Resilient ICT Innovation and Deployment

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1. Introduction

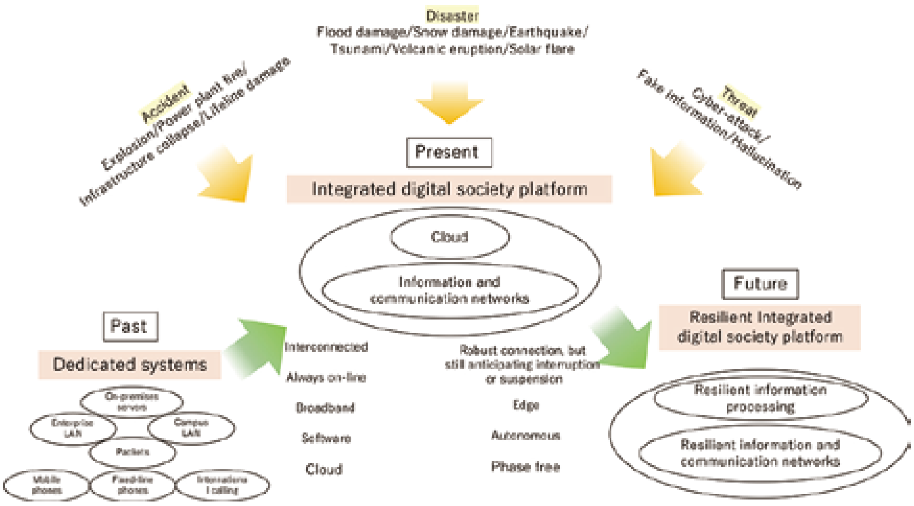
In this article, we discuss a current trend toward "Phase Free" information and communication networks with enhanced resiliency and some surrounding issues. We then introduce related NICT R&D efforts in resilient wireless communication technologies, optical fiber network technologies, edge-cloud technologies and natural-environment sensing technologies, and also efforts to deploy results of this research.

2. Information and Communication Networks and Resilience

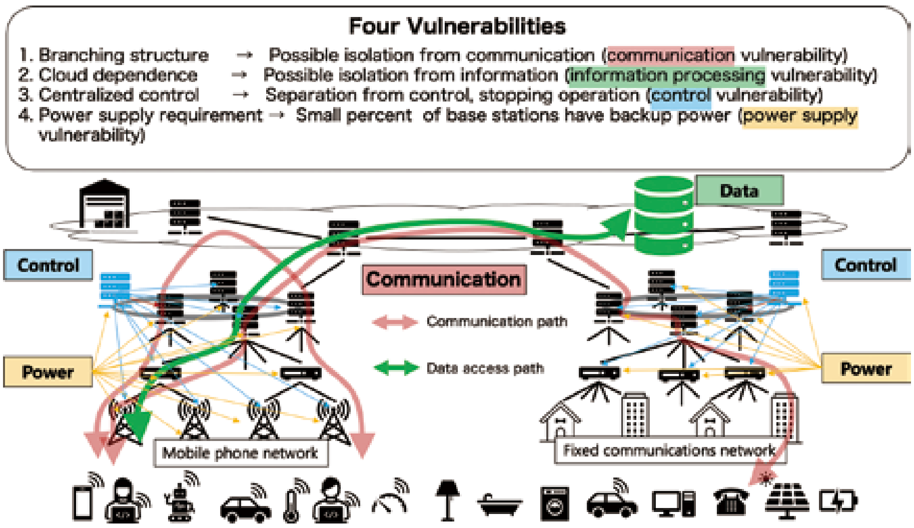
Network systems that exist for different purposes have become interconnected and grown into infrastructure for our comprehensive digital society (Figure 1). Large-scale disasters and accidents, cyber attacks and other cyber threats that are being realized with the spread of generative AI are all becoming potential threats to this infrastructure. As such, even though we are using this infrastructure in every-day circumstances, there is a need for it to have even stronger resilience than it does at present.

Our information and communication networks, which form the core of this infrastructure, have four fundamental vulnerabilities (Figure 2). The first is a "communication" vulnerability. Networks divide into branches from top to bottom, and a fault in any communication device can interrupt all communication below it. The second is an "information processing" vulnerability. With the current focus on cloud implementations, any intermediate degradation in communication or the cloud infrastructure will suspend services. The third is a "control" vulnerability. Most current systems utilize centralized control, in which a set of controllers controls the entire system, so there is a risk that if control communication between any device and the controlling device is obstructed, the service will be suspended. Finally, there is a "power supply" vulnerability. Prompted by The Great East Japan Earthquake and Tsunami in 2011, mobile base stations in important locations such as city offices and disaster hospitals have been equipped with batteries, but these efforts are still inadequate (they will be accelerated by revisions to the Radio Act).

■ **Figure 1: Trend toward resilient social infrastructure**

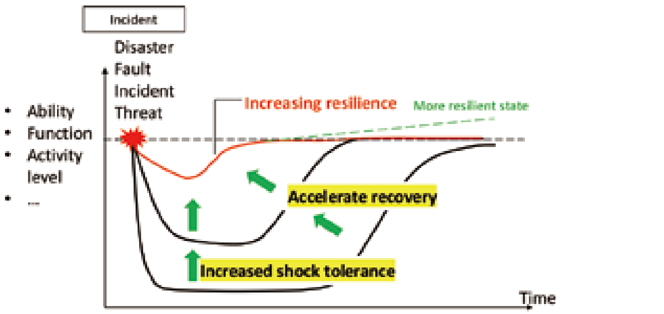


■ **Figure 2: Information and communication network vulnerabilities**



Resilient information and communication networks can be defined as providing performance and functionality that can minimize any degradation in information and communication capability and minimize the time to full recovery to pre-incident performance, even when incidents such as natural disasters or faults occur, or even provide better performance than before the incident (Figure 3). Ideally, this will include a systematic and quantitative approach, with research and development on individual technologies, but also on overall network system architectures.

■ **Figure 3: A definition of resilience of information and communication networks**



Source: Based on a figure provided by the Cabinet Secretariat, National Resilience Promotion Office

3. Resilient ICT Innovation and Deployment

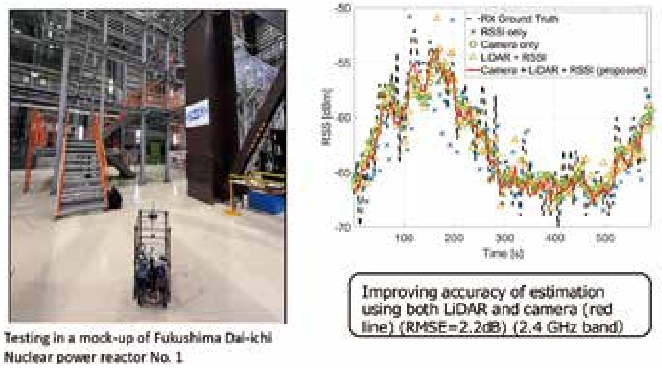
The NICT Resilient ICT Research Center was established in 2012, prompted by the 2011 Great East Japan Earthquake and Tsunami, to perform research and development on ICT that is resilient in disaster, and to promote its deployment in society. Here, we introduce some of the R&D since FY2021 and deployment of the results.

3.1 Resilient Wireless Communication Technology

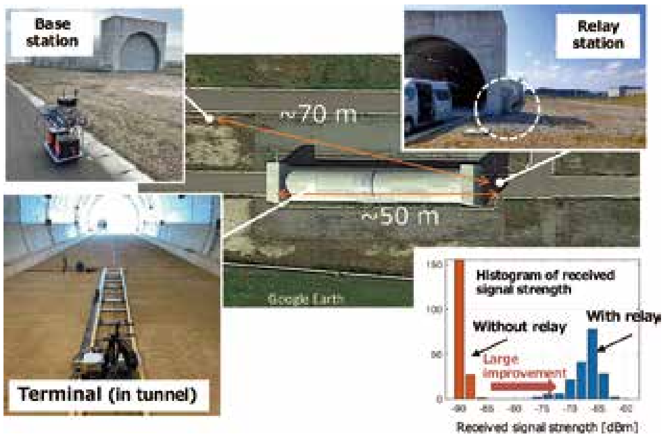
With earlier technologies, the objective was to realize low-latency, highly reliable communication even in the most difficult radio-wave environments, such as when propagation losses exceed the 150 dB permitted by 5G (3GPP Release 17), or when the frequency band is crowded with much noise. A typical example of a difficult environment is a nuclear power plant, where the internal structure is complex and covered with lead. In development of technology to accurately predict radio-wave propagation several seconds into the future, we used AI with data on spatial unevenness of internal structures, collected using camera video and LiDAR. As a first application we aim to use it for wireless control of swarm robots performing work to decommission the nuclear reactor in Fukushima. We have conducted R&D on methods for multiple frequency bands, conducted tests in a mock-up of the Fukushima Dai-ichi nuclear power plant (at the Japan Atomic Energy Agency), and confirmed the ability to predict approximately one second into the future with over 95% accuracy (estimates within ±3 dB of signal strength).

For cooperative control of swarm robots, sub-millisecond low latency is essential. When extending the communication range with relays, this was difficult to attain using conventional technologies. As such, for the 2 GHz and 4.9 GHz bands available for wireless robot control, we conducted R&D on new methods to greatly reduce relay processing time. For the 4.9 GHz band,

■ **Figure 4: Estimating radio wave propagation (reception field strength) using AI**



■ **Figure 5: Successful short-range radio relay in a tunnel, outside of communication range**



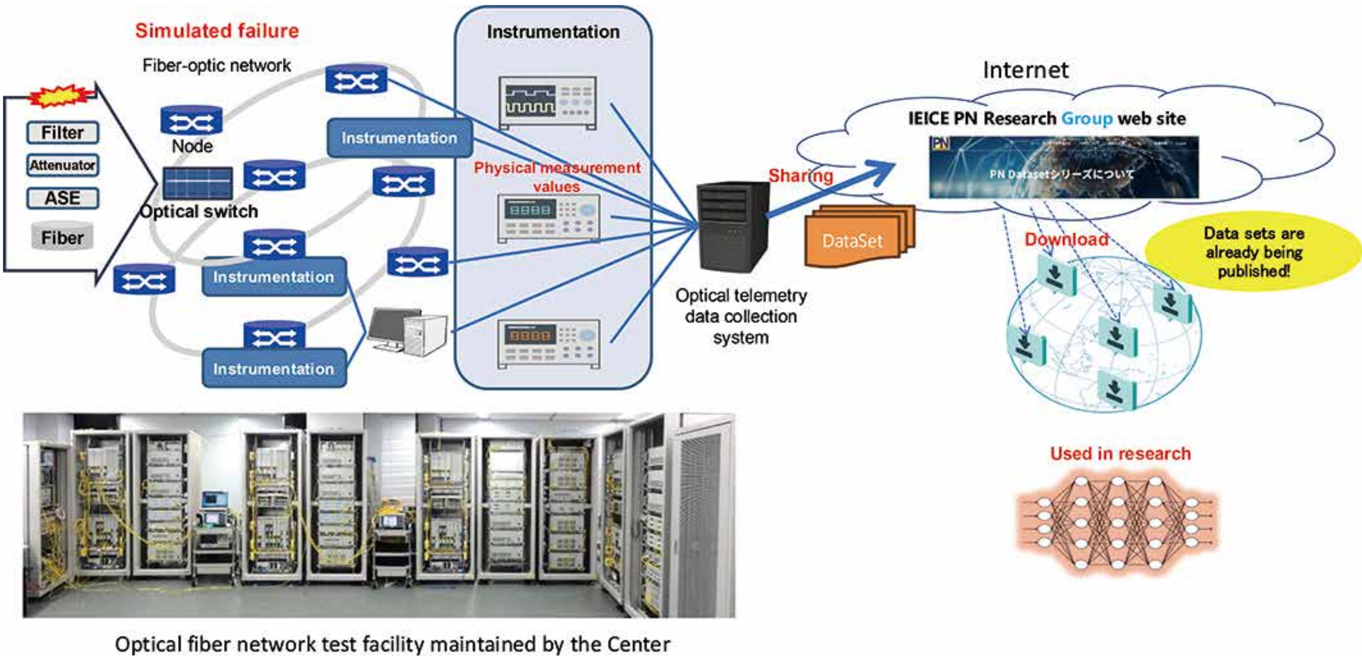
we have confirmed relay processing with latency far below target, in less than two microseconds, in practical testing. This result has already been adopted in 3GPP Release 18 (5G-Advanced) Network-controlled Repeater Standard TS38.213 and others. The method also has strengths independent of communication formats and standards, and can be used to expand the communication range of wireless communication systems already installed in plants and other facilities.

In another case, we are developing a method for synchronization between stations, which applies to cooperative coherent communication among multiple distributed stations and achieves both gain preservation and reduced overhead. This is expected to be adopted in the 3GPP Release 19 NR MIMO Phase 5 standard. We are also researching a method to apply quantum annealing to multi-user detection on base stations, and have demonstrated simultaneous connection to four devices for the first time in field testing.

3.2 Resilient Optical Network Technology

Optical networks have characteristics that support long distances and high capacity, so they are used widely in core, metro and access networks. Any interruption or reduction in throughput, whether due to disaster, break-down or device degradation with age, can have an extremely broad effect, so prior prevention is important. For this reason, we have utilized our large-scale optical-fiber network test facilities and conducted R&D on optical telemetry data-gathering systems, which can collect various types

Figure 6: Collection and publication of data on network failures to promote research for detecting early signs of them



of physical measurements from optical fiber networks over long periods of time. We simulated various types of network failure while switching aspects such as network configuration, so that we can detect even early-warning signs for network failures. We have begun sharing the data set obtained for research purposes, through the web site of the IEICE Technical Committee on Photonic Network. Use of this data set can enable research on network control methods that can detect signs of network failures and actively adjust to avoid them. In fact, by focusing on degradation in transmission quality due to cross-talk between cores in multi-core fiber optical networks in optical signal data over time, we designed a machine learning model able to predict loss of logical communication links based on the data, and can now detect such warning signs successfully.

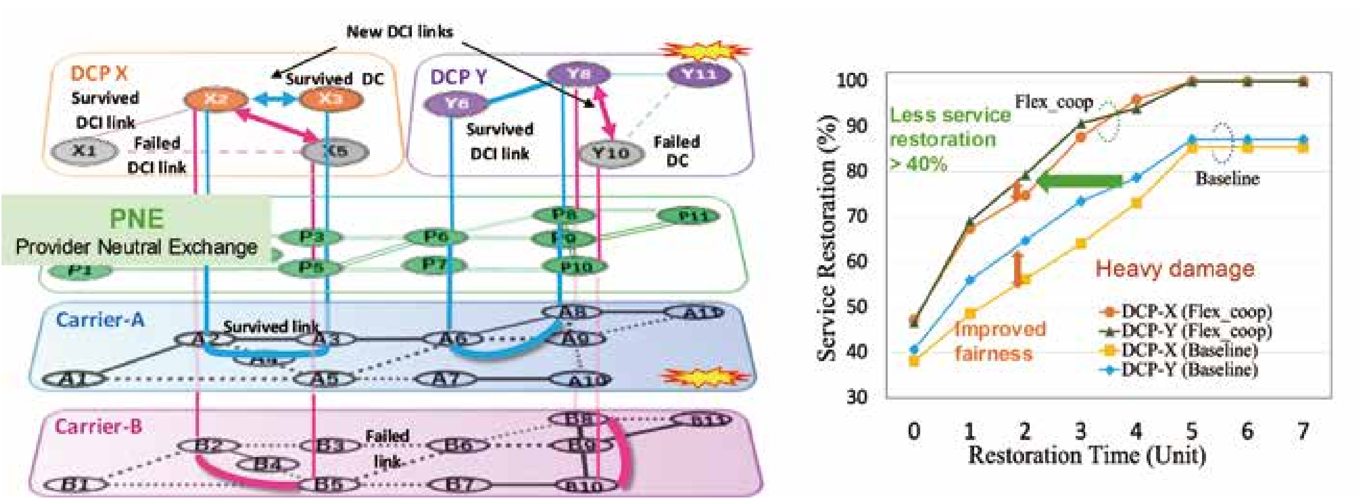
As with efforts to implement roaming between operators during and after disaster, there is great anticipation of cooperation among operators and also among cloud service providers as cloud services expand. In collaboration with University of California, Davis in the USA, we have conducted R&D on new architectures for cooperation between communication and cloud service operators.

A provider-neutral exchange (PNE), which is independent of all operators, receives abstracted resource information from each operator and by matching it with data center needs for some failures, the time required to reach 80% recovery from when the cloud service fault occurred was reduced by more than 40%, compared with earlier research. This confirms a clear effect of cooperation between operators.

3.3 Resilient Edge/Cloud Technology

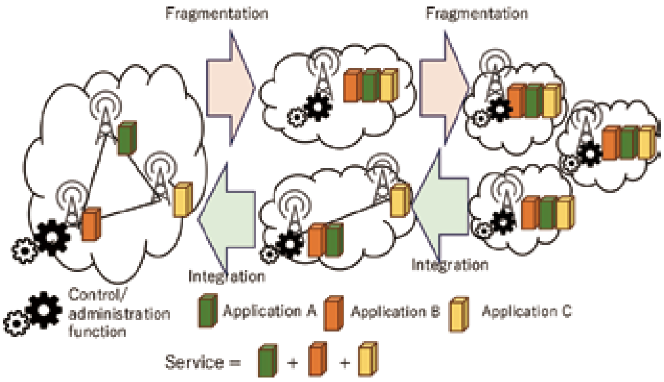
Cloud and edge-cloud services are assumed to be stable and always on-line, so they are vulnerable to communication

Figure 7: Reduction in recovery time through cooperation among communication and cloud operators



disruptions. With the assumption that communication disruptions will occur, we propose an "autopoietic" edge-cloud architecture that is able to continue providing functionality virtually, even when communication becomes unstable, and we are conducting R&D on this approach. Autopoiesis is a concept in theoretical biology whereby the organic structures and expression of life are generated. Figure 8 gives an image of how services could reorganize autonomously through autopoietic edge-cloud architecture. Normally (on the left), a single service composed of applications A, B and C is controlled by an independent control/administration function. Even if the network becomes fragmented (on the left), control and administration functions and applications can be regenerated according to changes in resources within the network, continuing to provide their services. Details of the technologies implementing this are beyond the scope of this article.

■ **Figure 8: Autopoietic reorganization of edge-cloud services**

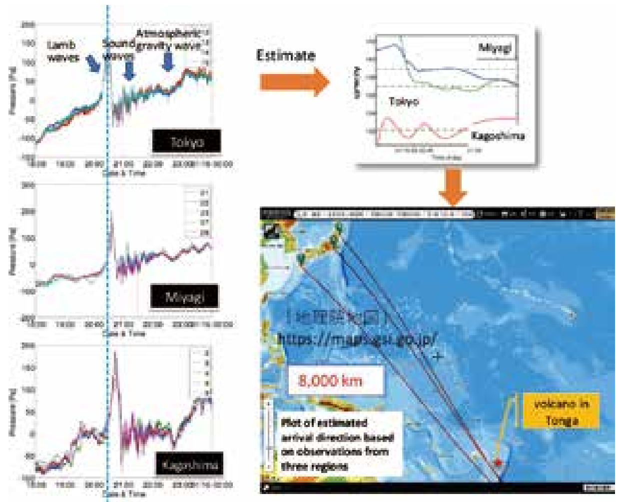


The predecessor of this technology is the Cross-Agency Information and Communication System (X-ICS, "cross-ics"), which is a cloud sharing system able to collect and share information among disaster response agencies (fire, police, self-defense force etc.) during a large-scale disaster, even if public communications networks are interrupted. We are conducting R&D on this system jointly with other organizations and under the umbrella of the Cabinet Secretariat Strategic Innovation Program (SIP). Each node of X-ICS is composed of computers with multiple communication interfaces and operation is autonomous and distributed, with no facility performing overall control and administration. In areas where public communication is suspended, information can be transmitted directly between the nodes by packet relay over Wi-Fi, and capacity of communication with the internet is maximized by bundling multiple connections. In FY2025, development of functionality was completed, and we are conducting field testing with disaster response agencies.

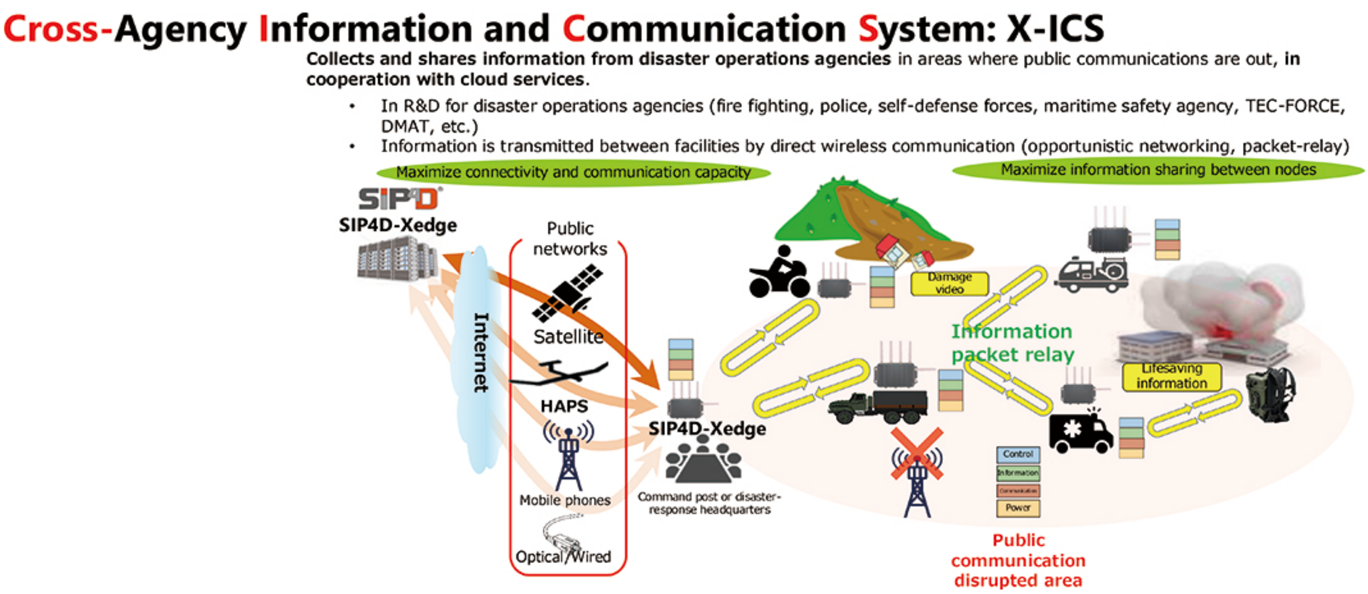
3.4 Resilient Natural-Environment Sensing Technology

We have developed sensors for infra-sound (sound-waves below the audible frequency band, produced by phenomena such as tsunami and volcanic eruption) using MEMS sensors and small microphones, that reduce cost and power consumption while having the same bandwidth and sensitivity as conventional precision microbarometers. We have installed them in 25 locations

■ **Figure 10: Estimating the sound source from the Tonga underwater volcanic eruption**



■ **Figure 9: X-ICS ("cross-ics") overview**



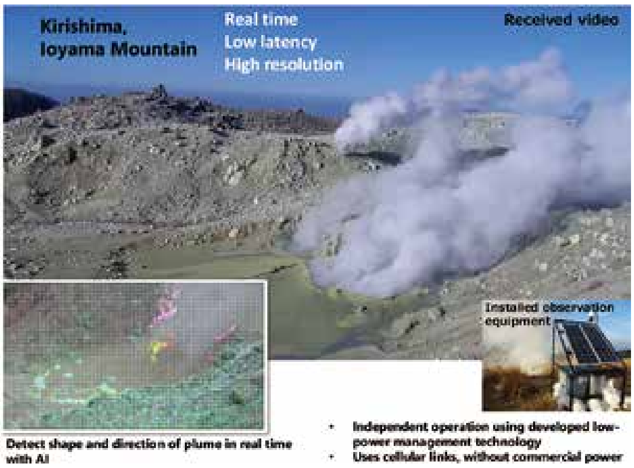
throughout Japan and are collecting observations. Some of this data is published for research purposes on the Japan Weather Association web site. We have developed a method for analyzing and visualizing sound-source location (i.e., where the tsunami or eruption occurred) and as an example, were able to estimate the source location and direction of arrival of the tsunami caused by the Tonga underwater eruption in November, 2022.

We have conducted R&D on a method to detect eruption plumes, wave height, affected birds and other wildlife and other factors using machine learning to process received images, based on a technology able to compress and transmit high-resolution images from off-the-shelf cameras over public mobile networks. For example, we developed a method able to detect eruption plumes, which are particularly difficult to detect, with high rates (F-value over 90%). By reducing the computation load we were able to detect plumes in areas surrounding a volcano, where power and computing capability are limited. This is being field-tested near Sakurajima, a volcano in Kagoshima Prefecture.

We have installed a wave-height measuring system on a seawall in Toyama Prefecture, and are conducting continuous testing, including overnight. We have confirmed the ability to measure heights exceeding the heights of the seawall through the night, which was difficult to do using the previous, contact-type sensors.

We have developed an original low-power management technology and enabled long-term infra-sound and video observations using only self-generated power that relies mainly on solar battery. This has been operating at Kirishima Ioyama, a volcano located at the border of Miyazaki and Kagoshima prefectures, for more than three years (Figure 11). The received video has been provided on a trial basis to three surrounding municipalities and been used daily to assess the volume, direction and other aspects of volcanic plumes, as well as in volcano disaster prevention by the municipalities.

■ Figure 11: Volcano observation using high-resolution video with independent power supply

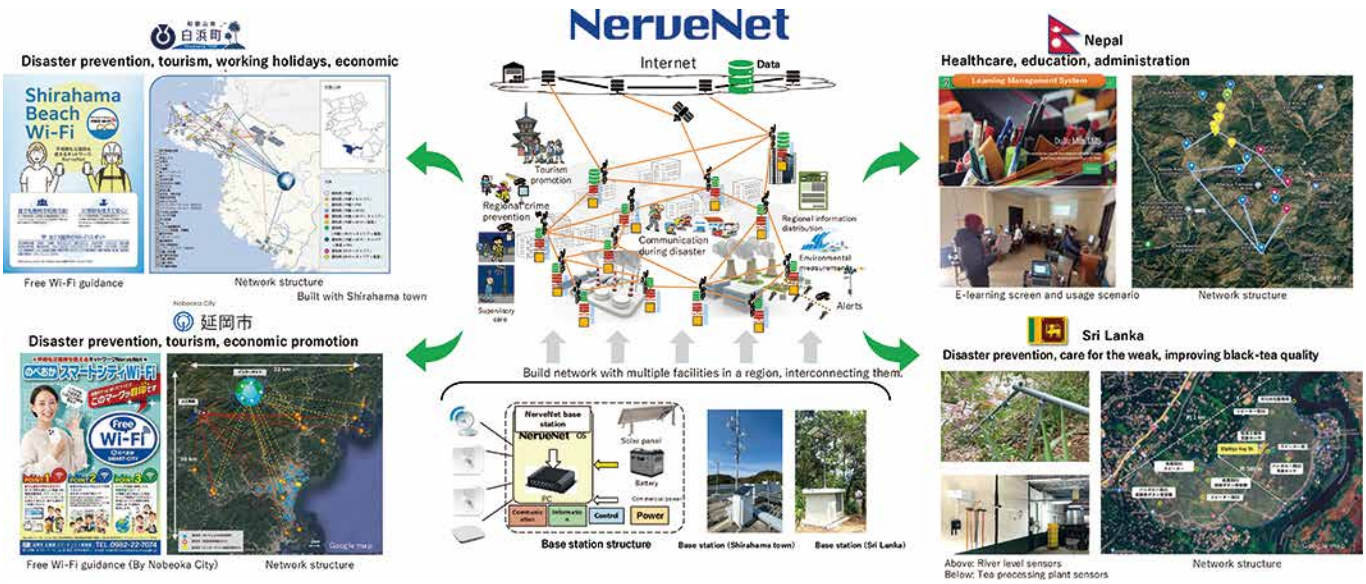


3.5 Resilient ICT Deployment

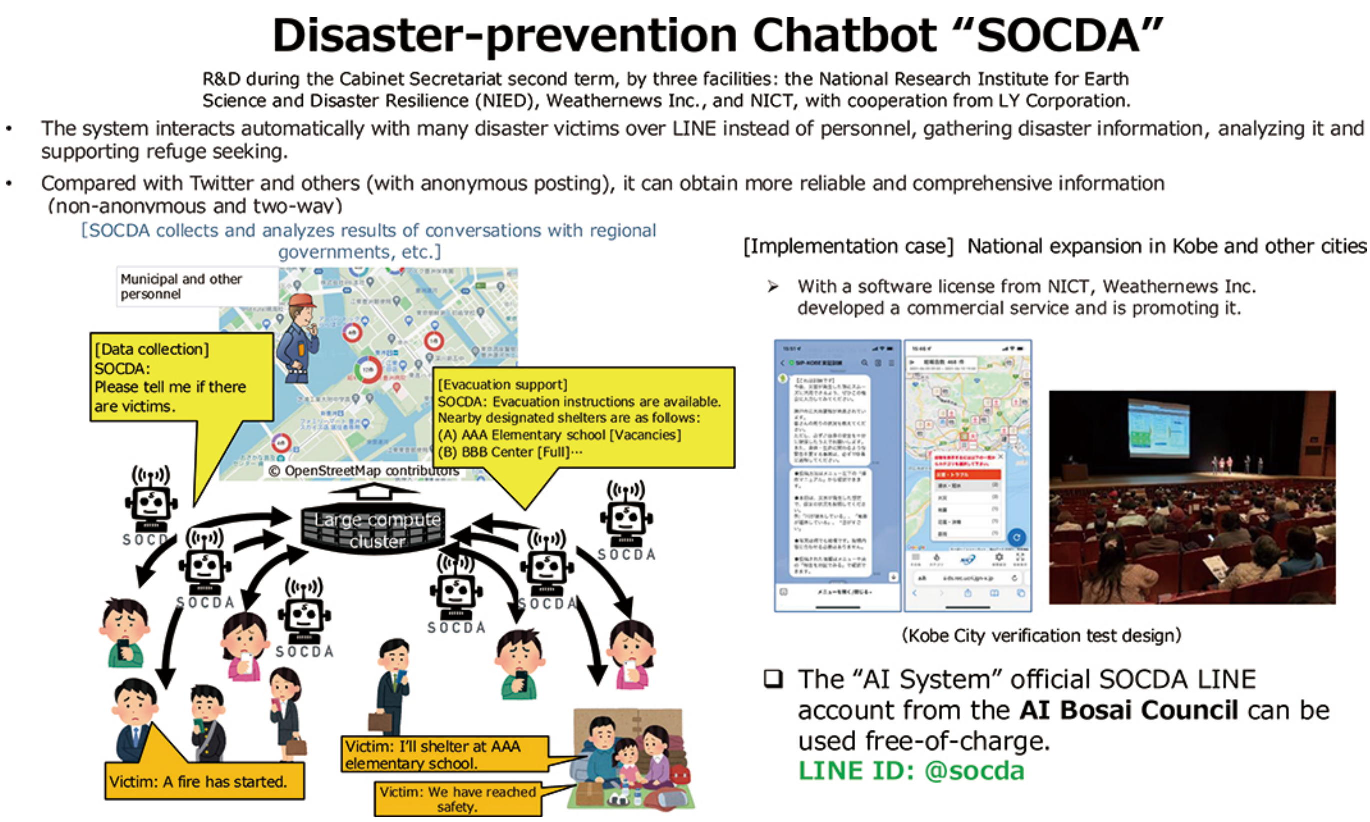
NerveNet, a kind of X-ICS predecessor, is a network composed of multiple base stations that have overcome the vulnerabilities, installed and mutually interconnected within a region, and providing the four functions shown in Figure 2. If it experiences a partial failure, the entire network does not fail, and if the fault is recovered, the whole network automatically returns to normal operation. The network can maintain communication using a route that avoids the damaged part, and even if the Internet connection is lost, it can maintain certain services using internal information processing functions. It consumes less power than a public mobile phone base station, and can operate for at least three days if there is a power outage, using solar panels and batteries. Practical application of this has begun as a disaster-resilient regional communication and digital platform in some locations in Japan, Nepal, and Sri Lanka.

The "SOCDA" ("soku-da") disaster prevention chatbot that we have researched, developed and implemented under the Cabinet Secretariat SIP, is a system that can automatically converse with affected residents in place of municipal staff who

■ Figure 12: Example deploying NerveNet, a regional digital communication platform



■ **Figure 13: Overview of the "SOCDA" disaster prevention chatbot**



will be busy with other disaster response, gathering and analyzing victim information and providing support. Currently, it has been introduced by 120 municipalities.

■ **Figure 14: Contributions to ITU, APT and 3GPP and guidebook publication**

Each of these research results has been reflected in ITU or APT reports or 3GPP standards. The Resilient ICT Research Forum, which our office is part of, has also created, published, and posted on the web, the "Introducing Disaster-Resilient Information and Communication Networks" guidebook, oriented mainly for municipalities, working to improve resilience both domestically and internationally.

4. Conclusion

The demand for resilience in everything holds great promise and is an ongoing theme. Technically, research and development on both individual parts and the overall architecture are needed, and adoption of the results requires creation of resilience standards and evaluation methods. Measures must then be taken to introduce the technology based on the standards and evaluation methods, implemented by society as a whole and including industries beyond ICT. As a member of society, we will continue to engage in technical R&D and deployment of these results.

Acknowledgements

I would like to express thanks to everyone at the Resilient ICT Research Center, who created the technologies described here.