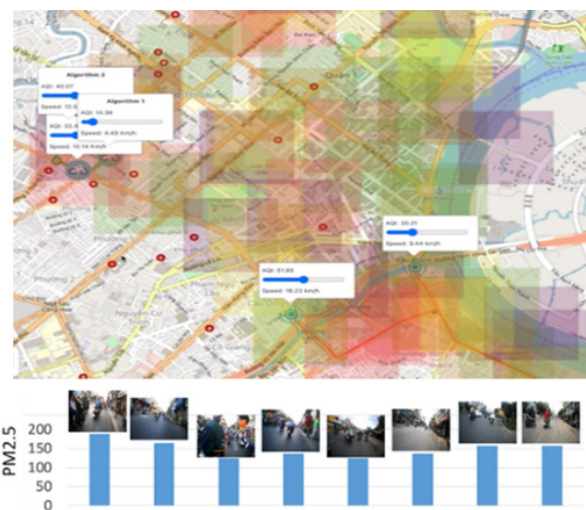
Appendix Fig. C-5-1: Construction of Expressive 3D Avatars using PEXR

C-5-7. 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).

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 (278). 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 (276). 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-5-1). Furthermore, efforts are being made to improve the interoperability of diverse data and models and to standardize international measures (280). 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 (281). 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-5-2). 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 (282). 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.



Appendix Fig. C-5-2: Example of Route Guidance to Avoid Air Pollution Risk

C-6. Bio-ICT and Brain Information Communications (related to Section 2.8)

C-6-1. Co-evolution of AI and Brain / Neuroscience

The relationship between AI and brain / neuroscience is not one-way imitation. Rather, the two have developed while exchanging research methods and concepts. Progress in deep learning has made it possible to analyze high-dimensional neural data, accelerating extraction of spatiotemporal neural patterns and representational structures. At the same time, findings from neuroscience have been incorporated into AI research as principles of learning, adaptation, and representation. This bidirectional relationship can be understood as the co-evolution of AI and neuroscience.

AI is increasingly becoming a foundational technology for tackling the complexity of neuroscience. The human brain, with roughly 86 billion neurons and trillions of synapses, is an extremely dynamic and nonlinear system. Understanding it requires large-scale acquisition and analysis of data from diverse measurement and intervention techniques such as optogenetics, calcium imaging using GCaMP probes, electrophysiology, and behavioral analysis.

Machine learning and deep neural networks are now widely used to analyze the structures latent in these diverse, high-dimensional datasets. AI is being integrated into analysis of brain imaging and electrophysiological data, extraction of features related to neurological disorders, and signal decoding for BCI. Simulation using computational models also provides a means of testing hypotheses about brain function and cognition.

More recently, research has also begun to analyze AI models themselves in order to gain new perspectives on brain understanding. Viewing deep-learning models as optimization systems with internal components such as objective functions, learning rules, and architectures - as discussed by Richards et al. - has proven useful for theory formation in neuroscience. This stream of work, often called mechanistic interpretability, aims not only to improve AI interpretability but also to provide new tools for understanding natural intelligence.

C-6-2. Brain-Inspired AI and Neuromorphic Computing

Brain-inspired AI does not seek to reproduce the brain faithfully. Instead, it abstracts engineering-relevant properties seen in the brain - such as high energy efficiency, adaptability, and distributed information processing - and applies them to information processing technologies. Neuromorphic computing is a particularly important approach within this area because it attempts to implement those properties at the levels of computational platforms and devices, and can be regarded as a third computing architecture distinct from CPUs and GPUs.

A major reason neuromorphic computing did not achieve broad practical deployment in the past was the lack of a general-purpose programming model. Early spiking neural networks often depended

on hand-designed networks or local learning rules. They were useful for specific tasks, but flexible implementation of arbitrary tasks remained difficult, creating a high barrier to large-scale deployment and commercialization.

In recent years, this situation has changed markedly with the application to SNNs of gradient-based optimization methods established in deep learning. Theoretical advances such as surrogate-gradient methods and backpropagation through time have made it possible to train SNNs using data and loss functions. As a result, model development and deployment for neuromorphic hardware can increasingly follow workflows similar to those used in conventional deep learning.

At the same time, hardware design has changed. Whereas early neuromorphic circuits often used analog or mixed-signal designs and achieved very low power consumption at the cost of variability and manufacturability challenges, more recent designs based on digital CMOS spiking processors and simplified inference-oriented neuromorphic devices have made it more realistic to combine reliability, reproducibility, and scalability with high energy efficiency.

The convergence of software and hardware is clarifying a commercialization roadmap in which neuromorphic computing advances step by step from specific application domains. Edge AI, IoT devices, wearable equipment, and near-sensor processing - all of which require ultra-low power consumption and real-time operation - are especially promising markets where neuromorphic technologies can demonstrate clear advantages over conventional processors.

C-6-3. Whole-Brain Models and Large-Scale Brain Simulation

Research on whole-brain emulation and large-scale brain simulation does not aim at short-term, complete reproduction of the entire brain. Rather, it emphasizes establishing a methodology in which models are built at an appropriate granularity for the research purpose and then repeatedly validated and improved by comparison with measurement data. Recent advances in computational resources and AI are making it increasingly realistic to explore multilayer models and estimate their parameters.

In Japan, the RIKEN Center for Computational Science is promoting large-scale brain simulation using the Fugaku supercomputer. Efforts include mammalian-brain models integrating multiple regions such as the cerebral cortex, basal ganglia, cerebellum, and thalamus, along with development of frameworks optimized for Fugaku.

For smaller brains, whole-brain-level modeling and simulation of insect brains, especially that of *Drosophila*, have progressed rapidly. Open resources such as Fruit Fly Brain Observatory and FlyBrainLab support executable neural-circuit modeling and analysis based on anatomical data.

In Europe, EBRAINS has been established as an open research infrastructure integrating data, models, and computational resources. The Blue Brain Project at EPFL continues to advance high-fidelity cortical microcircuit modeling and foundational technologies such as morphology synthesis, automated model generation, and computational efficiency.

C-6-4. BMI/BCI and Brain Information Communications

BMI/BCI connects measured and decoded brain activity with external systems, but in practice relies on local signals from the brain. This makes it important to design such systems while considering whole-brain states and contextual relationships. Recent progress in non-invasive measurement and the use of brain-based models is helping to broaden the application range while reducing invasiveness.

BMI/BCI has traditionally focused on restoring or supplementing motor and language functions. More recently, however, research has extended to the boundary between treatment and enhancement. A representative example is neurofeedback, which feeds back brain activity to induce neuroplasticity and is now being explored not only for ADHD, epilepsy, depression, and PTSD but also for attention control, emotional regulation, and peak performance.

Applications are also extending beyond control within a single person to support understanding of interpersonal interaction. Studies using hyperscanning have shown that interbrain synchrony arising during conversation, collaboration, and empathic interaction is closely related to communication quality, mutual understanding, and empathy.

In parallel, AI-based decoding has significantly improved the ability to generate text from brain signals, support communication, and decode motor intention. At the same time, when these technologies are used beyond therapeutic purposes, ethical issues such as cognitive liberty, privacy, and social fairness become unavoidable.

C-6-5. Digital Twins in the Life Sciences

In healthcare and the life sciences, digital twins are evolving as adjustable computational models that imitate real biological entities and biological systems and are continuously updated using sensor data, imaging, and clinical information. Unlike conventional fixed-parameter models, digital twins evolve over time in response to observations from each target individual and can therefore support prediction and decision making that takes inter-individual variability into account.

A representative implemented example is the artificial pancreas for patients with type 1 diabetes. In the system approved by the U.S. FDA in 2016, data from wearable glucose sensors are fed into a mathematical model that simulates glucose metabolism and recalculates the necessary insulin dose about every five minutes for automated administration.

In cardiology, applications to arrhythmia treatment are advancing. Patient-specific heart structures reconstructed from diagnostic imaging can be used to build digital twins that simulate propagation of electrical signals, thereby helping to predict optimal ablation sites before surgery.

Digital twins are also being explored for highly complex biological phenomena such as immune responses. In studies of pneumonia infection, frameworks have been proposed that mathematically represent movement and interaction of immune cells and update the model using patient-specific data.

Digital twins are increasingly important for drug discovery and basic life-science research as well, especially when combined with organoids derived from patient iPS cells or with organ-on-a-chip platforms. More recently, studies have also begun to use AI to generate large numbers of virtual patients and conduct large-scale in silico trials on digital twins.

C-6-6. Nano / Molecular ICT Devices

In recent years, molecular ICT devices have begun to form a platform for obtaining internal biological information with high sensitivity and low invasiveness by converging with nanomaterials, flexible electronics, and quantum measurement technologies. From the perspectives of technology maturity and functional role, they can be organized into three layers.

Biocompatible devices represent sensing platforms close to social implementation. Integrated flexible electronics can continuously measure biological signals such as heartbeat, electromyography, and neural activity while following the motion of skin or organs. Research is also progressing on disposable devices using biodegradable materials and on remote monitoring combined with wireless communication.

Molecular information devices - which use DNA, proteins, or even cells themselves as media for information recording, transmission, and processing - remain at the basic-research stage. Even so, they offer the possibility of information processing based on principles different from those of conventional electronic devices and may open up information domains that ICT has so far struggled to handle, such as chemical and biological signals involving ambiguity, including smell and taste.

Quantum sensors are another notable element. Ultra-small diamond quantum sensors, discussed also in Chapter 2.6, can detect temperature and magnetic-field changes at the molecular and cellular scale. The data they obtain are indispensable for validating and updating digital twins and may also enable non-invasive multipoint observation inside biological implementation twins such as organoids and organ-on-a-chip systems.

C-6-7. Biological Implementation Twins: Organoids and Organ-on-a-Chip

Whereas digital twins represent biological phenomena and organ

functions through computational models, biological implementation twins physically reconstruct organ functions using actual cells and tissues, thereby serving as physical counterparts capable of reproducing multicellular interactions and microenvironments that are difficult to capture in computation alone.

Organoids are one concrete example. These are small three-dimensional tissues formed by self-organization of stem cells or tissue-derived cells and can partially reproduce the structural and functional features of real organs. By spatially arranging different types of organoids and allowing them to interact, it becomes possible to investigate inter-tissue interactions and biological mechanisms closer to those in vivo.

Organ-on-a-chip, meanwhile, uses microfluidic and related technologies to control physical and chemical environments with higher reproducibility and operability. It can faithfully mimic important in vivo conditions such as blood flow, transport of substances, and tissue boundaries while enabling stable evaluation of drug responses and disease formation processes.

C-6-8. Research Trends in Implementation and Utilization of Biological Intelligence

The implementation and utilization of biological intelligence is an emerging technical field that seeks to connect the intelligent functions inherent in living systems to information-processing systems and use them as a new computational substrate. Here, biological intelligence refers to dynamic information-processing capabilities such as learning, adaptation, and behavioral control that represent, transform, and output information in response to environmental inputs.

The organoids and organ-on-a-chip systems discussed in Chapter 2.9 are primarily intended as experimental models for improving reproducibility of organ functions and pathological states. Recently, however, research has begun to move beyond using living tissues only as models and toward measuring, stimulating, and connecting biological intelligence itself to information-processing loops for ICT use. Representative examples include organoid intelligence (OI) and the use of intelligence functions derived from insects.

OI studies investigate how learning and adaptation arise by measuring and stimulating the activity of brain organoids. At the same time, the use of insect nervous systems represents another direction, one that seeks to incorporate highly efficient sensory processing and behavioral control - such as olfaction - into sensors, robotics, and information-processing systems.

This does not only mean direct cyborg-style control of insect bodies. It also includes extracting and engineering into ICT the compactness, efficient sensorimotor integration, and environmental adaptability that insects possess. Research has reported limited demonstrations in which microelectrodes and wireless stimulators are attached to insect nervous systems to externally influence behaviors such as flight.

In parallel, insect sensory and information-processing mechanisms - including olfactory, auditory, and tactile systems that are highly sensitive and energy efficient - are also being mimicked and implemented as IoT sensors for environmental monitoring and autonomous systems, without necessarily involving control of live insects. As with OI, this line of work frames biological intelligence as an information-processing resource that can be connected to and exploited by ICT.

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| | |
|------------|---|
| July 2023 | Release of version 1.0 |
| March 2025 | Update version 1.1 - Update section 1.1.1 - Add section 1.3 to describe the trend in AI |
| March 2026 | Release of version 2.0 |

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