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Smart Multi-mode Networking Architecture Using NB-IoT and LoRa with Bi-direction Communication Function for Remote Monitoring Applications

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Keywords：**IoT, NB-IoT, LoRa, Multi-mode communication**

ABSTRACT

Wired communication is characterized by high reliability and stability; however, it is difficult to string and has a limited placement area in IoT devices. Wireless communications are characterized by high deployment flexibility; however, their transmission performance is easily affected by weather conditions, electromagnetic waves, obstacles, and other factors.

To maintain the transmission advantages of the above two and resolve the signal instability or interruption that often occurs when using single-mode communication transmission, this study proposes a smart multi-mode networking architecture using NB-IoT and LoRa with a bi-directional communication function. Multi-mode communication nodes (MMCN) can intelligently and automatically switch to different wireless communications (such as 4G, NB-IoT, or LoRa), according to the current transmission environment. An MMCN can also be used with a multi-hop wireless network (MWN) to transfer data packets between end nodes and relay nodes to increase the transmission distance of the networking architecture.

The MMCN was deployed in experimental environments to explore the relationship between the transmission performance of the MMCN and weather conditions, temperature, deployment locations, and obstacles. The results showed that the packet loss rate could be reduced by 6% during heavy rain, and the radius of the transmission range beyond the base station signal coverage could be increased by more than 1 km. This indicates that the system is robust and can be used in various applications.

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INTRODUCTION

IoT has been used in a wide range of applications and its output value is expected to increase continuously in the future. The communication technologies commonly used in current networking architectures can be divided into wired and wireless communications. Wired communications are characterized by high reliability and stability, but difficult wiring, and limited placement areas for IoT devices. Wireless communications are characterized by high deployment flexibility and are very suitable for IoT applications; however, their transmission performance is susceptible to weather conditions, electromagnetic waves, obstacles, and other factors.

In this study, we propose a hybrid smart multimode networking architecture using NB-IoT (narrow band – Internet of things) and LoRa (long range) with a bi-directional communication function to maintain the transmission advantages of the above two modes while ensuring the reliability and stability of the transmission. In this architecture, several small embedded devices are used as multi-mode communication nodes (MMCN) with the following characteristics: (1) MMCN automatically switches to 4G, NB-IoT, or LoRa wireless communication mode according to the current transmission environment to reduce packet loss caused by unstable or interrupted transmission signals and build a stable and reliable transmission network architecture. (2) LoRa technology is adopted to implement a multi-hop wireless network (MWN) in this study. The MWN is used to transmit information between the end nodes (EN) and relay nodes (RN) to extend the wireless network connection range and the transmission distance. (3) When the IoT architecture realizes a bi-directional communication function, fixed IP services need to be rented from telecom providers to reduce the downlink transmission needs and the cost of implementing IoT applications.

In this study, we also conducted performance transmission experiments to explore the relationship between the transmission performance of a smart multimode communication networking architecture and weather conditions, air temperature, deployment locations, and obstacles. The results can serve as a reference for introducing this architecture into real industrial applications of IoT.

A. Multi-mode Communication Networking Architecture

Single-mode communication may fail to address all the needs and problems of IoT applications because many networking architectures combine wired and wireless communication to develop dual-mode or multi-mode communication. For example, the networking device proposed by Zhuo (2014) provides Zigbee, Bluetooth, Wi-Fi, and other communication modes that can be selected by users according to different application scenarios. In addition, switching between multiple communication modes is also possible, depending on the purpose or communication environment. One technique uses a low-power wide area network (LPWAN) for general transmission and only long term evolution (LTE) communication for updating the system or uploading data to the cloud (Lu, 2019; Sensor.live Team, 2020). Another method determines the use order of each communication mode according to the signal intensity, center frequency, sensitivity, and other factors in the application environment (Lee, 2008; Chang, 2018).

B. NB-IoT and LoRa Technology

LPWAN is a wireless communication technology with the advantages of low power consumption, long distance, and low cost. It uses a narrow bandwidth for transmission and is suitable for applications where the distance between nodes is relatively long, and the amount of data transmitted is relatively low. Sigfox, LoRaWAN, and NB-IoT are the most commonly used LPWAN technologies (Mekki et al., 2018; Robert et al., 2018; Merritt, 2019; El-Aasser et al., 2021; Jradi et al., 2021).

NB-IoT uses authorized frequency bands for transmission, ensuring higher network transmission quality and data security, and can be deployed directly on existing 2G/3G/4G base stations. Duangsuwan (2018) and Chen et al. (2017) used sensors to collect data and uploaded it via NB-IoT to develop a data-monitoring platform. Because LoRa uses an unlicensed frequency band, users must establish the gateway themselves. However, this provides greater in the topology design of networking architecture nodes. Wang et al. (2018) used LoRa for transmission in alpine areas and vast agricultural environments in the hinterland, which always have weak base station signals.

Besides NB-IoT combined with LoRa, communication networking architectures have also been proposed. For example, Tang et al. proposed a distribution network fault-monitoring system in which signals are collected by child nodes through sensors and transmitted to the master node through LoRa. The master node uploads data to the cloud service platform using NB-IoT (Tang et al., 2019). Zhang et al. (2019) proposed an LPWAN information monitoring system with a bi-directional communication function; however, a fixed IP address from a telecom provider was a prerequisite.

The smart multi-mode networking architecture proposed in this study differs from that in the literature. In the aforementioned literature, NB-IoT and LoRa transmission functions were constructed in the master and child nodes, respectively, which may interrupt transmission when the distance between them is large. A network architecture that achieves upstream and downstream transmission functions with a floating IP is also proposed in this study.

SMART MULTI-MODE NETWORKING ARCHITECTURE

The system architecture used in this study is divided into three layers, as shown in Fig. 1. The functions and key technologies of each layer are described as follows:

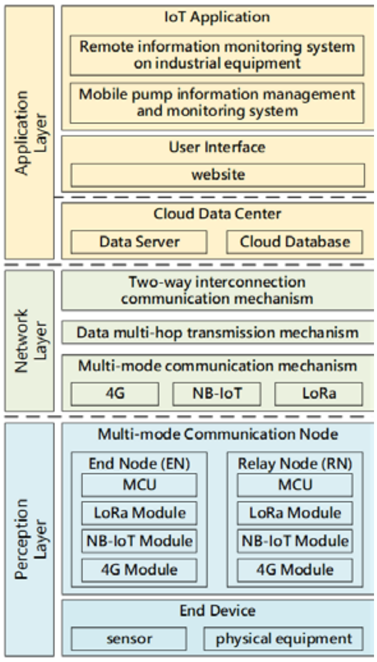

Fig. 1. System diagram of the smart multi-mode communication networking architecture

1. Perception Layer: The MMCN is designed in this layer with a microprocessor control unit (MCU) as the sensing and controlling center and wireless communication modules, such as 4G, NB-IoT, and LoRa modules. It conducts bi-directional data

exchange with other layers through multi-mode communication to collect and upload data from physical equipment and sensors, as well as receive and execute control commands issued by users.

2. Network Layer: Several mechanisms are designed in this layer: (a) Using a smart multimode communication mechanism, the MMCN can automatically switch to different wireless communications to achieve stable transmission. (b) Using a smart relay networking mechanism, an MWN can be established to expand the transmission range of the networking architecture. Finally, (c) The bi-directional communication mechanism can be used to upload the information collected by the perception layer to the application layer, and the control commands issued by the application layer can be sent to the perception layer.
3. Application Layer: In this layer, the data server is designed as a data processing center. It sorts the sensing data and stores them in the cloud database. The cloud database defines the required data types and formats. The data stored in the database are available for IoT applications.

A. Hardware Architecture of Multi-mode Communication Node

The hardware architecture and functional module diagram of the MMCN are shown in Fig. 2. The MMCN is designed in the perception layer and uses a multimode communication module for bi-directional data exchange with other layers. It collects physical equipment and sensor data, and uploads them to the cloud. It can also receive and execute control commands issued by users.

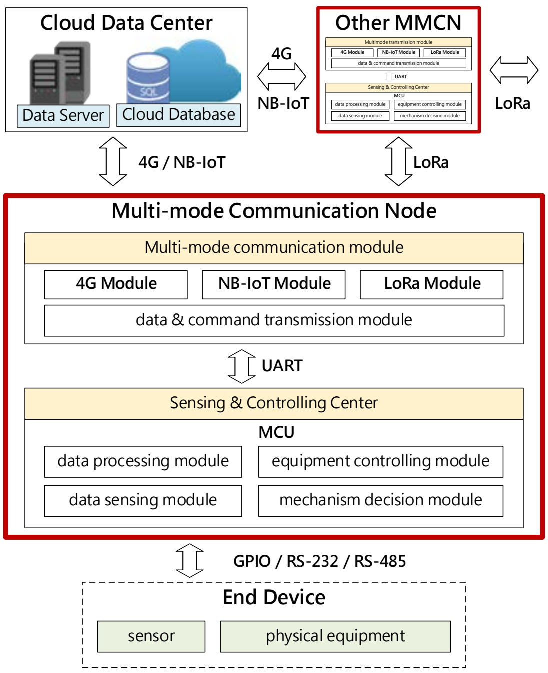

Fig. 2. Hardware architecture and functional module diagram of the MMCN

The MMCN connects with physical equipment through different communication interfaces, such as GPIO, RS-232, RS-485, and other commonly used industrial communication interfaces. It can read the sensing data or operating parameters of the physical equipment as digital or analog data, which can be applied to various and changeable IoT application devices. In addition, data packets can be directly transferred to the cloud data center through 4G or NB-IoT communication in multi-mode transmission modules, or transferred to other nodes via LoRa communication and uploaded to the cloud data center indirectly.

The MMCN studied here includes the following functional modules:

1. Data sensing module: collects the sensing data and data of the physical equipment.
2. Data processing module: filters and processes sensor data, adds Node ID, and forms data packets.
3. Transmission mechanism decision module: automatically switches to 4G, NB-IoT, and LoRa wireless communication according to the current environment for transmission.
4. Bi-directional communication module: Uploads the data packet and receives the control command code issued by the user.
5. Equipment controlling module: Interprets the control command code and issues control commands to physical equipment.

B. Software Architecture of Multi-mode Communication Node

1) Design of data packet

The data-processing module forms a data packet that is subsequently uploaded using the communication module. The data packet is divided into node ID and sensing data. The Node ID is formed from the MAC Address (Media Access Control Address) of the Raspberry Pi hardware. Data sensing is the main component of the data packet. It consists of real-time data collected by the data sensing module, such as oil pressure, voltage, and rotation speed.

2) Smart multi-mode communication mechanism

In this study, a smart multimode communication networking architecture is proposed to avoid signals that are often unstable or disconnected during data transmission. Multiple modes of communication are possible in this networking architecture, including the 4G, NB-IoT, and LoRa. It can intelligently and automatically switch to the current optimal signal-transmission mode to enhance the transmission performance of the networking architecture. A schematic of transmission using the smart multimode communication networking architecture is presented in Fig. 3.

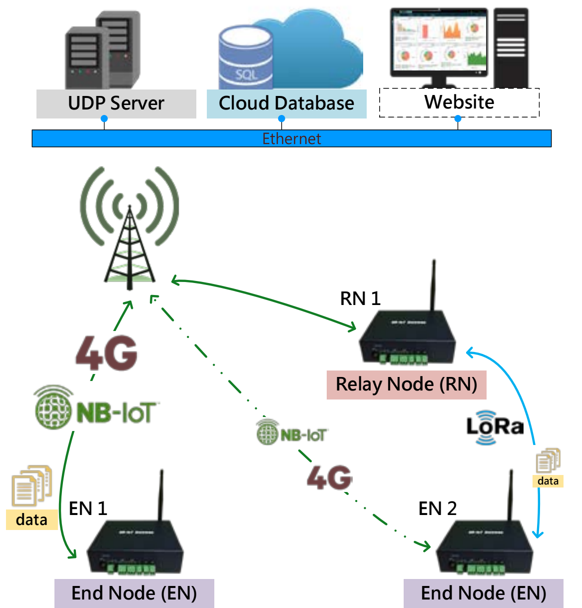

Fig. 3. Schematic of transmission using the smart multi-mode communication networking architecture

The operational process of the MMCN based on the data returned by the 4G, NB-IoT, and LoRa communication modules determines the communication mode with the best signal quality and uploads data packets. If the signal quality of all the wireless communication is inferior, the data packet is stored in the node until the next information sensing and then re-uploaded.

To confirm the strength of the NB-IOT network signal, SNR (Signal-to-Noise Ratio), SINR (Signal-to-Interference plus Noise Ratio), RSRQ (Reference Signal Receiving Quality), RSRP (Reference Signal Receiving Power), CSQ (Cell Signal Quality) are usually used as the references. The CSQ parameter is used as the basis for judging the signal strength of the NB-IOT network in this study. The way to obtain it is to use the RSSI (Received Signal Strength Indication) strength indicator tool, when a test instrument sends a signal to the terminal network device, it will immediately report the received signal in dBM (decibel relative to one milliwatt). The calculation method of CSQ is (CSQ=(the returned dBN+113)/2).

The transmission process of the 4G communication module can be divided into two steps: (Step 1). The MMCN determines the 4G communication quality as good, poor, or abnormal, according to the CSQ value returned by the 4G module. If the 4G signal quality is good, proceed to (Step 2). The MMCN switches to the transmission mode and sets the IP address of the data server. After the MMCN confirms that it is correctly connected to the server, it uploads the data packet using 4G communication and waits for the next transmission.

When the value of CSQ is between 0 and 5, it means that the signal strength is weak and the terminal equipment cannot work normally. The normal range of CSQ value is between 5 and 31. The larger the number, the stronger the signal strength and the terminal device can operate in normal situation. When the CSQ value is 99, it means that the signal is invalid. At this time, it is necessary to check whether the SIM card of the terminal device is installed or not.

The communication quality determination method of the NB-IoT communication module is the same as that of the 4G communication module; however, the transmission process differs slightly.

3) Smart relay networking mechanism

When the MMCN is located far away from the base station, its transmission signal strength decreases with distance or interference from obstacles; hence, data cannot be correctly uploaded by 4G or NB-IoT. The smart-relay networking mechanism in this study is designed to solve this problem, and its transmission scenario is shown in Fig. 4. When an MMCN cannot connect to the Internet, data can first be transferred to another MMCN for data transfer. In this study, the MMCN beyond the coverage of the base station signal is the EN, and the node that receives and transmits data from the end node is the RN.

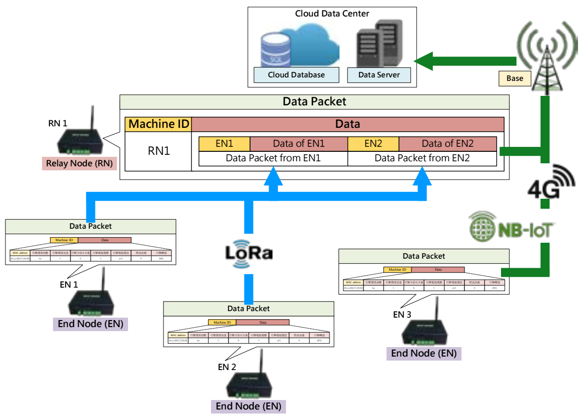

Fig. 4. Schematic of a smart relay networking mechanism

C. *Remote Information Monitoring Platform*

1) Design and planning of data server

The data server receives and processes data packets of the MMCN and transfers them to the cloud database. Thus, the sensing information of the equipment can be stored in the cloud database through different wireless communication modes.

A data server was built using the VS 2017 C# program to receive and process data packets of the MMCN and transfer them to the cloud database. A cloud database is a database that typically runs on a cloud computing platform. There are two common deployment models: Users can run databases independently on the cloud using virtual machine images, or they can purchase access right to database services maintained by cloud database providers. The databases available on cloud, some are SQL (Structured Query Language) based and some are NoSQL data model. The scalability and availability of the database are evaluated by the services provided by the cloud database. The operational process is divided into three steps. Step 1 is to set up the data server, to run the data server, and finally connect it to the SQL cloud database.

The data server developed in this study receives the data packets uploaded by MMCN via the transmission control protocol (TCP), filters and converts the data format, and uploads them to the corresponding SQL data table for storage. Therefore, the MMCN can be regarded as the TCP client when establishing the TCP connection, whereas the data server is the TCP server.

2) Bi-direction communication function

The bi-directional communication function can be used to transmit sensing data or receive downlink control commands. The transmission process is illustrated in Fig. 5. In the past, when realizing bi-directional communication, fixed IP addresses were first obtained. After importing this developed function into the IoT architecture, bi-directional communication was implemented using floating IP.

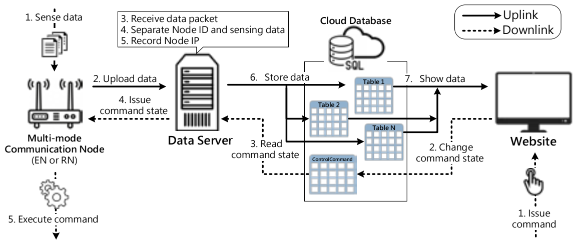

Fig. 5. Flow chart of bi-directional communication function operation

IMPLEMENTATION RESULTS: CASES STUDY

A. *Implementation Results of Smart Multi-mode Networking Architecture*

The MMCN comprised the Raspberry Pi, 4G, NB-IoT, and LoRa modules. The hardware specifications for communication modules are summarized and listed in Table 1. The development environment configuration of the data server included the Windows 10 operating system, Visual Studio2017 development environment, and C# programming language. In this study, a data server was built on a personal computer with a fixed IP. Its primary functions were receiving and processing MMCN data packets and storing them in the cloud database. According to the node ID received, the data server determined whether the node already existed in the smart-networking architecture. In the case of a new node, it automatically generated a field in the cloud database; otherwise, it stored the sensing information in the cloud database. The number or node distribution in the networking architecture was dynamically adjusted using this mechanism to build more flexible IoT applications.

The cloud database was developed using the Windows 10 operating system and Microsoft SQL Server 2018. In this study, a cloud database was built in a server room with a fixed IP to store the data packets uploaded by the MMCN. The data stored in the cloud database could be graphically displayed on a monitoring platform or used as a data source for productivity and yield analysis. The ability to gather and store sensing information is essential for building IoT applications.

Table 1. Hardware specifications for communication modules.

	Chip	Working Frequency	Operating Temp.	Size(mm)
4G Module	E840-TTL-4G05	B1/B3/B5/B8 B38/B39/B40/B41	-40℃~85℃	82×84×24
NB-IoT Module	SIM7000C	B1/B3B5/B8	-40℃~85℃	30.2×65
LoRa Module	SX1262	850~930MHz	-40℃~85℃	82×62×25

Note：B1:2100;B3:1800;B5:850;B8:900;B38:2600;B39:1900;B40:2300;B41:450(MHz)

B. *Portable Pump Information Monitoring System*

The networking architecture proposed in this study was introduced into a portable pump to facilitate data acquisition and multimode bi-directional communication functions, as shown in Fig. 6. The upgraded portable pump has already been deployed throughout Taiwan, including Pingtung and Taichung county.

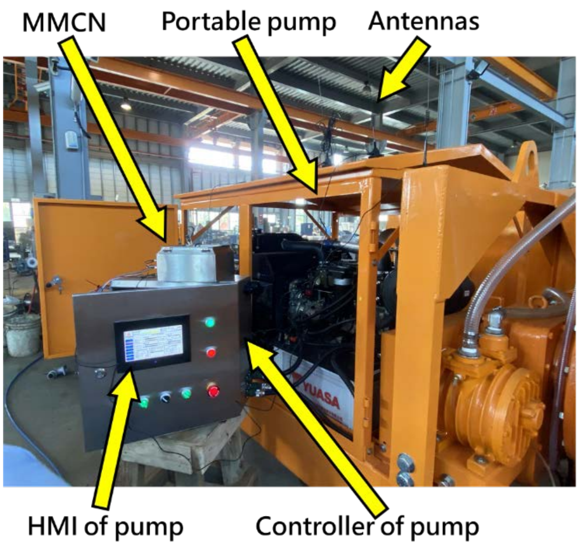

Fig. 6. Introduction of the implementation result of the smart multi-mode networking architecture into a portable pump

In this study, an information management monitoring platform was constructed based on the

ASP.NET web application, as shown in Fig. 7–10. Users can browse the web remotely from their computers, mobile phones, and other mobile devices anytime and anywhere to see the location, number of deployments, and real-time information about the portable pumps in various places.

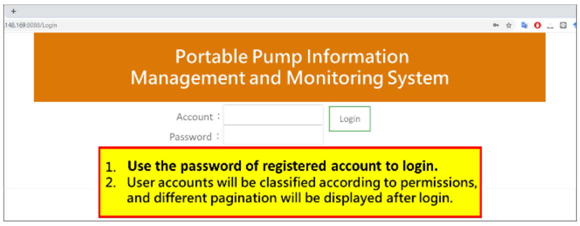

Fig. 7. Login interface of the information management monitoring platform

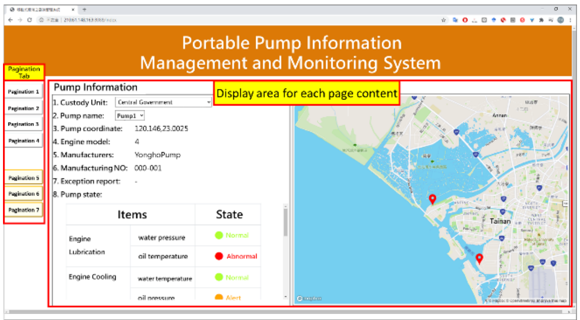

Fig. 8. Main page of the information management monitoring platform

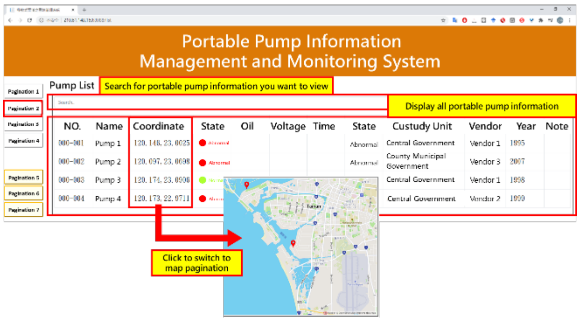

Fig. 9. Equipment list page of the information management monitoring platform

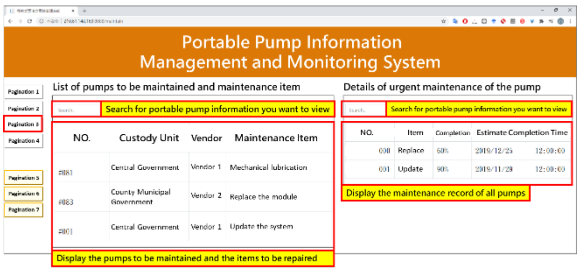

Fig. 10. Maintenance list page of information management monitoring platform

C. *Remote Information Monitoring System for Industrial Equipment*

The results of implementing the remote information monitoring system for industrial equipment are shown in Fig. 11. The system consists of the MMCN, PLC, HMI, small pumping motor, and operation indicator light.

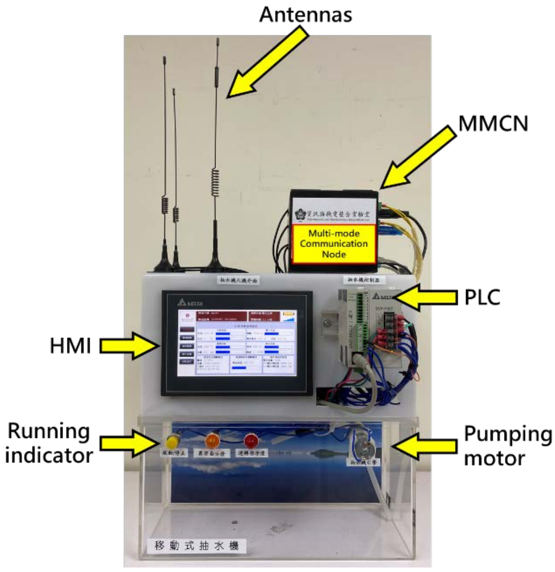

Fig. 11. Results of implementing the remote information monitoring system for industrial control equipment

The operation process first reads the value stored in the PLC using the Modbus industry protocol and then uploads it to the remote information monitoring platform. In addition, the remote control function can be operated through a remote information monitoring platform, and start or stop commands can be issued remotely. After receiving the command, the MMCN drives the PLC and controls the small pumping motor remotely. The architecture in this study can also be used for the remote information monitoring of all equipment that meet industrial specifications.

The remote information monitoring system for industrial control equipment is shown in Fig. 12. It contains the following functions: (1) real-time operation parameters: displays the real-time information of industrial control equipment and the current communication mode used by the MMCN; (2) location of equipment: displays the current location of industrial control equipment on the map; (3) Historical operation curve: presents the historical record of industrial control equipment information with a line diagram; (4) issuing start or stop commands through the remote control button, and controlling industrial control equipment remotely across counties, cities, or factories.

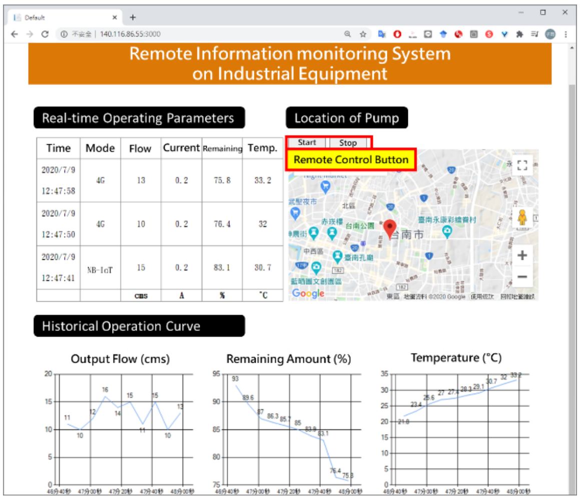

Fig. 12. Remote information monitoring system for industrial equipment

PERFORMANCE COMPARISON AND DISCUSSION

The following experiments were designed and set up to explore the transmission performance of a smart multi-mode networking architecture with a bi-directional communication function under different transmission environments. During the transmission performance test experiment, the LoRa transmission parameters were set to a bandwidth of 915 MHz, transmission power of 1 W, and air data rate 2.4 K bps. In each experiment, the MMCN sent the data packets 100 times. The number of packets received was obtained by calculating the amount of data stored in the database. The packet loss rate (PLR) was calculated by substituting the data into (1).

$$PLR(\%)=\frac{Total\ number-number\ of\ received\ packets}{Total\ number}\ x\ 100\% \tag{1}$$

A. *Discussion of the Influence of Impact Factor on PLR*

In this study, single-mode communication nodes (SMCN) and MMCN were simultaneously used for transmission tests under different weather conditions, temperatures, and deployment locations. The environmental settings and results of each experiment are described below.

1) Influence of weather conditions on PLR:

The transmission performance was tested on sunny, light rain, and heavy rain days.

According to the results presented in Fig. 13, the PLR of the SMCN under different weather conditions exceeds that of the MMCN, and the PLR of the SMCN is 3.67% higher on average. The transmission performance of both SMCN and MMCN were affected by weather conditions. PLR was higher on rainy days than on sunny days and more severe on rainy days. Thus, the adoption of a smart networking architecture effectively improved the reliability and robustness of transmission, which is more suitable for IoT applications where data transmission is required under poor weather conditions.

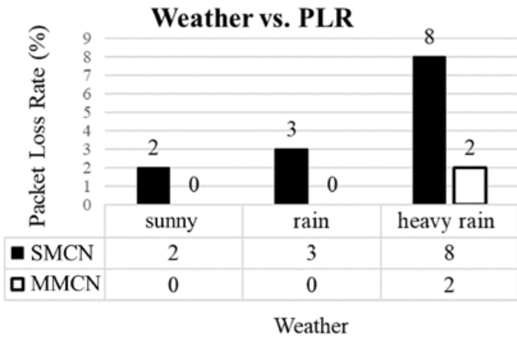

Fig. 13. PLR of SMCN/MMCN under different weather conditions

2) Influence of temperature on PLR:

The transmission performance was tested at the same location at different times of the day, and the temperature and PLR were measured and recorded. As shown in Fig. 14, the PLR of SMCN and MMCN are quite similar at different times and temperatures. The results indicate the absence of significant correlation between the temperature and PLR; therefore, it is inferred that the daily temperature has little influence on the transmission performance. Moreover, MMCN have a very low PLR at different temperatures, which makes them more suitable for IoT applications that require prolonged outdoor exposure.

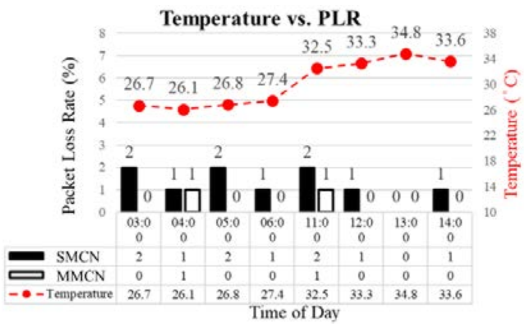

Fig. 14. PLR of SMCN and MMCN at different times and temperatures

3) Influence of deployment locations on PLR:

The networking architecture was deployed in cities with relatively good signals from the base station, as shown in Fig. 15 (A). It was also deployed in suburbs with weak signals from a base station or no base station signals, such as the seaside and hillside. Therefore, we selected the Taijiang National Park R.O.C. and Hsinhua Forest R.O.C. as the experimental scenes for the seaside (Fig. 15 (B)) and hillside (Fig. 15 (C)), respectively.

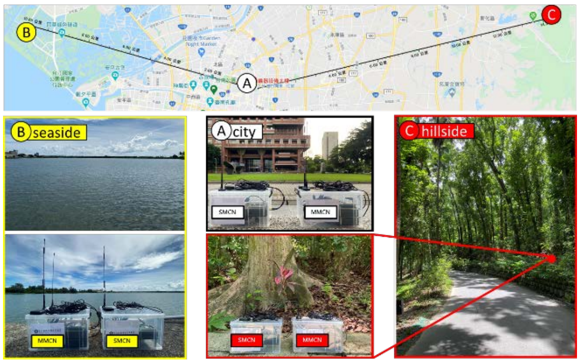

Fig. 15. Schematic of the SMCN and MMCN deployed at different locations

As shown in Fig. 16, the PLR is higher when nodes are deployed in the suburbs than when they are deployed in cities. Moreover, the PLR of the SMCN significantly increased when it was deployed in suburban areas because it relies only on 4G communication for transmission. When the SMCN was deployed in places where the signal of the base station was weak, packet loss occurred easily. However, the MMCN could automatically switch to NB-IoT and LoRa for transmission, in addition to 4G. Therefore, the PLR of MMCN deployed in suburban areas was higher than that in urban areas, but remained below 5%. Therefore, the results show that the MMCN exhibited better transmission performance and was less limited by the deployment location.

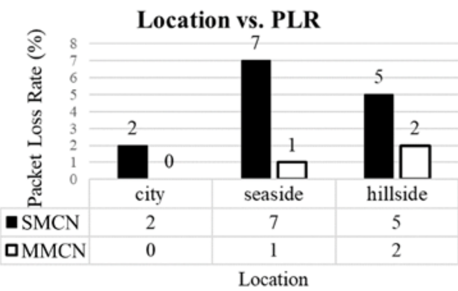

Fig. 16. PLR of SMCN and MMCN in the different deployment location

B. Influence of the Transmission Environment on PLR

The EN and RN were used for the transmission tests. EN was assumed to be located in a place without a base station signal and could only use LoRa to transmit information to the RN, which forwarded the data packet to the cloud data. In this study, the RN that could receive EN message packets was deployed on the top floor (10F) of the Instrument Center, National Cheng Kung University R.O.C. In addition, we explored the effect of a transmission environment with obstacles on the relay distance of the MMCN. The Shangri-La Far Eastern Plaza Hotel Tainan, which comprises 38 floors and has a vertical height of 128 m, is selected as the signal-masking obstacle. The connecting path between the RN deployment location and the obstacle location was considered as the main experimental route. The obstacle was located 1 km from the route. Three locations on this route were randomly selected as the deployment locations for every 300 m range. The final deployment scenario is illustrated in Fig. 17.

Fig. 17. Deployment location of the EN and RN

Fig. 18 indicates that the relay distance in the multimode communication networking architecture is significantly affected by obstacles on the transmission path. The test sites for this experiment were all located in urban areas, where there are more tall buildings, and the transmission environment is more complex, compared with suburban areas. However, it maintained a PLR of less than 30% within a 1 km relay distance. Thus, when an MMCN is deployed in suburban areas, longer relay distances and smaller PLR will be obtained. Therefore, it can be proved that the adoption of a smart multi-mode networking architecture can effectively improve the transmission distance of the networking architecture to extend the application scope to areas without base station signal coverage, which aids the development with more IoT applications.

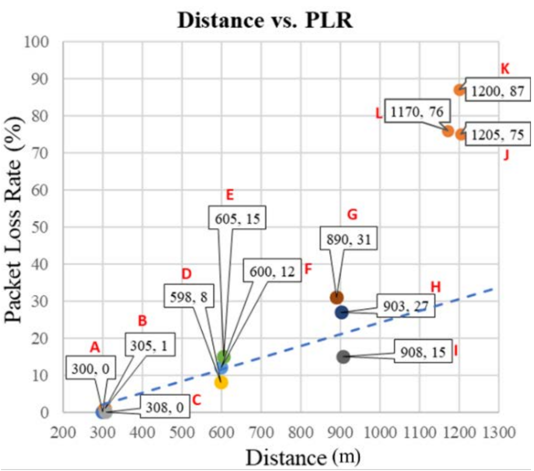

Fig. 18. PLR of EN deployed at different relay distances

CONCLUSIONS

A smart multi-mode networking architecture with a bi-directional communication function was designed and implemented in this study and the following conclusions were drawn: (1) The packet loss caused by transmission signal instability or interruption could be reduced to build a stable and reliable transmission networking architecture. The results showed that the PLR could be reduced by at least 6% during heavy rains. (2) A smart relay mechanism could be designed to resolve the limited transmission range owing to the distribution location of telecom base stations to expand the connection range of the networking architecture. The results showed that the radius of the transmission range beyond the base station signal coverage could be increased by more than 1 km in urban areas. (3) The functions of sensing data and issuing control commands in a relatively low-cost manner, which is suitable for IoT applications with bi-directional information transmission needs, could be achieved. (4) Existing portable pumps could be upgraded to use smart-networking equipment. The portable pump information monitoring system could be implemented with the innovative management mode. (5) The networking architecture could be introduced into industrial control equipment and a bi-directional communication function could be achieved. (6) The results indicated that the transmission performance of the proposed smart multimode networking architecture was affected by the different weather conditions and deployment locations. (7) The relay distance between the EN and RN was affected by the distance between the nodes and obstacles in the transmission path.

In addition to the above applications, the proposed architecture can be introduced into a factory to realize the large-field Industrial Internet of Things. Thus, monitors an entire factory or multiple factories can be monitored, which is both practical and feasible.

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具 NB-IoT 及 LoRa 多模雙向通訊之智慧聯網架構設計與實現

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摘 要

本研究設計與實現多模雙向通訊智慧聯網架構，具智慧多模通訊機制、智慧中繼聯網機制與雙向互聯通訊機制，可在進行傳輸時智慧自動化切換使用 4G、NB-IoT 及 LoRa 無線通訊，解決使用單一通訊傳輸時訊號不穩或中斷的問題；亦可透過多跳無線網路(Multi-Hop Wireless Network, MWN)，讓資訊封包在終端節點與中繼節點間轉送，增長聯網架構傳輸距離；並可以在不向電信商租用固定 IP 服務的情況下，以較低成本實現上傳感測數據及下達控制命令的雙向傳輸功能。

最後，本研究設計於具不同影響因子的實驗環境下進行傳輸性能測試，探討多模雙向通訊智慧聯網架構之傳輸性能與天氣、氣溫、部署地點及障礙物之間的關聯。實驗數據顯示，多模雙向通訊智慧聯網架構在大雨時便可減低 6%封包遺失率，且可以在基地台訊號覆蓋範圍外額外增長半徑 1 公里以上的傳輸範圍。