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An Analysis of Network Performance Requirements for Industrial IoT Services based on 5G Non-Public Network in Smart Energy

Sookhyun Jeon
ICT Testing & Certification Laboratory
TTA
Seongnam-City, Korea
shjeon@tta.or.kr

JaeSeung Song*
Department of Computer and Information Security
Sejong University
Seoul, Korea
jssong@sejong.ac.kr

Younghyun Kim
KEPCO Research Institute
Korea Electric Power Corporation
Daejeon-City, Korea
younghyun.kim@kepco.co.kr

Ji-Myong Kim
ICT Testing & Certification Laboratory
TTA
Seongnam-City, Korea
jmk905@tta.or.kr

***Abstract*—In the overall fifth generation (5G) network market, the 5G Non-Public Network (NPN) market is expected to grow on a large scale. The telecommunications market will transition from being operator-led to being more driven by 5G NPNs. This suggests that enterprises and industries will increasingly opt for their own private networks, providing them greater control and customization over their network operations. By 2035, the 5G NPN market is expected to dominate the traditional operator-led market. This signifies the scale and impact of the digital transformation and Industry 4.0, where advanced networking and connectivity become increasingly critical. In particular, we emphasize the need for 5G NPNs for substations, indicating that these critical infrastructures could greatly benefit from the robust, reliable, and low-latency communication offered by 5G NPN. This can help improve the operational efficiency, safety, and data accuracy of these sites. The use of 5G NPN, coupled with advanced technologies like AI and Digital Twins, can significantly aid the digital transformation of substations and other facilities in the smart energy sector. These technologies can help with real-time monitoring, predictive maintenance, and optimization of these facilities, leading to improved operations and sustainability.**

Keywords*—5G Non-Public Network (NPN), Safety and surveillance industrial IoT service, Multi-access Edge Computing(MEC), Ultra-Reliable Low Latency Communications (URLLC).

I. INTRODUCTION

Mobile communication technology has been developed with an emphasis on improving communication speed for personal mobile communication services such as calls, text messages, and video viewing in land environments. However, 5G mobile communication is developing into a technology that plays a role as a core economic infrastructure enabling the realization of an intelligent information society based on the convergence of Information Communications Technology (ICT) mobile communication technology with other vertical industries. In line with the trend of this era, some high-technology industrial companies require the use of their own customized security policies and local data management system [1]. 5G NPNs are playing a significant role in meeting the specialized communication needs of various industries. The unique features of 5G NPNs make them particularly suited to mission-critical applications that demand high reliability, low latency, and data security. In particular, it is possible to build and operate a proprietary mobile communication infrastructure with a relatively small investment in a specific regional space [2].

Table I shows a comparison between commercial mobile telecommunication and 5G NPN in terms of the service coverage, number of operator, spectrum use, facility investment scale, service provider, service customer, and main purpose of use. In summary, commercial mobile telecommunications networks are designed to provide widespread coverage and support a wide range of customers and use cases. On the other hand, 5G NPNs are designed for specific location and use cases and serve a more limited customer base. The specific requirements and characteristics of each type of network will vary depending on the specific needs of customers and use cases they serve. This table provides a generalized comparison and there may be exceptions or additional complexities in specific scenarios [3].

As 5G NPN has been applied to various industries such as manufacturing, logistics, public utilities, and medical care, it has enabled the emergence of convergence services that realize digitalization and intelligence of information and communication technology and operation technology. For example, by implementing a cyber-physical system that flexibly interlocks all entities such as workers, machines, and products based on 5G NPN in smart factory that represents manufacturing innovation, productivity improvement and quality control optimization can be expected [4]. In the case of smart city, by using 5G NPN as a specialized wireless access network for social infrastructure such as roads, electricity, gas, and water, cities can improve the efficiency of their operations, increase safety and security, and provide a more comfortable living environment for citizens [5].

In this article, we introduce safety and surveillance Industrial IoT services based on 5G NPN in smart energy. In the context of smart energy, 5G NPN can be used to support a range of industrial IoT services related to safety and surveillance, such as real-time monitoring of energy generation and distribution systems, rapid response to energy-related emergencies and asset tracking and condition monitoring to support the deployment of IoT devices.

TABLE I. COMPARISONBLE BETWEEN COMMERCIAL MOBILE TELECOMMUNICATION AND 5G NON-PUBLIC NETWORK

Category	Commercial Mobile Telecommunication	5G Non-Public Network
Service coverage	Wide area, meant for general public access	Restricted to specific location, such as a factory, campus, or business premises
Spectrum use	Licensed spectrum bands	Licensed or unlicensed spectrum bands
Facility investment scale	High; involves extensive infrastructure to provide broad coverage	Comparatively lower; infrastructure is deployed only for a specific area
Service provider	Mobile telecommunication operator	Industry enterprises
Service customer	General public, businesses, other organizations	Specific enterprise, organization or a closed group of users
Main purpose of use	General purpose, catering to a wide variety of use cases, from personal communication to mobile broadband	Specific purpose tailored to the needs of the enterprise or organization, such as Industrial IoT, automation, or high-security communications

In light of the above considerations, this article brings the following contributions:

- A detailed review of the concept, structure, and technical requirements of safety and surveillance Industrial IoT services through 5G NPN, especially presenting a reference model and service scenario for detecting and diagnosing anomalies in susbstation equipment through 5G NPN.
- In-depth analysis of the network requirements for Ultra-Reliable Low-Latency Communication (URLLC) of 5G NPN, which enables quick control in case of any anomaly in the power equipment. It is a communication technology that minimizes data transfer delay and maximizes reliability, necessary for crucial industrial applications like real-time control.

The remainder of the paper is structured as follows: Section II presents basic concept and architecture including important key enabling technologies to support this system. Key use cases and system description are described in Section III. In Section IV, we present and provide the measured results for the network latency through implementation and evaluation. Finally, we draw the conclusion remarks with future works in Section V.

II. BASIC CONCEPT AND ARCHITECTURE

A. *Safety and Surveillance Industrial IoT services using 5G NPN*

Substation premises, which serve as national infrastructure protection facilities, have typically restricted the use of wireless communication technologies such as Wi-Fi and LoRa. However, 5G NPNs are now enabling a safe wireless communication environment within these substations, facilitating the convergence of electrical energy and new ICT. In this paper, we propose the three types of safety and surveillance Industrial IoT services that monitor substation facilities and equipment in real time, based on the 5G NPN. These three types of intelligent substation services include IoT

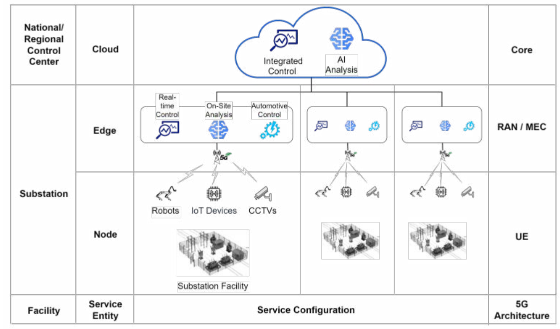

Fig.1. Service concept and configuration of safety and surveillance industrial IoT service based on 5G NPN

preventive diagnosis service, robot-based inspection service and intelligent security assessment service. Through the application of these services, substations can harness the power of 5G and IoT technologies to improve their operations, enhance safety, and drive the digital transformation of the energy sector.

B. *Service Concept and Configuration*

To construct and operate safety and surveillance industrial IoT services within substation premises, three service entities are required: a node within the substation premises, an edge at the boundary of the substation, and a cloud in the national/regional control center, as depicted in Fig.1. From the perspective of the 5G NPN infrastructure, each of these service entities require nodes such as User Equipment (UE), a Radio Access Network (RAN), and a 5G Core. At the node entity, it is necessary to collect data required for the service with robots, IoT data acquisition devices, CCTVs, and so on. This entity also provides functionalities for equipment control during anomaly monitoring. At the edge entity, This entity performs real-time monitoring, on-site analysis of collected data based on AI, and automatic control functions. The edge entity processes data closer to the source, reducing latency and allowing for quicker responses to events. Finally, the cloud entity provides integrated monitoring and AI-based comprehensive analysis capabilities. This entity can handle vast amounts of data and perform complex computations, supporting more advanced AI functionalities and large-scale data storage.

By establishing these entities, the industrial IoT service can leverage the strength of each to create a comprehensive solution that maximizes the benefits of 5G NPN infrastructure. It enables real-time data collection, rapid processing and analysis, and efficient control operations, enhancing the safety and efficiency of substation operations.

C. *Important Key enabling technology*

The inception of the 5G NPN was rooted in the need to utilize high-performance and highly reliable wireless mobile communication technologies for specific-purpose application services. This is characterized by three key characteristics: Enhanced Mobile Broadband (eMBB) for ultra-speed, Ultra-Reliable Low Latency Communications (URLLC) for ultra-low latency and Massive Machine Type Communications (mMTC) for massive connectivity [6]. The following shows a short description of each feature:

- *eMBB: It* focuses on delivering ultra-high data rates, increased capacity, and improved user experiences for

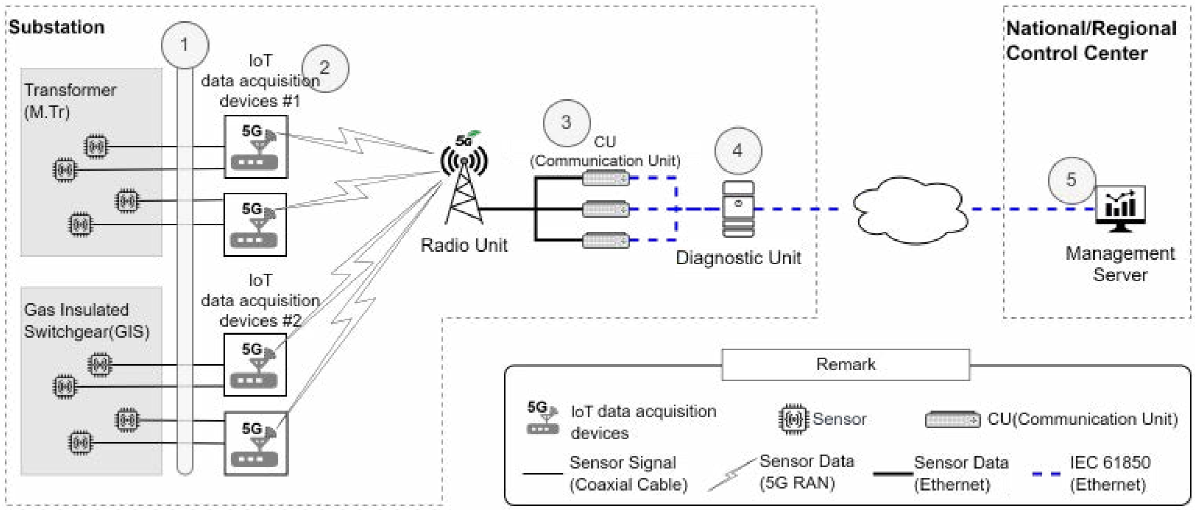

Fig.2. Service overview of IoT preventive diagnosis service based on 5G NPN

applications such as streaming high-definition videos, virtual reality(VR), and augmented reality(AR). It aims to provide significantly faster download and upload speeds compared to previous generations of mobile networks such as 3G and 4G, enabling seamless multimedia experience and data-intensive applications.

- *URLLC:* It is designed to provide extremely low-latency and ultra-high reliability for mission-critical applications that require real-time communication and near-zero latency. This characteristic is essential for application like autonomous driving, industrial automation, remote surgery and public safety systems, where immediate response times and uninterrupted connectivity are crucial.
- *mMTC:* It focuses on enabling massive connectivity for IoT devices. It aims to support a massive number of connected devices with varying data requirements, such as sensors, wearables, smart home devices, and industrial IoT applications. mMTC aims to provide efficient resource utilization, extended battery life for devices, and scalability to accommodate the growing number of IoT connections.

Especially in industrial settings, convergence services based on 5G NPN necessitate the efficient utilization of not only traditional mobile phones and PCs, but also cutting-edge technologies including robots, sensors, high-resolution cameras, and AR/VR terminals [7]. These technologies are essential to effectively leverage the capabilities of these devices and enable innovative applications within industrial environments. In essence, 5G NPN provides the bandwidth, reliability, and connectivity necessary to bring the Industrial Internet of Things (IIoT) to life.

Multi-access Edge Computing (MEC) is a critical component of 5G networks. It extends cloud computing capabilities to the edge of the network, thereby facilitating faster processing and analysis of data closer to the point of collection, which is essential for many latency-sensitive applications. MEC also reduces the load on network resources by minimizing the amount of data that needs to be transported to centralized data centers [8]. The fundamental premise of MEC is a shift in the location of application service servers. Traditionally, these servers were operated in centralized data centers, simply acting as data communication channels over the internet. However, with the advent of 5G MEC, these servers can now be located closer to the edge of the mobile network, nearer to end-user devices [9].

This architectural shift to MEC has two primary benefits. First, it significantly reduces transmission delay, enabling near-real-time processing of application services and data. This is essential for latency-critical applications, such as autonomous vehicles, industrial automation, and remote surgery. Second, it allows for improved user experiences by enabling high-bandwidth, low-latency applications such as video streaming, gaming, and AR/VR. Therefore, by merging edge computing with 5G networks, MEC becomes a powerful enabler for a wide array of converged services and applications, opening new opportunities for innovation across various industries.

From the perspective of 5G NPN, MEC enables to reduce latency, optimize network utilization, enhance data privacy and provide scalability. In conclusion, MEC can significantly enhance the capabilities of a 5G NPN, empowering organizations to unlock the full potential of their networks. By supporting critical applications and improving user experiences, MEC can drive innovation and facilitate digital transformation across various industries.

III. KEY USE CASES AND SYSTEM DESCRIPTION

As mentioned in Section II, safety and surveillance industrial IoT services using 5G NPN consist of IoT preventive diagnosis service, robot-based inspection service and intelligent security assessment service. In this chapter, we present an overview, reference model and procedure of IoT preventive diagnosis service, which aims to detect faults in advance by collecting, processing, and analyzing real-time status data rate and information of power equipment through 5G NPN in the substation.

A. Service Overview

IoT preventive diagnosis service refers to the task of performing preventive diagnosis of substation equipment by

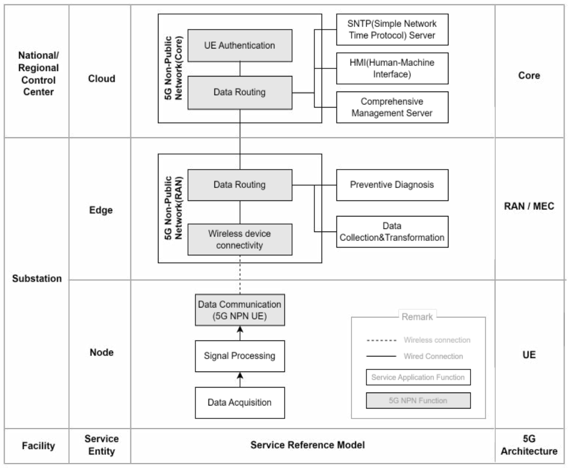

Fig.3. Service reference model of IoT preventive diagnosis service based on 5G NPN

collecting, processing, and analyzing real-time data on potential faults and operational status information that may occur within the main equipment of the substation, such as Main Transformers (M.Tr.) and Gas Insulated Switchgear (GIS). This service utilizes IoT sensors and IoT data acquisition devices, which include 5G UE to detect potential faults in advance. The preventive diagnosis tasks for substation equipment include partial discharge and circuit breaker operation diagnosis for GIS. For M.Tr., the tasks involve partial discharge diagnosis, abnormality detection of the on-load tap changer (OLTC), bushing diagnosis, and dissolved gas analysis.

Fig. 2 shows a generalized scenario of the IoT preventive diagnosis service. The IoT data acquisition device collects data from sensors installed on M.Tr. and GIS. The data collection period can be adjusted by user settings. It digitizes the signals acquired from sensors and transmits them to the Communication Unit (CU) through 5G NPN. It can also report any abnormal situations that occur in the data acquisition device and connected sensors (Steps 1 and 2). The CU converts the collected data from the IoT data acquisition device into the IEC 61850 standard protocol, which is used for substation automation, and sends it to the Diagnostic Unit (Step 3) [9]. The diagnostic unit continuously monitors the operational status of M.Tr. and GIS using diagnostic algorithms to determine the presence of any internal abnormalities. The results of abnormality determination, including abnormal situation event data and important data, are sent to the management server (Step 4). The management server integrates and manages the abnormal situation event data and important data collected from the preventive diagnosis systems operating in all substations (Step 5).

B. Service Refernce Model

As shown in Fig.3, the reference model of the IoT preventive diagnosis service consists of three service entities such as the node, edge, and cloud. The node for IoT preventive diagnosis service is defined as an IoT data acquisition device with three functional elements. These elements include:

- Data acquisition function: It involves capturing the signals measured by the sensors attached equipment of the substation. This function collects the sensor signals and prepares them for further processing.

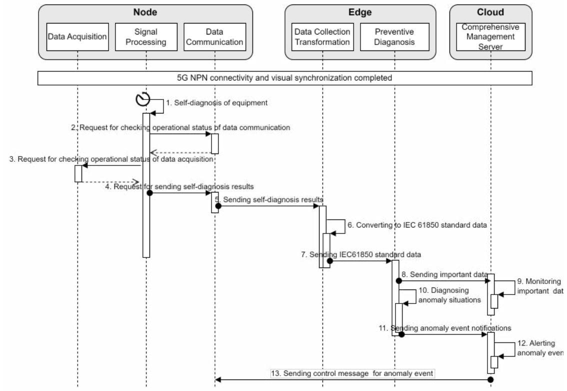

Fig.4. Service Procedure of reporting the equipment status in IoT preventive diagnosis service

- Signal processing function: It processes the acquired sensor signals and converts them into digital data.
- Data communication function: Using the 5G NPN UE installed in the node, this function transmits the acquired digital data based on the 5G infrastructure. It enables the transfer of the processed data to the comprehensive management server for analysis, storage, or other purposes.

The edge of IoT preventive diagnosis service consists of the 5G NPN Radio Unit (RU), CU and diagnostic unit. There are two functional elements of the edge. The first element is '*Wireless device connectivity*', that ensures data communication without communication dead zones for all IoT data acquisition devices installed within the substation, allowing seamless wireless connectivity in both indoor and outdoor environments. The second element is '*Data routing in 5G NPN RAN*' that includes data collection/ transformation and preventive diagnosis functions. The preventive diagnosis involves transmitting diagnostic results and important equipment data to the HMI and comprehensive management server.

The cloud of IoT preventive diagnosis service consists of 5G NPN Core and comprehensive management server. There are two functional elements of the cloud, UE authentication and Data routing in 5G NPN Core. UE authentication is the process of verifying the identity and legitimacy of UE. It helps protect the network from unauthorized access and ensures secure communication between 5G NPN UE and infrastructure. Data routing in 5G NPN Core includes SNTP server which is used for visual synchronization of IoT data acquisition device, HMI and comprehensive management server. It provides integrated control capabilities, enhancing the efficiency and reliability of the IoT preventive service.

C. Service Procedure

To ensure the stable operation of the IoT preventive diagnosis service, IoT data acquisition devices provide a functionality to periodically report the status of their equipment such as sensors and communication devices to the preventive diagnosis and comprehensive management server. Fig. 4 shows the service procedure of reporting the equipment status in IoT preventive diagnosis service. The signal processing function in the node executes the self-diagnosis of equipment according to a pre-defined interval. It requests in the node for checking operational status of data communication and operational status of data acquisition, and

TABLE II. MEASUREMENT RESULTS OF LATENCY IN IOT PREVENTIVE DIAGNOSIS SERVICE

RU #	Measurement Results		
	RSRP(dBm)	***SINR(dB)***	***RTT(ms)***
1	-62.93	33.50	8.9
2	-62.92	33.51	9.2
3	-62.85	33.52	9.0
4	-62.93	33.50	9.2
5	-62.85	33.50	8.8
6	-62.84	33.53	9.0
7	-62.95	33.48	10.2
8	-62.99	33.49	8.9

sends self-diagnosis results to the data communication function that transmits the self-diagnosis data through 5G NPN infrastructure.

The data collection and transformation function in the edge coverts the received self-check result data into IEC 61850 standard data and delivers the converted IEC 61850 standard data to the preventive diagnosis function. It transmits the received IEC 61850 data to the HMI and comprehensive management server in case of important data. With this important data, the comprehensive management server function in the cloud performs the received important data on the real-time monitoring.

The preventive diagnosis function in the edge executes the preventive diagnosis algorithm using the received IEC 61850 standard data and related data as input, performing anomaly detection for the substation equipment. After that, it notifies the detected anomalies to the comprehensive management server. The comprehensive management server function in the cloud generates alarms corresponding to the received anomaly data with HMI function. Finally, it transmits the control message to the data communication in the node in order to deal with the anomaly event.

IV. IMPLEMENTATION AND EVALUATION

The IoT preventive diagnosis service emphasizes the importance of a comprehensive management server to swiftly detect and control equipment during abnormal situations in substations. In particular, by leveraging 5G NPN and MEC technology, latency can be minimized across the UE, RU, MEC server and comprehensive management server. This allows for immediate response services if abnormal situations are detected. A key part of this approach involves ensuring that the network meets low latency and minimal packet loss requirements for both upstream and downstream traffic. This involves conducting tests under specific conditions, with results indicating whether or not the network meets the Key Performance Index (KPI) target.

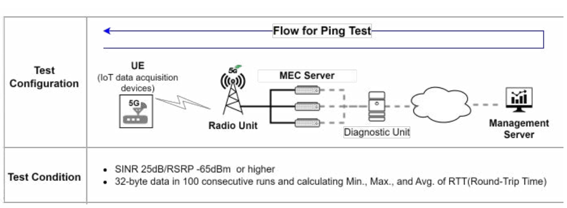

Fig.5 Test configuration and condition for the requirements of low latency in 5G NPN

The testing setup and conditions, as depicted in Fig 5, involve selecting an area with strong signal strength and good quality for fixed point measurement. This is determined based on a Signal-to-Interference-plus-Noise Ratio (SINR) of at least 25dB and a Reference Signal Received Power (RSRP) of -65dBm or higher. All experiments were performed using the Diagnostic Monitoring (DM) tool with DM License Key and GPS antenna, which is used for collecting, analyzing, and visualizing data from mobile networks to assess their performance, troubleshoot issues, and optimize their configuration. This tool supports 5G chipsets from Qualcomm, Samsung, MediaTek and Hisilicon. In the test, 32-byte data is sent in 100 consecutive runs from the User Equipment (UE), and the round-trip time (RTT) for each run is recorded. The minimum, maximum, and average RTT should be then calculated to verify the latency. Latency was measured across eight indoor RUs, with the tests focusing solely on the network-level delay instead of service-level delay that includes the operational systems of the service. This means that the scenario where multiple UEs perform simultaneous PING tests was not considered. The network requirement's initial KPI target was set at below 16ms. However, test results showed a measured latency that ranged between 8 to 10ms depending on the RUs, indicating successful achievement of the latency KPI. These results highlight the potential of leveraging 5G NPN and MEC technologies to achieve low-latency response times in IoT preventive diagnosis services, thereby enabling swift detection and control of equipment during abnormal situations in substations.

V. CONCLUSION

In this article, we have conducted an analysis of the appropriate network architecture and design required to facilitate safety and surveillance Industrial IoT services within the smart energy sector. This is a key consideration for maximizing the effectiveness of 5G NPNs, enabling businesses to boost their safety protocols and operational efficiency. In addition to these aspects, we aim to continue our research and analysis of network requirements, such as communication quality, coverage, and throughput, necessary for the effective support of this service by 5G NPN. This research will provide a beneficial reference for future service model deployments.

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