TYPE Review
PUBLISHED 13 March 2025
DOI 10.3389/frcmn.2025.1563161



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RECEIVED 19 January 2025
ACCEPTED 20 February 2025
PUBLISHED 13 March 2025

CITATION
Monden K and Kaneko M (2025) Challenges of future communication technologies for resilient internet of energy.
*Front. Commun. Netw.* 6:1563161.
doi: 10.3389/frcmn.2025.1563161



# Challenges of future communication technologies for resilient internet of energy

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Natural disasters have become more frequent and severe, posing threats to critical infrastructure such as power systems. The Internet of Energy (IoE) offers a solution to optimize energy systems by means of Cyber-Physical Systems (CPS). In this paper, we propose the design of a resilient IoE, envisioned to make the global IoE system architecture intrinsically resistant to disasters, and investigate the requirements and challenges of IoE communication technologies considering disaster scenarios. In particular, we explore the recent advances of wireless communication technologies, and discuss their applicability and issues towards their integration for resilient IoE. Finally, the open research directions are identified and potential solutions are proposed in view of realizing a CPS tailored to resilient IoE.

KEYWORDS

**internet of energy, distributed energy resources, wireless networks, cyber physical system, disaster response**

## 1 Introduction

In recent years, natural disasters such as floods and landslides have become more frequent and severe due to climate change caused by global warming. Social infrastructures such as power systems and transportation systems, are being disrupted by increasingly severe disasters, threatening people's safety and security. In particular, the energy system is a vital infrastructure that supports our lives, and an increase in power outages due to disasters can induce huge financial losses due to the suspension of economic activities. Besides, it has been shown that augmenting prevention and response costs to face energy system failures would result into significantly higher electricity prices (Hijazi and Dehghanian, 2022). Hence, as a countermeasure against global warming, countries around the world are accelerating their efforts to achieve carbon neutrality by 2050, following the Paris Agreement of COP21 and the UAE Consensus of COP28. In parallel, governments and international organizations are strengthening power grid resilience through policies, regulations, and technical standards. Legal frameworks mandate grid reinforcement, smart grid deployment, and energy security measures (Agency for Natural Resources and Energy, 2020; U.S. Department of Energy, 2024). Complementing these efforts, the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) have established standards that provide technical guidelines for resilient infrastructure, including disaster preparedness and DER integration (International Electrotechnical Commission, 2020) (IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated

Electric Power Systems Interfaces, 2018). These combined regulatory and standardization initiatives align with our approach to strengthening energy system resilience.

Achieving carbon neutrality requires the transition of the energy system from one based on fossil fuels to one based on renewable energy resources. The mass installation of renewable energy resources increases the variability of energy supply, while electrification requires additional energy demand. Cyber Physical System (CPS) can be a solution to cope with these changes and make energy systems more efficient and reliable. The realization of CPS requires collecting sensing data of energy systems in cyberspace, big data analysis with A.I., simulation by digital twin, feedback of the analysis outcomes to the physical space, and decision making based on the feedback.

To realize such CPS for power systems, the concept of Internet of Energy (IoE) (Shahinzadeh, et al., 2019; Kafle, et al., 2016) has recently emerged. The IoE enables a variety of applications through the collaboration between the energy supply side and the consumers' demand side, such as optimization of supply-demand balance. Several studies have provided an overview of the technologies needed to achieve a smart city based on the IoE (Ali et al., 2023; Mishra and Singh, 2023). For instance in (Ali et al., 2023), a comprehensive perspective was provided on IoT and Grid resiliency. However, it did not address communication requirements nor architectures that are specifically related to disaster response. Similarly, reference (Mishra and Singh, 2023) gave an overview of the required IoT technologies for energy optimization in smart cities. However, resiliency issues and communication requirements in case of disaster occurrences have not been addressed.

In this article, we analyze and discuss how to make IoE more resilient to disasters, by proposing the concept of resilient IoE. In order to achieve resilient IoE, the communication platforms that link physical space and cyberspace within CPS are of prime importance, therefore we will mainly focus on their roles. Indeed, although several proposals of communication platforms for IoE and smart grids can be found in the literature (Marzal, et al., 2019; Liu et al., 2021; Leligou, et al., 2018), such platforms are yet to be standardized, while the assessment criteria for selecting appropriate communication methods have not been discussed. There have been several proposals to utilize Electric Vehicles (EVs) as temporary energy resources (Yang, et al., 2020; Ustun et al., 2015; Zhang, et al., 2022a), as they may help minimizing the impact of power outage from the grid in disaster situations. However, the requirements for a global system architecture and robust communications were not considered.

Therefore, in this article, the issues towards realizing resilient IoE are identified, and novel system architecture and technological solutions are advanced. Namely, we propose a resilient IoE design based on a system architecture that intrinsically integrates disaster scenarios. Then, we identify the specific communication requirements under emergency situations, and analyze the applicability and shortcomings of existing wireless and wired communication technologies. Furthermore, the challenges of future communication technologies for resilient IoE, and for realizing their CPS are examined, after which potential solutions and open research directions are provided.

The contributions of this article are summarized as follows.

1. We review the main features of existing IoE technologies and discuss their shortcomings in the event of a disaster. By contrast, we propose a new concept for a resilient IoE design and clarify its system architecture requirements.
2. We analyze the roles and requirements of communication platforms that integrate disaster scenarios, and evaluate the applicability of existing wireless communication technologies.
3. We identify challenges and potential solutions for future communication technologies, and provide research directions to enhance the resilience of energy supply systems during disasters.

The remainder of this paper is organized as follows. Section 2 introduces the concept of IoE, and Section 3 describes related work. In Section 4, we propose the system architecture for resilient IoE in disaster scenarios, and Section 5 discusses communication requirements. In Section 6, we analyze the challenges and open research directions for realizing resilient IoE and its CPS. Finally, section 7 concludes this paper.

## 2 Internet of energy

Smart grids, which utilize ICT to enhance electric power systems, are being developed in various countries. In recent years, the concept of IoE (Shahinzadeh, et al., 2019; Kafle, et al., 2016) has been proposed to further exploit IoT technologies in the power system. The IoE is not limited to the evolution of the power system as in the smart grid but can realize a variety of applications through the collaboration between supply side and demand side. The supply side includes the power generation, Transmission, and Distribution (T&D) systems. The demand side includes the facilities and users that consume electricity. The smart grid focuses primarily on improving the system within the supply side, while the IoE extends the system by including the demand side. This extension allows the entire system to be better adapted through applications, such as optimizing supply planning based on demand-side data, or adjusting the demand side in response to supply-side constraints.

To realize applications enabling supply and demand system collaboration, the integration of various technologies encompassing sensing, advanced communications, AI/machine learning, edge computing and other IoT-related areas will become necessary. For instance, by enabling early detection of an imminent disaster through more advanced and realtime sensing, it will become possible to prevent it or to minimize its damages. By performing data processing on the devices side - such as smart meters - using edge computing, it will be possible to reduce communication loads and to maintain power supply through local control even if communication is disrupted. In addition, integrating AI and machine learning would enable to optimize the automatic configuration of microgrids in the event of a disaster. The cornerstone supporting such emerging technologies is the communication platform. In this landscape, we will mainly focus our discussions and analysis on the requirements and challenges pertaining to the design of communication platforms that are specific to IoE.

In order to clarify the requirements for communication technologies, let us first discuss the applications envisioned for

IoE, which can be categorized into monitoring and energy management. Smart metering through Advanced Metering Infrastructure (AMI) is a typical application of monitoring, which remotely collects the electricity consumption status of consumers from electricity meters, namely, the smart meters, and which have communication capabilities (Orlando et al., 2022; Gallardo et al., 2021; Park, et al., 2020; Andreadou et al., 2018). By collecting detailed demand trend data for each consumer, energy supply plans can be adjusted to actual demand, thereby improving the efficiency of the energy system.

By controlling Distributed Energy Resources (DERs[1]) such as Photovoltaic system (PVs), wind power, and on-site power generation and energy storage such as EVs, the system is being considered to function as a Virtual Power Plant (VPP), providing adjustability and avoiding curtailment of renewable energy output.

In VPP, the aggregator controls energy resources and consumer devices on the demand side in an integrated manner. A function called Demand Response balances supply and demand by limiting demand or providing power from energy storage when supply and demand are tight, and shifting demand or storing power in batteries when the generation is excessive and there is oversupply.

The utilization of EVs is an important application of VPP. EVs can play the role of energy storage in the regional grid as connecting to the power system, and help balance and regulate the power supplied to the grid by controlling charging and discharging (Yang, et al., 2020). In particular, when a disaster occurs and the power supply from the power system stops, the power stored in EVs and the power generated by DERs can be used to maintain the power supply in the regional grid. This constitutes an illustrative use case for the proposed resilient IoE concept.

# 3 Utilization of DERs and EVs during emergencies

If the energy stored in EVs can supply power to the regional grid during a power outage due to disaster, damages may be minimized. To solve this issue, Power System Management Situations for Emergency Situations (PSMS-ES) (Ustun et al., 2015) has been proposed, enabling power supply to be maintained by configuring a local emergency microgrid, and by matching supply and demand.

PSMS-ES collects operable parts of the grid, the status of DER, the State of Charge (SoC) of EVs and the demand of energy. The operable parts of the grid are required to set up the emergency microgrid. The status of DER is required to know the availability of power supply, while the SoC of EVs is required to know the availability of power supply and charging. PSMS-ES collects the status through a polling service via the communication network and matches supply and demand according to the priority of the demand side. It is necessary to communicate with each entity, and PSMS-ES assumes that data can be collected through reliable communication links even during emergency. While DERs are mostly geographically fixed, EVs can move to different locations to supply their stored power to the grid. However, communication may not be possible during an emergency due to the destruction of infrastructures such as cellular base stations. In this case, PSMS-ES cannot collect the information required to maintain power supplies by the local emergency microgrid. Therefore, communication technologies adapted to EV mobility will become crucial. To build a resilient IoE system, it appears vital to enhance the resiliency and reliability of these communication systems and to ensure that all connected devices, including those in EVs, can communicate effectively even in disaster cases. Additionally, cybersecurity risks must be considered, as unauthorized and malicious access to EVs or DERs could disrupt emergency power supply and compromise safety. Ensuring secure communication, authentication, and access control is essential to protect these systems from cyber threats, especially during disasters.

# 4 System architecture of resilient IoE

## 4.1 Conventional architecture for IoE

The conventional architecture for IoE, which additionally considers the cyber-physical system and the communication system based on the architecture described in (Shahinzadeh, et al., 2019), is shown in Figure 1.

In the supply side, renewable energy sources such as large-scale PVs, wind farms, and hydroelectric generation are connected to the grid, and supply energy to distribution side through transmission lines and substations. Battery Energy Storage System (BESS) stores surplus power, which supports the stability of the power supply by releasing stored power in smart homes are connected to the distribution grid. DERs such as PVs are also connected to the distribution line. EVs can be charged and discharged through charging stations. Each system is connected to the network using various communication technologies such as NTN, Wi-Fi, and Cellular to create CPS. Transmission System Operator (TSO)s, Distribution System Operator (DSO)s, aggregators and the demand side cooperate in cyberspace and reflect this in physical space control. Hence, future IoE will utilize collected data from demand and supply sides, and will be optimally operated by CPS.

## 4.2 Architecture of IoE for emergency case

As shown in Figure 2, a Resilient IoE enables to provide energy as long as possible, without shutting down the entire system, even in the event of failures in emergency cases. Let's assume that the power supply from the generator connected to the transmission system is disrupted due to disconnection from the transmission system to the distribution system or below. Conventionally, when power supply from the transmission system is interrupted, the distribution system is also without power supply, resulting in a power outage. However, by configuring a microgrid on the demand side and providing VPP functions during a disaster, it is possible to maintain power supply by using the energy stored in DERs such as PV and smart homes, and EVs. Therefore, the proposed resilient IoE system significantly improves existing IoE systems by enhancing the ability to maintain power supplies during emergencies. To realize this, system coordination becomes paramount, by collecting information on the distribution system, DERs, and demand to quickly grasp and comprehend the situation at hand, during emergency. The newly

1 IEEE2030.11 DOI: 10.1109/IEEESTD.2021.9447316.

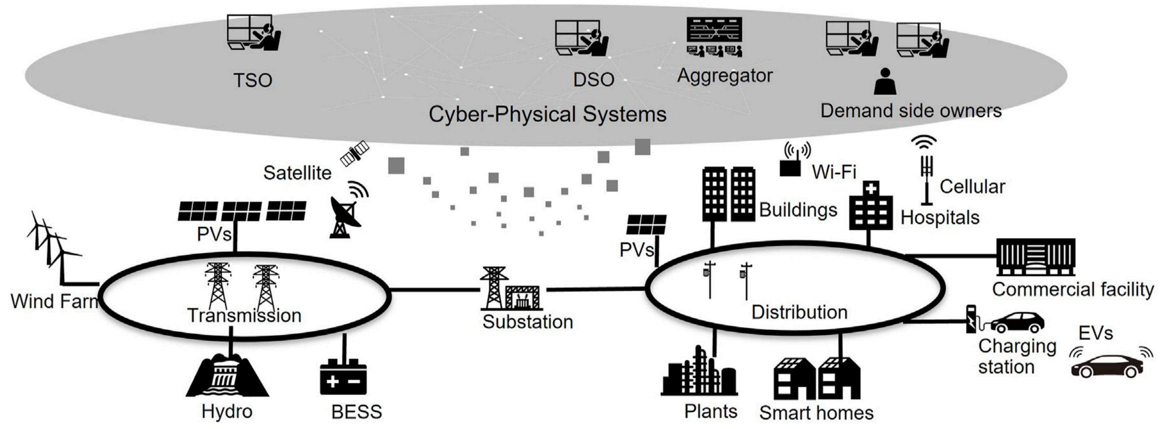


FIGURE 1
Conventional architecture for IoE.

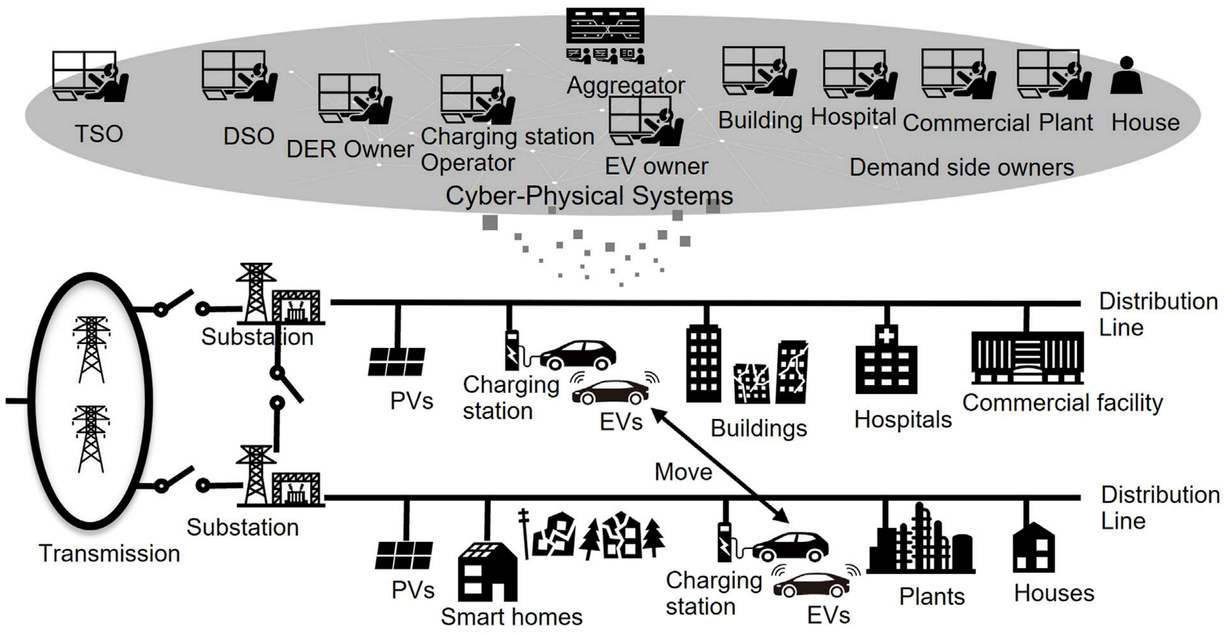


FIGURE 2
Architecture of Resilient IoE for emergency cases.

proposed system architecture and information flow are also required to clarify the behavior of the system in the event of a disaster. The role and importance of system coordination in emergency cases is discussed in 4.3. and the system architecture and information flow are discussed in 4.4.

## 4.3 The role and importance of system coordination in emergency cases

### 4.3.1 Case without system coordination

When a disaster occurs and power supply from the transmission system is disrupted, even if DERs connected to the distribution grid are available and able to generate power, they cannot supply power through the grid without coordination among DSOs. Namely, this may cause oversupply from DERs exceeding demand, thereby leading to power outages due to supply-demand imbalance. EVs are also capable of supplying stored power as long as they can travel to areas suitable for connecting to the grid, but it is difficult for EV owners or charging station operators to be aware of actual power supply demands and their required locations. Therefore, current EVs are in general unable to supply their stored power.

### 4.3.2 Case where system coordination is enabled

In this case, even if power supply from the transmission system is disrupted, it can be maintained through system coordination

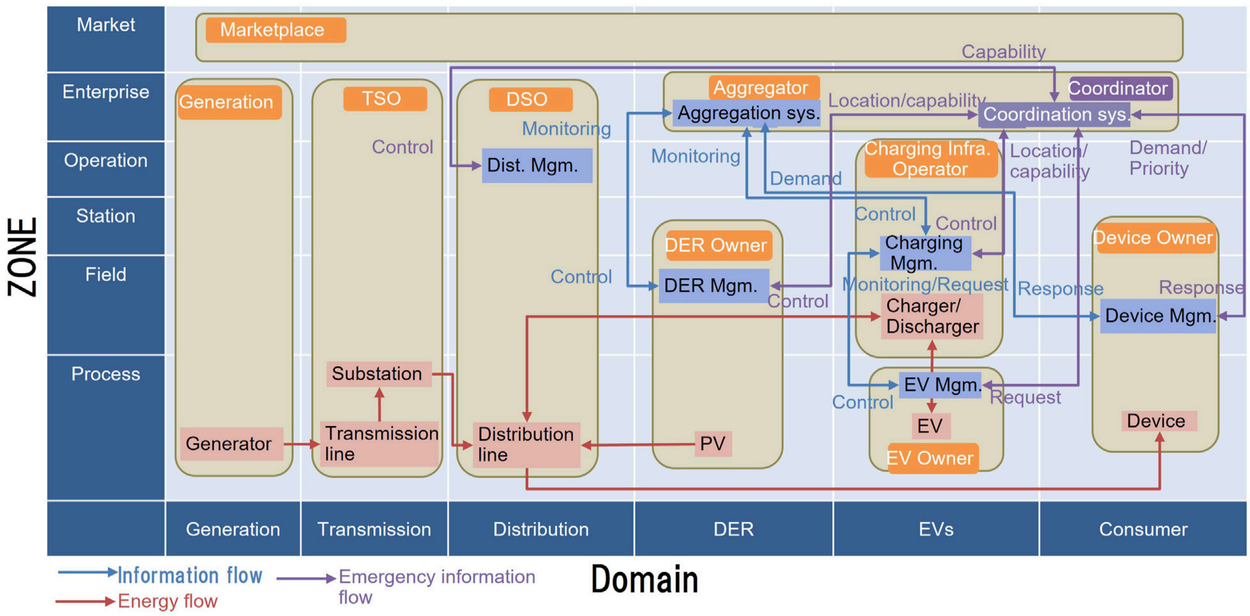


FIGURE 3
Domain-Zone SGAM of IoE considering disaster response.

between distribution system, DERs, EVs and the demand side. By collecting information on power demand, location and priority on the demand side and matching it with the amount of available power, power supply can be maintained for a certain period of time according to priority such as PSMS-ES (Ustun et al., 2015). EVs will also be required to travel to provide power in areas of shortage, or to charge surplus power from the grid in areas of power excess. In order to achieve this, it is important for each system to cooperate and to share information on their capabilities and demands. Moreover, given the difficulty to predict damage to each system in advance, it appears necessary to share information after a disaster has occurred. Therefore, the communication platform for sharing information during an emergency must be resilient.

## 4.4 Smart Grid Architecture Model (SGAM) for resilient IoE

The architectural model of the smart grid is standardized in the Smart Grid Architecture Model (SGAM) (CEN-CENELEC-ETSI Smart Grid Coordination Group Smart, 2024). Resilient IoE model of domain-zone considering system cooperation is described in SGAM as shown in Figure 3.

The Domain was classified as Generation, T&D, DER, EVs, and Consumer. Zones are classified as Market, Enterprise, Operation, Station, Field, and Process, according to the definition of SGAM. Under normal circumstances, electricity generated by the generator is supplied to the demand side through transmission line, substations, and distribution line. On the demand side, monitoring data of PV, EV, and demand devices are collected by the aggregator, and they cooperate by sending control instructions to each device to balance supply and demand.

In the event of a disaster, a stakeholder with the role of coordinator of a microgrid is needed, e.g., the aggregator in Figure 3 can play this role. The coordinator obtains the capability of distribution system, the location and supply capacity of DERs and EVs, the energy demand from the demand side and mediates, then sends a request to each stakeholder.

For system coordination, the communication system is paramount for data collection and information sharing. Messages required for system cooperation are described by the Interoperability layer, shown for Resilient IoE for disaster recovery in Figure 4.

Normally, stakeholders operate their own systems for their specific purposes. TSOs and DSOs provide supply and demand balancing. DER owners supply energy according to their generating capacity. EV owners contract with operators to use their charging and discharging services. On the demand side, plants, buildings, and smart homes optimize energy consumption according to their respective FEMS/BEMS/HEMS[2] functions. The emergency information flow for disasters shown in Figures 3, 4 is performed. In the event of an emergency situation or a disaster, the requirements in terms of communications among the different entities are analyzed in the following section. In Figure 4, communications within each system is described at a lower level than the Information Layer. The selection of communication protocols and communication media depends on each system, and while some communication protocols may be standardized, others are not. It is hence necessary to select and implement each

2 FEMS: Factory Energy Management System, BEMS: Building Energy Management System, HEMS: Home Energy Management System.

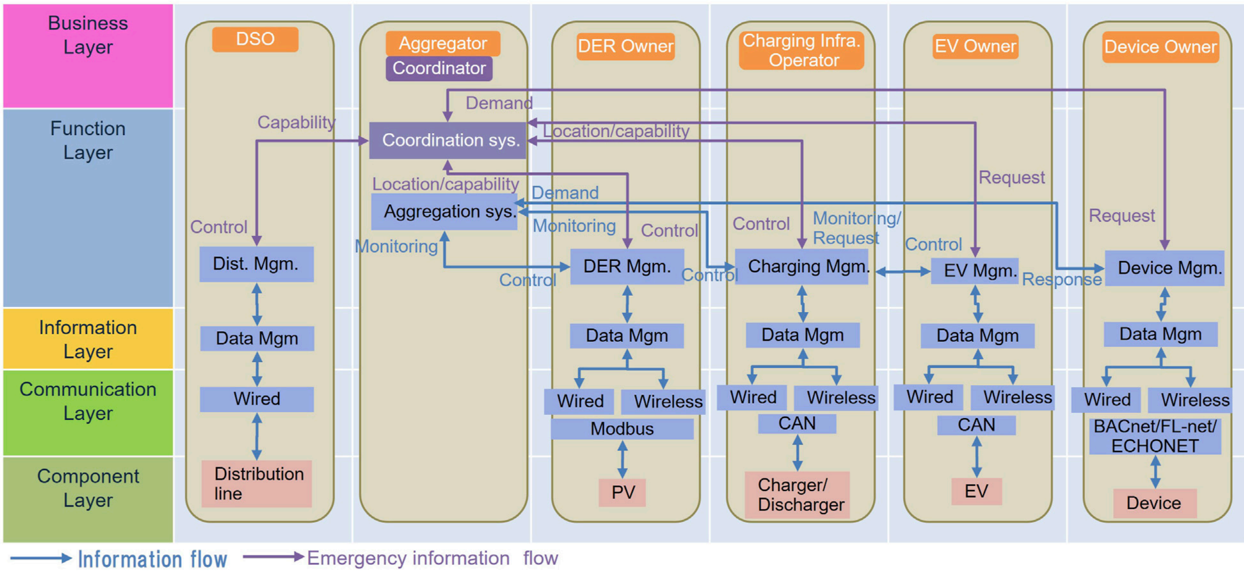


FIGURE 4
Interoperability layer SGAM of IoE considering disaster response.

| | Scalability | Resiliency | Data rate | Coverage | Energy efficiency | Low Latency |
|---|---|---|---|---|---|---|
| DSO | L | H | M–H | L | L | M |
| DERs | H | H | L | H | L | M-H |
| Charger/EVs | H | H | L – H | H | L | M-H |
| Demand Device | H | L – H | L – H | H | M | L – H |

FIGURE 5
Communication requirements for Resilient IoE.

communication technology appropriately, according to the specific requirements of each system as described next.

# 5 Requirements of communication system for resilient IoE

The requirements for communication systems are shown in Figure 5, and discussed based on Figure 4 in terms of scalability, resiliency, data rate, coverage, energy efficiency and latency. The higher level requirements are labeled "H" and the lower level requirements are labeled "L". As detailed, those whose priorities depend on applications or devices are labeled L-H.

## 5.1 Communication requirements between TSO/DSO and coordinator

When the coordinator detects a disaster, the coordinator collects information from each system, which also assess their damage status. Generally, T&D systems monitor their own status by SCADA (Supervisory Control And Data Acquisition) system (Pinzón, et al., 2020). Dedicated communication systems are operated and maintained for T&D operations based on optical fiber, fixed radio, metal, and power line communication according to operational requirements. T&D is a large-scale system, hence it is also important to consider improving the disaster resistance of dedicated communication methods. While it is crucial to strengthen the resilience of individual systems, we hereby focus more on the resilience of the entire IoE system itself.

TSO/DSO and the coordinator communicate with each other at the Function Layer and Business Layer, so enterprise communication services are generally used through wired internet communication. Despite covering a wide-area and being large-scale, the number of TSO/DSO entities is not expected to be high. It is assumed that communication may be disabled due to power outage for the facilities where the systems are located. Therefore, it is necessary to back up power to facilities with batteries, as well as alternative communication lines. The data rate from the TSO/DSO should be high as the information includes the status of large-scale T&D systems. Coverage area is predetermined considering the physical location of servers. As the power consumed by communications is small compared to the power consumed to run the server, reducing communication power consumption would make little contribution, as compared to energy savings in servers. Moreover, high latency can lead to delays in starting the power supply, but limited delay is acceptable as this would not immediately lead to an imbalance between supply and demand, nor system shutdowns. Hence, communication links between coordinator and TSO/DSO must be resilient to power failures and cope with extremely high data rates.

## 5.2 Communication requirements between DERs and coordinator

The coordinator collects information of power generation capabilities from DERs and sends requests to supply. DERs may be scattered over a wide area or located in rural areas. Considering rooftop PVs of smart homes, the number of DERs is large. Since DERs will be key to power supply, it will be very important to be able to monitor and control them. High throughput may not be necessary, but minimum required throughput should be provided. Once the power system goes down, the power supply to DER's communication system may also be disrupted, making it impossible to monitor the situation. Therefore, it is necessary to back up power for the communication system with storage batteries until the DER starts supplying power. High latency in controlling large distributed power supplies can lead to imbalances in supply and demand, resulting in power outages, therefore low latency is required. Hence, communication links between coordinator and DERs must have wide area coverage, not only in urban but also rural areas, be resilient to power outages, scalable and with low latency for control.

## 5.3 Communication requirements between Chargers/EVs and coordinator

Charging stations and EVs may be located in outdoor, indoor or underground parking lots, as well as in multi-storey parking lots. While wired or cellular technologies are cost-effective for normal situations, power outages can disrupt both networks. As stations are crucial for using EV-stored power, the communication medium for EVs must be wireless as mobility is required. When a large number of EVs detect a disaster and simultaneously upload their sensed data to the coordinator, this may result into bursty communications. The required data rate is thus high, especially in the uplink, as EVs may transmit sensed images using their cameras, which is very useful to understand the surrounding situation and navigating to destination. EVs may need to provide power after moving to the area guided by the coordinator. It is hence necessary to have a wireless system that can withstand such bursty transmissions. Meanwhile, energy efficiency is not as important for these communications because EVs are expected to provide power. When EVs supply power, they should be controlled with low latency to maintain balance between supply and demand. Hence, communication links between coordinator and chargers/EVs must be able to cover various locations, scalable to a large number of chargers/EVs, resilient to system failures of the cellular network, and to maintain low latency for control.

## 5.4 Communication requirements between demand device and coordinator

Finally, BEMS and FEMS are enterprise systems, utilizing internet communication services through wired or cellular networks. Critical facilities like hospitals often have battery storage or private power generation, providing temporary power. The situation in the facility can be monitored with this temporary power supply, but the systems depend on infrastructure for external communications, as with the coordinator. For such critical facilities, communication resiliency is of paramount importance. In addition, the number of homes managed by HEMS is large, so the system must be able to handle bursty transmissions. Latency requirements depend on the demand volume of the device. If the device has a high demand volume, it needs to be controllable with low latency due to its high impact on the grid. Hence, communication links between the coordinator and important facilities must firstly be resilient to system failures of standard communication systems, while communications between the coordinator and other demand side systems must be scalable to a large number of systems.

No single communication technology can meet all the requirements mentioned here, and there are trade-offs associated with the features of each technology. The required properties and trade-offs of wireless technologies according to the requirements of resilient IoE are discussed in 6.1.

We next illustrate the requirements discussed above through a simple use case scenario.

## 5.5 Use case scenario of real world disaster and related communication requirements

When an earthquake hits a residential area and causes widespread damage to the existing infrastructure including the power grid, the resilient IoE system immediately begins to assess the situation, such as infrastructure damage, DER capabilities, consumer demands, and configures the microgrid to resume energy supply according to the information flow described in Figure 4. The coordinator detects the disaster through sensors and collects the information from the DSO, DERs, chargers/dischargers, EVs, and consumer devices in the residential area. Therein, the coordinator supervises the matching of supply and demand by utilizing the PV on the smart home and the EV owned by each household to form a microgrid. Then, by sending control messages and requests to each device, the energy supply is resumed.

We conduct a quantitative analysis considering use cases for the basic requirements of communication: scalability, data rate, coverage, and low latency. Let the number of nodes be denoted as $n$, and $n_{DSO}$, $n_{DER}$, $n_{EV}$, $n_{DD}$ represent the number of nodes for DSO, DER, EV, and Demand devices, respectively. For scalability, we consider the Residential area, which is expected to have the highest number of nodes. We examine the feeder, which supplies power from the substation to the distribution area, as the unit of analysis. The distribution capacity of one feeder is denoted as $C_d$. Although there are not only residential houses but also commercial facilities and factories in the Residential area, we focus on residential houses as the main demand devices. Assuming that HEMS controls multiple demand devices within a residential house, we assume one node per residential house. The average power consumption per node is denoted as $P_{DD}$ and the design load ratio to the distribution capacity is denoted as $L_c$. Setting $L_c$ to an appropriate value also requires designing by forecasting future demand growth and DER deployment growth, but for sake of simplicity, in this study it is set as a constant (Cong, et al., 2021). In this case, the average number of demand devices per node is as follows:

$$n_{DD} = \frac{L_c C_d}{P_{DD}}$$

Moreover, assuming the penetration rates of PV and EV per household as $L_{DER}$, $L_{EV}$, respectively, $n_{DER}$, $n_{EV}$ are calculated as follows:

$$n_{DER} = L_{DER} n_{DD},$$
$$n_{EV} = L_{EV} n_{DD}.$$

Next, we consider the data rate. According to Figures 3, 4, we denote the data rate required by each entity as $r$ and $r_{DSO}, r_{DER}, r_{EV}$ *and* $r_{DD}$, respectively. For simplicity, assuming that the minimum packet size for uploading and downloading data during a disaster is the same for all entities and denoted as $D_{min}$, and denoting the maximum delay requirement for downloading and uploading as $d_{down}$ and $d_{up}$ respectively, the total minimum required data rate can be estimated as,

$$r = \left( \frac{D_{min}}{d_{up}} + \frac{D_{min}}{d_{down}} \right) n.$$

We then consider coverage. Assuming that the residential plots are square and the length of one side is denoted as $l_{res}$, and the number of branches of the feeder is denoted as $b$ , if the residential buildings are arranged facing each other across a road, the length of one feeder, denoted as $l_{feeder}$ is approximately given as,

$$l_{feeder} = \frac{l_{res} n_{DD}}{2(b+1)}.$$

Considering a specific use case, it can be reasonably be assumed that $C_d$ is equal to 5000 [kW] (Distribution System Operation Standards in Kyushu Electri Power, 2024) and that $P_{DD}$, which is equivalent to the power consumption of a household, is equal to 1.5 [kW], and setting $L_c$ to 60% (Cong, et al., 2021), we obtain

$$n_{DD} = 5000\,[kW] \times \frac{0.6}{1.5\,[kW]} = 2000.$$

Next, we consider $L_{DER}$ and $L_{EV}$. The target PV panel installation rate for new houses in Japan is 60% (Energy Trend, 2021), so we set $L_{DER}$ to 60%. Assuming that the household vehicle ownership rate is 80% (Japan Automobile Manufacturers Association, Inc, 2016) and the EV penetration rate among them varies widely from country to country, but the IEA predicts that 50% (IEA, 2024) of new car sales in 2035 will be EVs. Therefore, the EV penetration rate is assumed here to be 50%. $L_{EV}$ becomes $0.8 \times 0.5 = 0.4$, which is 40%. Therefore:

$$n_{DER} = 0.6 \times 2000 = 1200,$$
$$n_{EV} = 0.4 \times 2000 = 800.$$

As for $D_{min}$, although the protocol is not standardized and the data size cannot be determined in AMI (Orlando et al., 2022; Gallardo et al., 2021; Park, et al., 2020; Andreadou et al., 2018), which is a typical example of residential monitoring, we can assume $D_{min} = 256\ [Bytes]$ as the data size according to these references. The allowable delay times are 200 msec for monitoring and 100 msec for control, according to the previous research (Marzal, et al., 2019). Therefore, we have $d_{up} = 200\ [msec]$ and $d_{down} = 100\ [msec]$ resulting in the following required minimum total data rate,

$$r = \left( \frac{256\,[B]}{0.2\,[sec]} + \frac{256\,[B]}{0.1\,[msec]} \right) n = 3.8n\ [kB/sec].$$

Therefore, $r_{DSO} = 3.8 \times 1 = 3.8\,[kB/sec], r_{DER} = 3.8 \times 1,200 = 4560\ [kB/sec]$, $r_{EV} = 3.8 \times 800 = 3040\ [kB/sec]$ *and* $r_{DD} = 3.8 \times 2000 = 7600\,[kB/sec]$.

For Coverage, since the average area of a detached house in Japan is 267 [$m^2$] (Ministry of Internal Affairs and Communications, 2023), we can assume $l_{res} \cong 15\,[m]$ and according to IEEE 33 bus model (Baran and Wu, 1989) $b = 3$, we have

$$l_{feeder} = \frac{15 \times 2000}{2 \times (3+1)} = 3750\,[m].$$

By contrast, coverage for DSO requires point-to-point communication with specific locations where the management system is deployed. Therefore, the minimum communication range is considered to be the area of a distribution substation. The area of a distribution substation is smaller than that of a transmission substation. The area may vary depending on the country or region, but it is generally considered to be less than a square of several hundred meters on each side. In (Wei, et al., 2023), the authors evaluated a wireless mesh network using an actual distribution substation with 100 m × 100 m. So we can assume quantitative coverage for DSO is $100\,[m]$.

The results of this use case analysis are summarized in Figure 6. In order to meet such requirements, we provide a generalized discussion in terms of future design issues and research challenges for enabling resilient IoE communications, in the following section.

# 6 Open research directions

## 6.1 Applicable wireless communication technologies for resilient IoE

In (Deepak et al., 2019), an overview of post-disaster emergency communication systems is given, where the advantages and disadvantages of applicable communication technologies in terms of LTE, Wi-Fi, IoT, D2D/MANET, UAV, and NTN, are discussed. However, this study is not IoE-specific. By contrast, we summarize in Figure 7 the required properties and trade-offs of wireless technologies according to the requirements of resilient IoE analyzed in the previous section.

| | Scalability[Number of nodes] | Data rate[kB/sec] | Coverage[m] | Latency[msec] |
|---|---|---|---|---|
| DSO | 1 | 3.8 | 100 | 300 |
| DERs | 1200 | 4560 | 3750 | 300 |
| Charger/EVs | 800 | 3040 | 3750 | 300 |
| Demand Device | 2000 | 7600 | 3750 | 300 |

FIGURE 6
Summary of communication requirements in the use case study for a residential area.

| | Scalability | Resiliency | Data rate | Coverage | Energy efficiency | Low Latency |
|---|---|---|---|---|---|---|
| Cellular | H | M | H | H | L | H |
| NTN | H | H | L-H | H | L | M |
| LPWA | H | L – H | L | H | M | L |
| Wi-Fi | L | M | H | L | L | H |
| UAV | L | H | L-H | L | L | L |

FIGURE 7
Required properties of wireless technologies for resilient IoE.

Cellular is scalable as it can accommodate a large number of terminals and provides high data rates and low latency, with a guaranteed coverage within the service area. On the other hand, although measures are taken against power outages, such as the provision of storage batteries in base stations, occurrence of service outages is still unavoidable. Also, energy efficiency is low due to high BS power consumption.

The strengths of Non-terrestrial Networks (NTN), including Satellite and High Altitude Platform Station (HAPS), are coverage and resiliency, and although data rates are limited, some methods providing high throughput are emerging. The technologies used in NTN can be categorized into three types, namely, Satellite broadband, Satellite mobile direct (or Satellite IoT), and HAPS. Satellite broadband is currently in operation and provides coverage over large areas, including rural areas. However, it requires a pre-installed ground station, making it difficult to cover disaster areas where such equipment is not installed. Satellite mobile direct, although not yet in operation, allows cellular devices and IoT terminals to be used as ground terminals without the need for pre-installed ground stations. HAPS, also not commercially deployed yet, allows a dedicated aircraft to fly into the stratosphere to communicate with ground devices. While the communication specification is still under development, it is expected that cellular devices will be able to be used as ground terminals. HAPS is flexible as it may start service whenever an aircraft will be permitted to fly into stratosphere (Jia et al., 2023).

LPWA is a scalable IoT communication system, accommodating numerous terminals with wide coverage and low power consumption, promising high resiliency, however this will depend on the method and system configuration.

Wi-Fi can increase resiliency by configuring mesh networks. A mesh network called Nerve Net has been proposed to improve the resiliency of communication systems (Mau-Luen et al., 2023). In this reference, a mesh network combining Wi-Fi and LoRa is used to improve the resiliency of communication networks during disasters. While Nerve Net is a useful complement to cellular, it is limited to local coverage.

A communication system utilizing UAVs for post-disaster network has also been proposed in (Mau-Luen et al., 2023) and is expected to have high resiliency. However, the number of terminals and the coverage are limited.

The various trade-offs pertaining to the communication technologies above may be summarized as follows: Cellular networks offer high data rates, low latency, and scalability to accommodate numerous terminals, but they have higher power consumption and are vulnerable to power outages. Non-terrestrial Networks (NTN), including Satellite and HAPS, provide extensive coverage and high resiliency, although their data rates are relatively limited, and their technologies are still emerging. LPWA is known for its wide coverage, low power consumption, and ability to handle many terminals, promising high resiliency, but its data rate is not high. Wi-Fi, particularly in mesh networks, increases resiliency, but its coverage is limited to local areas. UAVs offer high resiliency for post-disaster communication networks, but their terminal capacity and coverage are limited.

We next analyze the adequate technologies depending on the different entities of the IoE system.

## 6.2 Challenges for integrating adequate communication technologies

### 6.2.1 Communication technologies between TSO/DSO and coordinator

Resiliency is the most important requirement of communication with TSO/DSO. It is also important to have backup lines for higher resiliency. High data rate is also required for these links. NTNs should meet these requirements, and are also effective as a backup line.

### 6.2.2 Communication technologies between DERs and coordinator

Communications with DERs require highly scalability, resiliency, and wide area coverage, including rural areas. NTNs are effective for such requirements. In addition, considering that data rates may be low, IoT communications such as LPWA may be applicable.

### 6.2.3 Communication technologies between Charger/EVs and coordinator

Communications with charger/EVs also require high scalability, resiliency, and wide coverage including rural areas, hence NTNs are also effective as for DERs. However, supporting mobility and indoor/underground coverage is challenging. LPWA can be applied for low data rate applications. In particular, LR-FHSS (Boquet et al., 2021) can cover a wide area and has a very high scalability in terms of number of terminals. However, it is still a challenge when considering indoor and underground applications, as well as mobility support.

### 6.2.4 Communication technologies between Demand Device and coordinator

The heterogeneity of device features and applications for demand devices will result in a variety of applicable communication technologies. Given the requirements of high scalability, resiliency, and coverage including rural areas, NTN is also the most adequate, and is also effective as a backup line. However, it may be difficult to prepare a backup line in terms of cost effectiveness, so utilizing UAVs may be effective in post-disaster scenarios. High resiliency is especially important for communicating with critical facilities. NTN and LPWA are basically effective, however Demand Devices will need to be covered by UAVs or Wi-Fi/mesh network depending on the situation to ensure resiliency.

## 6.3 HAPS based resilient IoE

From the above discussion, NTN is clearly an adequate technology for every entity of the IoE system. Among NTNs, HAPS is particularly effective in terms of flexibility. It is possible to communicate with HAPS using cellular technology, but not all ground terminals are compatible with it. Gateways should hence be installed flexibly, in order to convert communication media. In addition, it is difficult to provide communication coverage to all ground terminals from the sky, so serving areas inaccessible from the sky is also a challenge. In this case, it would be effective to use UAVs to temporarily extend communication coverage. UAVs with multiple communication media can perform conversion by relaying between HAPS and other communications. Also, for areas where direct communication from HAPS is not possible, UAV relays can be used to extend the coverage area. Figure 8 shows the envisioned architecture of a resilient IoE system based on the HAPS platform. The aircraft is equipped with mobile base station functionality and flies over the disaster-stricken area. Communication with the ground station is possible using cellular technology. The UAV performs conversion and relay of communication to non-cellular ground station communication methods such as Wi-Fi. The aircraft is also capable of communicating with a coordinator located in the cloud.

In the use case of HAPS-based resilient IoE, communication with the affected area may be disrupted due to the interruption of power supply to the disaster area or damage to communication infrastructure such as cellular base stations, making it impossible to collect information as shown in Figure 4. When the disruption of communication in the disaster area is detected, HAPS aircrafts are deployed in the sky. Communication with ground devices directly connected by Cellular is restored, enabling state collection. In areas where devices cannot be directly connected by Cellular, UAVs are flown complementarily to increase the number of communicable ground devices. Furthermore, UAVs can establish a multi-hop configuration to expand the communication area and ensure redundancy of communication paths. By enabling ground devices to communicate with coordinators, it becomes possible to assess the power supply capacity of the DER and the demand for power without waiting for the restoration of the normal communication infrastructure, such as the cellular network, and to resume power supply maintaining a balance between supply and demand through supply-demand matching. In addition, power supply will be resumed to ground devices that have not been able to communicate due to power outages and whose status has not been collected, enabling power demand to be collected in stages, thereby expanding the scope of power supply and ensuring appropriate supply to satisfy power demand.

Ensuring the interoperability of wireless media and protocol standardization are also essential. In order to ensure interoperability between HAPS and ground devices, HAPS and UAVs, and between UAVs, if the connection between HAPS and ground devices/UAVs is cellular, it is necessary to enable roaming between carrier operators. Moreover, if a mesh network is to be constructed between UAVs, it is necessary to standardize the wireless media and routing protocols to ensure interoperability. In addition, the protocols shown in Figure 4 must also be standardized in order to construct the Resilient IoE system, and to maintain a balance between supply and demand.

The objective of the IoE system is to maximize the satisfaction of energy demand. It is necessary to consider and resolve both power system issues and communication issues. For the power system, it is required to match the available DER with the demand according to its priority level in order to maximize demand satisfaction, while accounting for the available distribution capacity and system constraints. When communication is restored, there is a possibility of burst communication whereby a large number of devices simultaneously upload information in a short period of time. Hence, some mechanism is needed to control congestion during this burst communication. In addition, communications between ground devices and UAVs, ground devices and HAPS, UAVs and HAPS, and HAPS and the cloud can be highly mobile and subject to dynamic fluctuations, so stable connections cannot be always guaranteed. Therefore, it is important to consider how to deal with intermittent communication. To evaluate this system, a model that incorporates both power system and communication

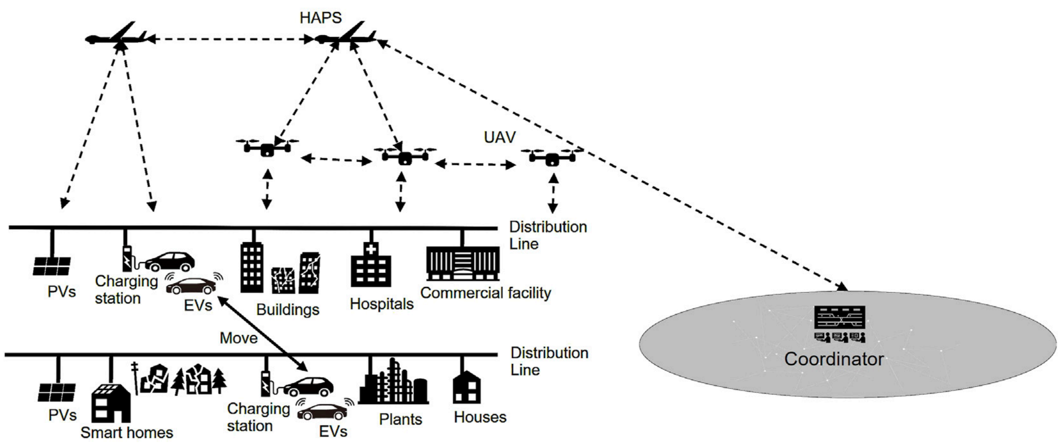


FIGURE 8
HAPS based resilient IoE.

constraints needs to be established. Regarding the power system constraints, conventional optimization algorithms consider large power generators. However, given the accelerated introduction of DERs and microgrids, these existing approaches are no longer applicable. More recently, optimization approaches that integrate the characteristics of DERs and microgrids have been developed (Iqbal et al., 2014; Ahmad Khan et al., 2016), but the impact of disaster occurrences and resiliency features have not been modeled. Hence, there are avenues of open research regarding the joint modeling of power and communication constraints that capture the specificities of resilient edge IoE, as well as the optimization and design of the global power system encompassing these intricate constraints, raising many difficulties.

## 6.4 Challenges for realizing CPS for the IoE system

Obviously, a flawless communication platform cannot be expected during emergencies. Therefore, it is necessary to consider challenges in realizing CPS under the assumption that communications may be disrupted. A CPS is composed of the collection of sensing data, virtual big data analysis with AI, simulation by digital twin (Bazmohammadi et al., 2022; Zhang, et al., 2022b) and feedback of optimized values to the real world. Following the categories, the challenges and their solutions are discussed.

### 6.4.1 Collection of IoE sensing data

Real-time monitoring and control of DERs is essential for maintaining supply-demand balance. For example, PV's power generation status and wind fluctuate over short periods of time, so it is necessary to monitor and forecast power generation in real time. Therefore, the challenges in data collection are to cope with massive and bursty data uploads, as well as missing data and delays. For massive and bursty data uploads, it is required to provide QoS mechanisms to prioritize essential data uploads in real time, and to avoid bursty communications by autonomously shifting the transmission timing. To minimize the impact of missing and delayed data, data completion is useful for monitoring them and for making forecasts. The use cases shown in 5.5 are for residential areas with one distribution substation, and in the event of a real disaster, it will be necessary to cover a larger area. Ultra-massive connectivity, ultra-fast and large capacity, and universal coverage communication systems are required. In 5G, three usage scenarios have been defined and designed: ultra-high speed, ultra-low latency, and ultra-high density connections, but ultra-massive connectivity, ultra-fast and large capacity, and universal coverage communications have not been achieved as discussed. Discussions on Beyond 5G and 6G have begun (Beyond 5G White Paper, 2024), but it is necessary to assume disaster scenarios and combine various wireless communication systems without relying on a specific wireless communication system to achieve ultra-massive connectivity, ultra-fast and large capacity, and universal coverage communication systems during disasters. Furthermore, incorporating edge computing or fog computing can significantly reduce the volume of data traveling through vulnerable networks during disasters. By processing data closer to the source, these computing paradigms help mitigate data congestion and enhance local autonomy. This localized data processing allows for quicker decision-making and reduces the reliance on centralized systems, which may be compromised during emergencies.

### 6.4.2 Big data analysis with AI

The collected sensing data is analyzed for applications such as matching supply-demand and determining the destination and the routes for EVs to charge or discharge. In this case, data integrity and trust of data can be a challenge. In addition, increased computation time consumes a lot of power and increases feedback delay to the real world. While technologies improving data integrity and reliability are vital, enabling power generation forecasts and supply-demand adjustments based on unreliable data is even more crucial. In addition, increasing computation time as well as limited uplink wireless communication resources require minimizing the amount of raw data uploading.

Integrating AI into big data analysis can significantly enhance its optimization. AI can analyze historical energy consumption patterns and weather data to predict future energy demand, even when some collected data is unreliable. This enables real-time matching of supply and demand, minimizing energy waste and optimizing the use of DERs. AI can also manage power supplies during emergencies, ensuring that critical infrastructures receive power even under scarce communication resources. Additionally, AI can detect and predict faults, reducing downtime and improving grid reliability. By employing AI-driven anomaly detection and predictive maintenance, the resilient IoE system can become more resilient and efficient, enhancing the stability and reliability of the power grid.

### 6.4.3 Digital twin

The utilization of digital twin technology allows for the simulation of diverse scenarios and the proactive consideration of measures for disaster preparedness, including system countermeasures and operations. However, the number of scenarios can be enormous, making it unrealistic to prepare for all of them. In addition, if the data that can be collected is limited, there may be a significant discrepancy between the real world and the digital twin. When data collection is limited, it becomes necessary to find ways to minimize the gap between the real power grid situation and its simulation in the digital twin.

### 6.4.4 Feedback with new values

Feedback to the physical space should be made in near real-time with minimal loss, however it is impossible to avoid any data loss nor delay. As Resilient IoE is required to maintain power supply as much as possible even if the communication with the coordinator is disrupted, it is necessary to consider autonomous control architectures and methods, such as autonomous configuration and distributed deployment of coordinators.

## 7 Conclusion

In this article, we have proposed a Resilient IoE system design aimed at withstanding emergency situations such as natural disasters. We have focused on the IoE communication platform, by analyzing the communication requirements, applicable wireless technologies and their shortcomings. We shed light on the challenges and open research avenues towards the integration of future wireless communication technologies, and the realization of CPS for Resilient IoE.

In addition to the discussed open research problems, as future research steps, we also highlight the importance of performance analysis, prototype development and test bed evaluation. For instance, a key step would be the modeling and performance evaluation of HAPS-based resilient IoE to verify the benefit of resilient IoE in real-world disaster scenarios.

## Author contributions

KM: Conceptualization, Writing–original draft, Writing–review and editing. MK: Investigation, Supervision, Writing–review and editing.

## Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported in part by the Grant-in-Aid for Scientific Research Kakenhi 22KK0156 from the Ministry of Education, Science, Sports, and Culture of Japan.

## Conflict of interest

Author KM was employed by Hitachi, Ltd.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

## Publisher's note



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