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# Cellular network-based IIoT architecture for time-critical control tasks of building automation

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ABSTRACT

Industrial Internet of Things (IIoT) adopting emerging cellular networks attracted great attention in various industrial fields, including the building sector. However, the capability of IIoT and the performance of cellular networks when applie for building automation (BA), especially for time-critical control tasks, are not effectively evaluated yet. The potential impacts of network constraints on the control performance also need further investigation for the alternative architecture. These fundamental questions have not been addressed sufficiently yet. This study therefore proposes a cellular network-based IIoT architecture as a newly-proposed and recommendable solution for building automation systems. The architecture consists of smart field-level devices embedded with cellular network-enabled IoT controllers and a configured cellular network. Performance of the latest cellular networks, including 4th generation (4G) and 5th generation (5G) networks, are experimentally tested under different conditions. A typical building time-critical control task is selected to assess the capability of proposed architecture. The results show that the proposed IIoT architecture adopting 4G and 5G networks has good capability for the time-critical control tasks.

## 1. Introduction

As one of the most attractive emerging technologies of Industrial 4.0, IoT (Internet of Things) technologies have already penetrated almost every industrial fields. With rapid applications of IoT technologies, it is estimated that there will be 75.44 billion IoT devices in 2025 [1]. The IoT technologies with the purpose of "connecting everything together" [2], can significantly benefit industrial applications, especially for those with many devices involved, including smart buildings. Meanwhile, the emerging communication technologies, e.g., high speed Wi-Fi, cellular network, with attractive features like high reliability and low latency [3], show great potentials to expand the IoT technologies applications in more time-critical tasks.

### 1.1. Consume IoT and industrial IoT (IIoT)

Since IoT technologies are involved in various application fields with different requirements, IoT can be categorized into two types based on their characteristics, named consumer IoT and industrial IoT (IIoT) [4]. The brief concepts of these two types of IoT are shown in Fig. 1.

Consumer IoT focuses on the human interaction to improve the sensing between human and surrounding environment with machine-to-user communication. The typical features of consumer IoT include monitor, management, on/off control, etc. Such features, with seconds to minutes tolerable delay and low data exchange frequency, do not have strict requirements on network performance. The typical application scenarios of consumer IoT include smart home and smart city [5].

Industrial IoT (IIoT) is a subset of the IoT concept. IIoT focuses on the industrial applications to provide machine-oriented services with massive machine-to-machine connections [6]. The typical features of IIoT include interlocking, supervisor control, and close-loop control. To support such industry-oriented features that involvehigh data exchange frequency, there could be very strict requirements on network performance, e.g., transmission reliability and network delay. The typical application scenarios of IIoT include smart manufacturing and smart logistics [5].

With difference application scenarios, there are significant differences between consumer IoT and IIoT in the network quality

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requirement, network selection, network connection type. For the network quality requirement, consumer IoT does not have strict requirement for the timing and reliability of the network. The main reason is that the applications of consumer IoT typically have low data exchange rate. For example, a smart home air quality monitor used in a study updates every 5 min [7].The update intervals of smart water meters in a smart city case can range from hourly to daily [8]. Thus, there are many options to ensure the delivery in such long data exchange period. By contrast, due to the high data exchange rate of industrial applications, IIoT has very strict network requirement to meet its needs. For example, the interlocking control may require high update frequency such as a time delay below 10–250 ms. Close-loop controls also require high update frequency and an update delay below 10–500 ms [9]. Thus, the network for IIoT should in the level of millisecond with high reliability to ensure the quality of services.

For the network selection, it is more flexible for the consumer IoT networks due to the even less requirement on network performance. Normally, consumer IoT can use ad hoc and mobile network to implement the required functions. By contrast, IIoT has high requirements on timing and network reliability. Currently, most of IIoT applications typically use the fixed and infrastructure-based networks to obtain the higher network performance [5].

For the network connection type, it is different between these two types of IoT owing to the different orientations of communication. Consumer IoT is normally in the form of client-server for human-centered interaction. Its connection focuses on integrating novel and heterogeneous devices into a network in a flexible and user-friendly way. Thus, the number of connections for consumer IoT is not too large. For the IIoT, the aim is to connect all of the field devices for industrial purposes. Thus, the connection is in the form of machine-to-machine orientation. The IIoT focuses on the feasibility of device connection rather than whether its user-friendliness. In the typical scenario of IIoT, e.g., in a factory, the connection density is high, meaning that there are substantial machine-to-machine connections in a network at same time.

### *1.2. Network constraints in the application of IIoT*

To expand the penetration of IIoT in the industrial fields, there are still issues need to be tackled. Such issues are mostly resulted from the network adopted in the tasks of IIoT. The control signals need to be transmitted through the networks that may not be reliable enough, especially for time-critical tasks. Once a network introduced to a control loop, the control process is formed as networked control. In this manner, the network could introduce some constraints, such as packet loss, time-varying transmission period, network schedulability and network-induced delays [10]. Among these constraints, network-introduced delays and packet loss are considered as two of the most significant issues for networked controls [11].

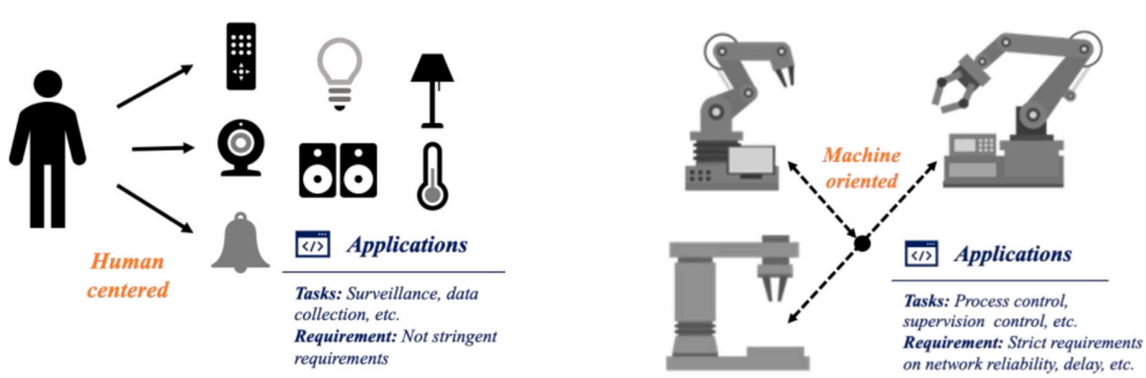
Delays in networked control system can be categorized as three types, including computational delay, network access delay, and transmission delay [12]. The latter two types of delays are regarded as network-introduced delays. These delays are normally caused by the limited data bandwidth, network traffic, and used protocols in the networks [13]. Due to the random and time-varying characteristics, delays may cause the heterogeneous coupling of components or subsystem in control systems, and lead to degradation of system performance or even unstable system operation.

Packet loss is an inevitable phenomenon in the network. It means that the packets, i.e., grouped data, transmitting in the network may loss. The typical reasons causing packet losses mainly include buffer overflow, network traffic congestion, and transmission error resulting from network link failures [14]. The packet loss can be classified as “active packet loss” and “network-introduced packet loss”. For the active packet loss, it is caused by discarding “out-of-dated” packets. When an “out-of-dated” packet is received, the best way is to discard it since the information in the packet is useless for control, and an “updated” packet is already received [12,15]. “Network-introduced packet loss” is caused by network failures, which means that the packet is lost or damaged in the transmission [10]. A study analyzed the impacts of packet loss on the networked control performance [16]. The results show that once the packet loss happened, a large group of packets may be lost continuously at one time. Thus, it is pointed out that packet loss is the most destabilizing reason for the networked control system.

Due to above network constraints, existing studies concluded that currently, the IIoT technologies are typically used to provide knowledge or information about physical systems rather than to directly substitute the traditional applications, especially for the automation applications. In fact, a study pointed out that “IIoT is not related to control applications at the field level, where bounded reaction time must be ensured” [6]. However, the new network communication technologies with lower latency and jitter can increase the range of possible IIoT applications [17].

### *1.3. Current IoT applications in buildings*

The IoT technologies also have more and more penetration in the smart building field. There are many practices using IoT technologies on the aspects of security, indoor environment and energy monitoring and management. For example, for the security management concern, Khairuddin et al. proposed a surveillance system using smart IoT devices to prevent unauthorized access. The smart IoT devices are used to capture and recognizing human faces by a pre-trained artificial intelligent model [18]. For the indoor environment management, Quan et al. proposed an IoT-based indoor environment monitoring system to measure the parameters of indoor environment, including the $CO_2$




A : Consumer IoT B: Industrial IoT

**Fig. 1.** Features of consumer IoT and IIoT.

concentration, temperature, and relative humidity [19]. For the energy management purpose, Elkhoukhi et al. presented a platform combining IoT technologies and machine learning approach for building energy management [20]. In these studies, lots of IoT sensors are used and integrated into the conventional building automation (BA) system. Such IoT sensors can upload the sensing measurements, which are aggregated to the central computer of the BA system, enhancing its management and monitoring functions.

As a basic function of BA system, the control functions, including supervisory control and local control, have limit penetration of IoT technologies. In the limited studies using IoT technologies in building controls, most of them concentrate on the supervisory control. Many of these studies also only use the IoT devices as an additional data source while the control decisions are still made in the central computer of conventional BA system. These studies usually have the objective of enhancing the supervisory control, such as, find a trade-off between electrical price and thermal comfort [21] or between energy consumption and thermal comfort [22].

Only very few studies considered directly use IoT devices to make control decisions. For example, Su et al. proposed a prototype of IoT-based distributed heating, ventilation and air-conditioning (HVAC) system optimized control structure [23]. In this structure, the components of HVAC systems are integrated an embedded IoT controller, which have a network interface to enable the communication of each other. In this manner, each component becomes a smart agent. Thus, the global optimization problem can be done among the smart HVAC devices in the field level locally. This manner makes the implementation of HVAC system optimal control more flexible. Li et al. proposed an enhanced control strategy for building process control implemented in the IoT environment [24]. The results show that the proposed strategy has better control performance and robustness in the IoT environment, and its deployment can fully utilize the capacity of smart devices. Wang et al. proposed a decentralized control structure and optimization methods [25]. In their structure, each smart HVAC component is installed a IoT controller where its mathematical model is written. Those smart components can communicate and collaborate with each other to optimize the operation of the HVAC system using a decentralized algorithm. These studies attempted to improve conventional centralized supervisory control manner of conventional BA systems with IoT technologies, which makes the supervisory control more flexible and effective.

From these studies, it can be observed that the current IoT applications in buildings are very much limited to certain types of applications. First, concerning functionality, the IoT applications in buildings mainly focus on the less- or non-time-critical tasks, such as data collection, monitoring, and less time critical control tasks such as supervisory control. These applications normally have minute or hour update interval, and do not have strict requirements on the network reliabilities. The applications of time-critical tasks in buildings, such as local process control, which is one of the fundamental tasks of BA systems and has a within-second level update interval and high requirements on the network reliabilities, are still rarely investigated. Second, considering the roles in BA systems, the IoT devices are normally used as accessories, playing supplementary roles in building controls. The main objective of their engagement is to improve measurement accessibility while not deeply integrated into the BA systems. As a conclusion, to reap the full benefits of IoT technologies in buildings, it can be expected to use the IoT technologies with proper architecture to provide a brand-new alternative option for the entire BA system and providing full functionality, rather than supplementary roles only. To begin with, it is necessary to deeply investigate the proper IoT architecture and proper networks types for implementation of typical BA functions, especially for the time-critical control tasks. The capacity and performance of IoT devices and networks also need to be seriously evaluated.

### 1.4. Cellular network application in industrial fields

Cellular networks have been widely adopted in many IoT applications today, such as the use of NB-IoT in smart metering [26]. However, some of the typical networks are not suitable for time-critical tasks in IIoT concerning latency and reliability. For example, NB-IoT is normally considered to have a delay of around 10s. It is normally applied to delay-tolerant services [27,28]. To meet the needs of increasing industrial applications, the emerging cellular networks, such as 4G LTE (4th generation with long term evolution) and 5G (5th generation) networks, are among the most attractive communication techniques for the IoT connectivity [29]. According to a published report, there are about 7 billion devices are connected through the cellular networks among the 28 billion Internet-connected devices [30]. These cellular networks can provide wide coverage of connections and high-quality network with low deployment cost and simplicity of management [31].

For industrial applications, there are a few special configurations or enhancements. For example, the private cellular networks or dedicated networks divided from commercial cellular network can be built for a group of IoT devices. The user-equipment-to-user-equipment (UE-to-UE) manner can be provided for directly communication. However, the cellular networks may still face some challenges to meet the strict requirements of latency and reliability for time-critical applications. There are few studies using cellular networks to empowered the industrial processes, showing mixed results of its feasibility. For example, Polunin et al. evaluated the 4G LTE network performance on the robot arm position control of an industrial process [32]. In their study, a private 4G LTE network was built for their industrial processes only. The results show that, even in the situation of high signal transmission power without other network load, the network cannot provide satisfactory performance compared to conventional wired manner. The latency of 4G LTE network can lead to undesired overshoot, oscillations, and even stopping the robot movement. Li et al. used the 5G network to control a gantry crane in a harbor with the edge computing technology [33]. The end-to-end communication manner is used to transmit the control signal. The results show that such communication manner with 5G network and edge computing can effectively reduce the latency and increase the reliability. From these contradicting studies, it can be observed that cellular networks have potentials to support IIoT applications for time-critical tasks but the performance of the cellular networks and their deployment architecture for specific industrial automation applications still needs to be seriously evaluated.

### 1.5. Current network structure in building automation system

The network for building automation system has many critical requirements. The main concerns are low latency and high reliability with low error rate transmission [34]. Currently, most BA systems are of a typical hierarchical structure, which can be divided into three levels typically: management level, automation level, and field level. These three levels form a tree-like structure, as shown in Fig. 2. This BA network structure is heterogeneous in different layers and requires gateways for communications. It can be observed that there are two typical types of networks, i.e., fieldbus and IP-based network. In the field level, the fieldbus deal with the real-time interaction with field-level devices, e.g., direct digital controllers (DDC), while not well support for massive connection and high-throughput data exchange. The sensors and actuators at the field-level have no communication and computation abilities, and thus need to be connected to local controllers via electrical cable through inputs/outputs of DDC or I/O modules. The IP-based network focuses on the system-level functions while not good at time-critical communication [35]. The data is hieratically aggregated to the central server at management level. The server optimizes system operation based on the aggregated data and provides optimized setpoint, which are then sent to the field-level devices hieratically.

The cellular networks can be seen great potentials of applying to the

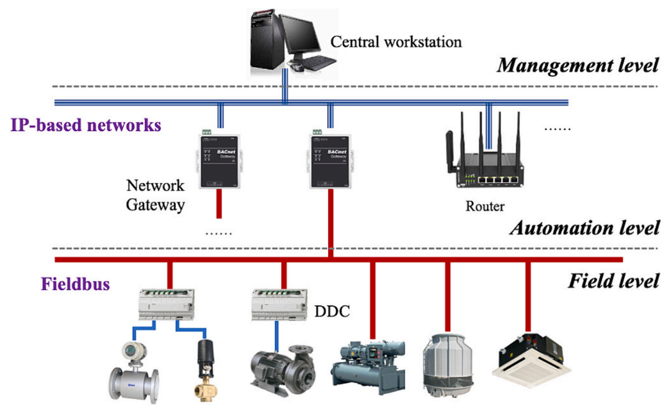



**Fig. 2.** The structure of conventional HVAC building automation system.

future smart building fields. With more penetration of IoT technologies, it highly desirable that the whole functions of a BA system in different levels are implemented through a uniform, high-performance and reliable wireless network. Thus, there should be higher demand on the network features and performance, such as: easy to be deploy with high network quality, supporting the system-level function on the management level, supporting the massive connections for building services equipment, and a more challenging one, meeting the real-time and high-reliable requirements for field-level controls. Current advanced cellular network technologies, e.g., 5G, is more concerned on the IIoT applications, which can provide lower than 10 ms delay and 99.99% reliability with high connection density [36]. Such features show attractive advantages of using cellular networks to connect IoT devices via wireless means for control tasks in future smart buildings.

### 1.6. Summary of current research gaps

In summary, it can be concluded from the above studies that the IIoT architecture with advanced cellular networks has desirable potentials to be applied in building controls. However, the IoT technologies are commonly applied in non- or less- time-critical tasks in buildings. The time-critical control tasks, particularly feedback process controls, still rely on the implementation within a single controller (e.g., DDC). Only a few limited studies have investigated the applications of IoT in time-critical control tasks and showed mixed results [32,33]. To fully reap the benefits of deep IoT penetration in buildings, some critical issues need to be further investigated. Firstly, the means of implementation and the capability of IoT devices directly used for the time-critical building automation tasks, such as building process controls, are still open question to be addressed. Secondly, it is essential to evaluate whether the networks can provide satisfactory performance for the time-critical building automation tasks, under different conditions and building layouts. Preferably, whether the current today's available technologies and services can provide satisfactory performance in real control applications also needs to be assessed experimentally.

This study, therefore, proposes a cellular network-based IIoT architecture for building time-critical control tasks in smart buildings. The proposed architecture includes smart field-level devices embedded with cellular network-enabled IoT controllers and a configured cellular network. The performance of advanced cellular networks in buildings, including 4G LTE, and 5G network, are experimentally tested under different typical conditions in the building. To assess the applicability of proposed architecture and network, a typical time-critical control task in buildings, the supply air temperature control of an air-handling unit (AHU), is used for experimental validation. The comparisons of control performance in the conventional direct digital control (DDC) architecture and the proposed architecture in different network conditions are conducted.

## 2. Proposed cellular network-based IIoT architecture and test arrangement

The basic methodology of this study is to design and propose a generic control architecture for time-critical control tasks in building automation, utilizing IoT technologies. A cellular network-based IIoT architecture is proposed and implemented adopting generic and most updated available technologies and services. The experimental study elaborated in this section using a typical control task in buildings is to validate the capability and performance of the proposed architecture.

### 2.1. Overview of proposed architecture

The proposed cellular network-based IIoT architecture consists of smart field-level devices and an industrial configured cellular network. The structure of proposed architecture is shown in Fig. 3.**a**. The structure of conventional DDC architecture is shown in Fig. 3.**b** for comparison. For the implementation of proposed architecture in this study, the smart sensor and smart actuator are developed. Both of them have abilities of data processing and network access. The smart sensor collects the measurements then packets and sends them to the smart actuator through the configured cellular network. The smart actuator makes the full local control decisions according to the received measurements and makes the actions. In contrast, in the implementations of conventional DDC architecture, sensors and actuators do not have computation ability. A DDC controller is responsible for aggregating the sensing measurements and making control decisions. The control outputs are sent by the DDC controller to the actuators for operation. All of the signals, e.g., measurements and control outputs, are transmitted through wires in analog form.

To test and validate the capability of BA systems adopting the proposed control architecture, a HVAC test rig, integrating the developed smart field-level devices, is constructed for performing a typical building time-critical task, i.e., supply air temperature control. In the network aspect, a 4G LTE cellular network is configured for the implementation of proposed IIoT architecture. In this case, the 4G network is applied for performing such a typical time-critical control task. Meanwhile, the performance of commercial 5G-standalone networks and 4G LTE network are assessed.

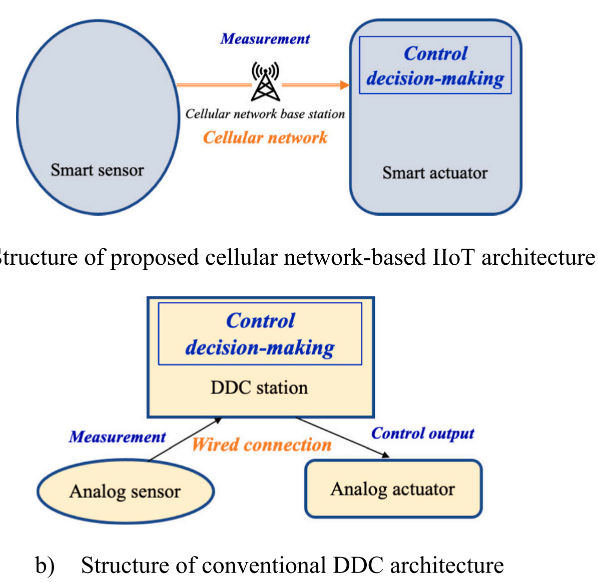



**Fig. 3.** Deployment of different architectures for building time-critical tasks.

### 2.2. Cellular network setting and configurations

In this study, two advanced network technologies are considered, i.e., the 4G LTE cellular network and 5G-standalone cellular network.

The 5G network is tested in Changsha, Hunan Province, China, where the 5G-standalone networks are deployed. It means that all the network infrastructures there support 5G and all network signals are transmitted using 5G core network. The 5G networks involved in this study are provided by three major commercial carriers. In this manner, we could get the more generic performance and get rid of the bias from focusing on a specific carrier network.

Due to the fact that the deployment of 5G network in Hong Kong is still in the transition stage, the 5G network is in non-standalone (NSA) mode, which means that the 5G network still partially relies on the 4G network facilities. This 5G-NSA network cannot fully realize the 5G features such as ultra-low latency. Thus, the 4G LTE cellular network, provided by a major commercial carrier in Hong Kong, is configured, tested and applied in this study. This network is intentionally configured to fit the IIoT scenario, i.e., for the building process control. The configurations include specific access point name (APN), fixed IP addresses, and user equipment-to-user equipment (UE-to-UE) connection. The specific APN is used to set a dedicated network, allowing the IoT devices to join the same network environment. It functions as a local area network separate from the commercial cellular network. The fixed IP addresses are provided to each smart IoT device to make it possible to be accessed by each other. The UE-to-UE connection is used to achieve direct communication among each device through the cellular network using their respective IP address. With such settings, it can avoid the unnecessary delay and unreliability caused by the transmission of cloud server, which is more suitable for the time-critical control task.

### 2.3. Overview of test rig

A compact HVAC test rig is constructed and used in this study. The schematic and photograph of the test rig are shown in Fig. 4 and Fig. 5, respectively. The main components of this test rig include a water tank with heater, a pump, a modulating valve, and an air-handling unit (AHU). The water tank with a heater is used to provide heat source for the AHU. The modulating valve is installed on the water loop of AHU to control the water flow rate through the AHU by change the valve opening. There is an exist fan coil unit in the laboratory, which is a part of the building HVAC system, to provide a heating load for the test rig. A computer is used to monitor the test rig operation and collect the operation data. A control cabinet with input/output (I/O) modules is used to transmit the sensing measurement and send the control signal when needed. The accuracy of flow rate meter is 0.5% FS ($\pm$ 0.035 $m^3$/h), and the accuracy of air temperature sensor is 0.1% FS ($\pm$ 0.15 K).

In the test rig, a modulating valve with low valve authority is selected and installed to provide a more dynamic process under its critical condition. This valve has low controllability under the low water flow rate. The valve will cut down the water flow when it lower than the minimum controllable flow. Meanwhile, the valve has significant hysteresis phenomenon, which also has negative impact on the process control. Thus, the control of the test rig is a challenging task.

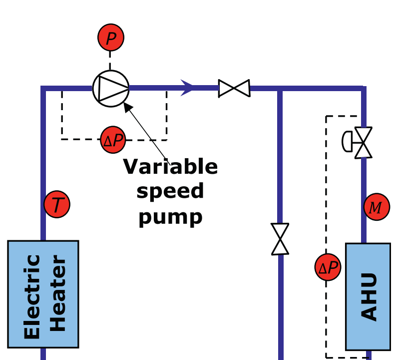



**Fig. 4.** Schematic of the test rig.

**Fig. 5.** Photo of the test rig.

### 2.4. Overview of cellular network enabled IoT controller and integration

A cellular network-enabled IoT controller is developed and embedded into the modulating valve, forming a “smart valve” as shown in Fig. 6. The controller mainly consists of a microcontroller unit, a cellular network module, and a 2-way relay. The microcontroller unit, employing an STM32 control board with 64 KB RAM and 256 KB program memory, is used to make the local control decisions. It can transmit the analog signal as the control output to control the valve opening. It can also access the current opening signal from the valve. A cellular network module is connected to the controller, providing the access of the cellular network and receiving packets of measurements and control setpoints. A 2-way relay is used to select the valve control signal from the alternative sources, i.e., from the IoT controller in the IIoT architecture and the control station (a computer) in the conventional DDC architecture, respectively.

The test rig also includes a smart sensor, i.e., supply air temperature sensor. The smart sensor is physically simulated by a computer, which is equipped with a cellular network module and existing analogue sensor

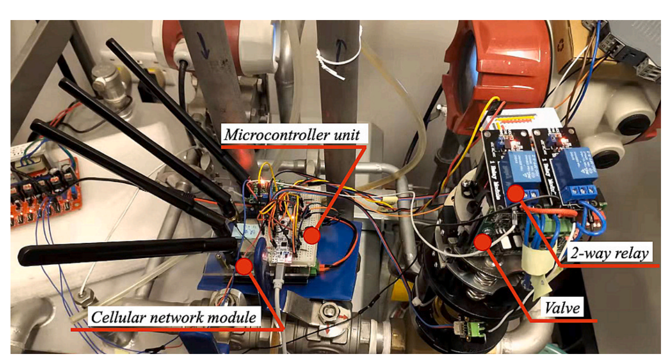



**Fig. 6.** Cellular network enabled IoT controller and integration of test rig.

with IO module. This smart sensor communicates with other smart devices (e.g., smart valve) via the cellular network.

### 2.5. Test arrangement

#### 2.5.1. Control strategy and its deployments

A typical time-critical control task in building, i.e., AHU supply air temperature control, is implemented to test and validate the capacity of cellular network-based IIoT architecture, as shown in Fig. 7. The valve opening is modulated by directly tracking the difference between the supply air temperature ($T_{sup}$) and supply air temperature setpoint ($T_{sup,set}$). The proportional and integral (PI) control is implemented in the controllers in two different control architectures.

In the deployment in the proposed cellular network-based IIoT architecture, the valve and sensor are "IoT-lization". These smart IoT devices join the dedicated cellular network by allocating the specific APN. Each smart IoT device hosts a user datagram protocol (UDP) client. This UDP protocol is widely used in networked control systems considering the timing of the information [12,15,16]. The IP addresses and port numbers are also allocated to the smart IoT devices for communication. The data (i.e., the measurement data ($T_{sup}$) and setpoint ($T_{sup,set}$)) are formatted in the JSON form, packed, and then transmitted to the smart valve through the cellular network by the smart sensor. The programs of the UDP client, data exchanging and parsing, and PI control are implemented in the embedded IoT controller of the smart valve. In this manner, the smart valve can directly control the valve opening.

In the deployment of conventional DDC architecture, the sensor and actuator are wired to the DDC station physically simulated by the computer. The DDC station with PI control implemented, i.e., acted by the computer, is responsible for the local decision making according to the aggregated measurements. The control output (i.e., valve opening) is sent to the valve in the analog form via IO module.

#### 2.5.2. Network conditions setting and test procedure

The typical advanced cellular networks (i.e., 4G LTE cellular network and 5G cellular network) under different network conditions are adopted in this study. Two typical conditions are chosen in the test for both networks, named "high connection density" condition and "low connection density" condition. For "high connection density" condition, a typical workday is selected. During the workday, the tested building has high occupancy and more network users. For "low connection density" condition, a public holiday is selected. During the public holiday, the tested building has low occupancy and less network users.

Concerning performance of the 4G LTE cellular network, performance of the end-to-end connection in the control test deployment is directly measured, as shown in Fig. 8**.a**. The PING method, which continuously sends multiple small packets to the receiver IP address then sending back, is adopted to measure packet loss rate and round-trip time (i.e., delay). The mechanism of PING methods is similar to the data exchange of networked control, where data are transmitted in small packets with a typical 1-s sampling interval of control systems. This method is recommended to assess the network condition [37]. 200 packets are sent for each condition to test the network connection performance before the control test start. Considering the application of the time-critical task in this study, the packets with delay high than 500 ms are also counted, which can be regarded as active packet loss. In the dedicated network, there is no specific protocol stack implemented to enhance real-time performance. The network only includes the tested smart IoT devices.

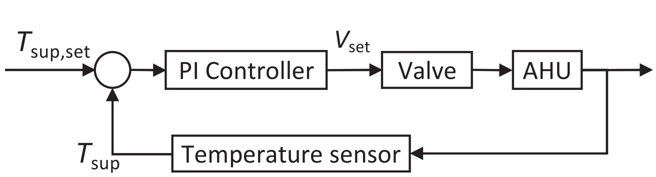



**Fig. 7.** Diagram of AHU supply air temperature control strategy.

In the evaluation test of 5G network performance, due to the configuration limited, the gateway and the carrier servers of domain name system (DNS) are used as the destinations to reflect the situation of the control test deployment. The route of gateway as destination is almost half distance as the end-to-end connection in the control test deployment. The route of DNS server as the destination is longer than that of the end-to-end connection in the control test deployment. The ping method is also adopted to assess the delay and packet loss.

#### 2.5.3. Control test procedure

To test and validate the capacity of cellular network-based IIoT architecture in conducting the time-critical control task (i.e., AHU supply air temperature control), the test procedures are as follows:

The water outlet temperature is set to 60 °C to provide the stable heat source for AHU coil. The initial room temperature is set to about 25 °C when the test start. The sampling interval is 1 s.

Before the start of each test, the modulating valve is fully closed, which means there is no hot water through the AHU. Thus, the initial supply air temperature ($T_{sup}$) of each test is close to the room temperature. It is similar to the startup condition in the real HVAC system in buildings.

In each test, three AHU outlet air temperature setpoints ($T_{sup,set}$) are tested to evaluate the control performance, i.e., reducing from 50 °C to 45 °C to 43 °C by steps after the output is stable. According to characteristics of the valve in this test rig, $T_{sup,set}$ lower than 45 °C could likely lead the instability of $T_{sup}$, due to the fact that the corresponding water flow rate is in the low controllability range of the valve. Thus, the $T_{sup,set}$ of 50 °C is used to evaluate the ability of the control architecture under the normal conditions, while the other two $T_{sup,set}$, i.e., 45 °C and 43 °C, are used to evaluate its ability under the high dynamic and critical conditions.

In this study, control performance at both dynamic and steady-state is assessed. The dynamic performance indicators include the overshoot, peak value, peak time and rise time. The steady-state performance indicators include the steady value, standard deviation and steady-state error. The oscillation range of the control output, i.e., supply air temperature, is also recorded, which can be used to assess the network impact on the control performance.

## 3. Test results and analyses

### 3.1. 4G cellular network performance in building

The distribution of 4G cellular network delay in both "high connection density" and "low connection density" conditions is shown in Fig. 9, and the statistical characteristics of 4G network under different network conditions are shown in Table 1. It can be seen that most of the delay in both conditions are in the low range, i.e., lower than 50 ms. The packet loss rates in these conditions are also in the low range without obviously continuous packet loss. However, under the "high connection density" condition, the packets have higher possibility with long delay. There are 7.5% packets with delay longer than 500 ms. In the real-time applications, such delay may cause the active packet loss, concerning additional computation time, meaning that the out-of-date packet will be discarded due to the arrival of updated packets.

### 3.2. 5G network performance in building

Although only 4G network is used in the control test in this study, the 5G network delay distributions under the different network conditions are measured and assessed as shown in Fig. 10. The statistical characteristics of 5G network under different network conditions are shown in Table 2. When using the gateway as the destination, it can be seen that the delay is very low under both conditions. Even in the case of "high

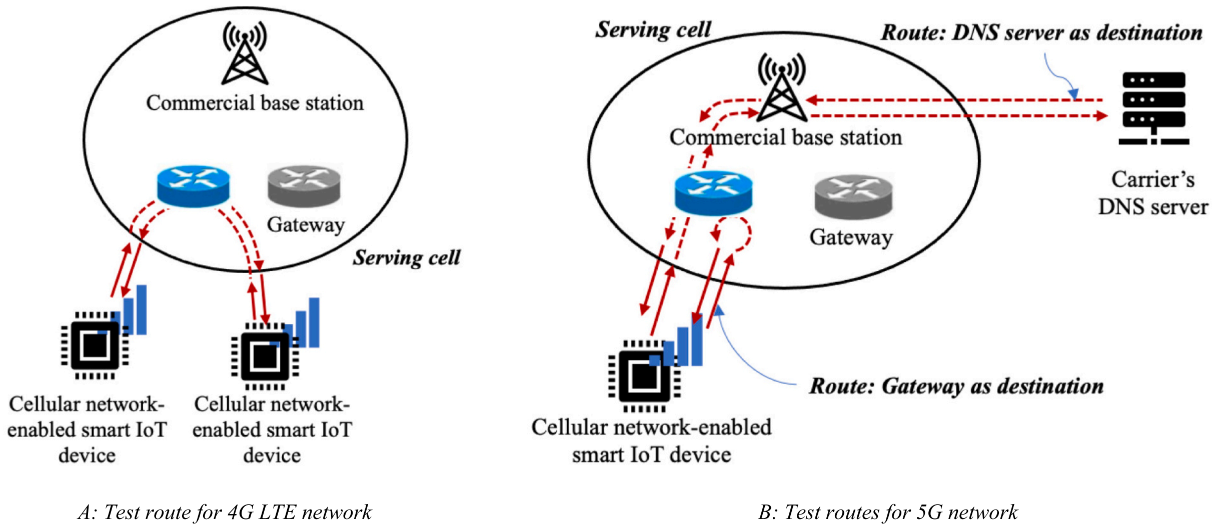



**Fig. 8.** Test route of network performance tests.

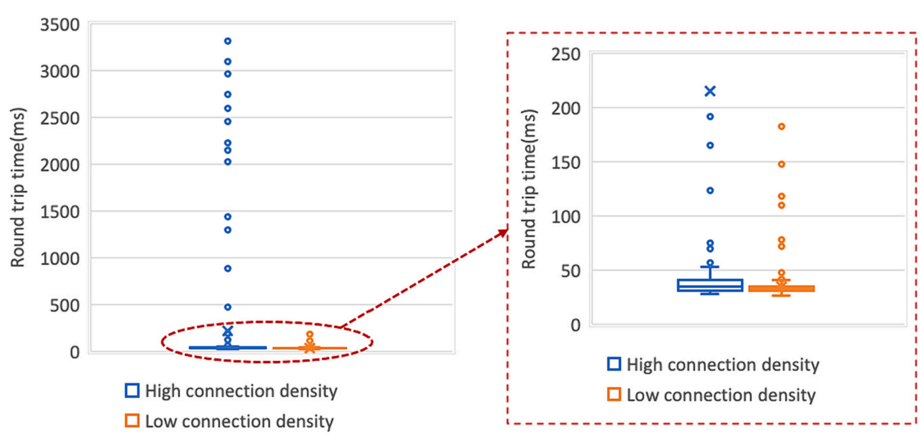



**Fig. 9.** Distribution of network delay in 4G network.

**Table 1**
Statistical 4G network characteristics under different conditions.

| | High connection density | Low connection density |
|---|---|---|
| Packet loss rate | 1.01% | 0% |
| Mean round-trip time (ms) | 215.2 | 35 |
| Max. round-trip time (ms) | 3317 | 183 |
| Round-trip time > 500 ms | 7.5% | 0 |

connection density" condition, the mean round trip time is still around 1 ms. When using the DNS servers as destination, nearly all roundtrip times of all three carriers are lower than 60 ms under "low connection density condition". Only one packet transmitted through carrier B network has the delay of 70 ms. Under the "high connection density condition", it can be seen the network performance is slightly impacted. Nevertheless, the mean round trip time of all three carriers is still around 35 ms. The network-introduced packet loss rate and active packet loss rate (i.e., delay higher than 500 ms) are low. Compared to the performance of 4G cellular network under the same conditions, the performance of 5G network has significantly improvement.

### 3.3. Control performance using conventional architecture

Fig. 11 shows the test results of the supply air temperature control using the conventional DDC architecture, which are used as the baseline for capacity comparison. The measurements controlled supply air temperature, $T_{sup}$) and water flow rate ($Q$), supply air temperature setpoint ($T_{sup,set}$) and the actual detected valve opening are shown. Table 3 shows the main control performance indicators in this test. It can be seen from the figure that, when the setpoint is higher (i.e., 50 °C), the valve can properly control the water flow rate at the relatively high value (i.e., around 0.34 $m^3$/h). Thus, the control can maintain a stable controlled variable ($T_{sup}$) with satisfactory accuracy around the setpoint. However, for the lower setpoints (i.e., 45 °C and 43 °C), the water flow rates are in the lower range, where the valve controllability is low. It can be seen that $T_{sup}$ is oscillating since the valve cannot properly regulate the water flow rate. The oscillation is more intensive in the lower setpoint (i.e., 43 °C).

### 3.4. Control performance using cellular network-based IIoT architecture

The major control and system variables when employing the cellular network-based IIoT architecture under the "low connection density" condition are presented in Fig. 12. Where, the supply air temperature measurements received by the smart valve ($T_{sup,IoTrcv}$) are also included. The main control performance indicators are shown in Table 4. During the test, there were 3 network-introduced packets losses, which means that the packet cannot be received due to the network. There is no active packet loss and large continuous packet loss. It can be seen that the control performance under the three setpoints is very close to that when

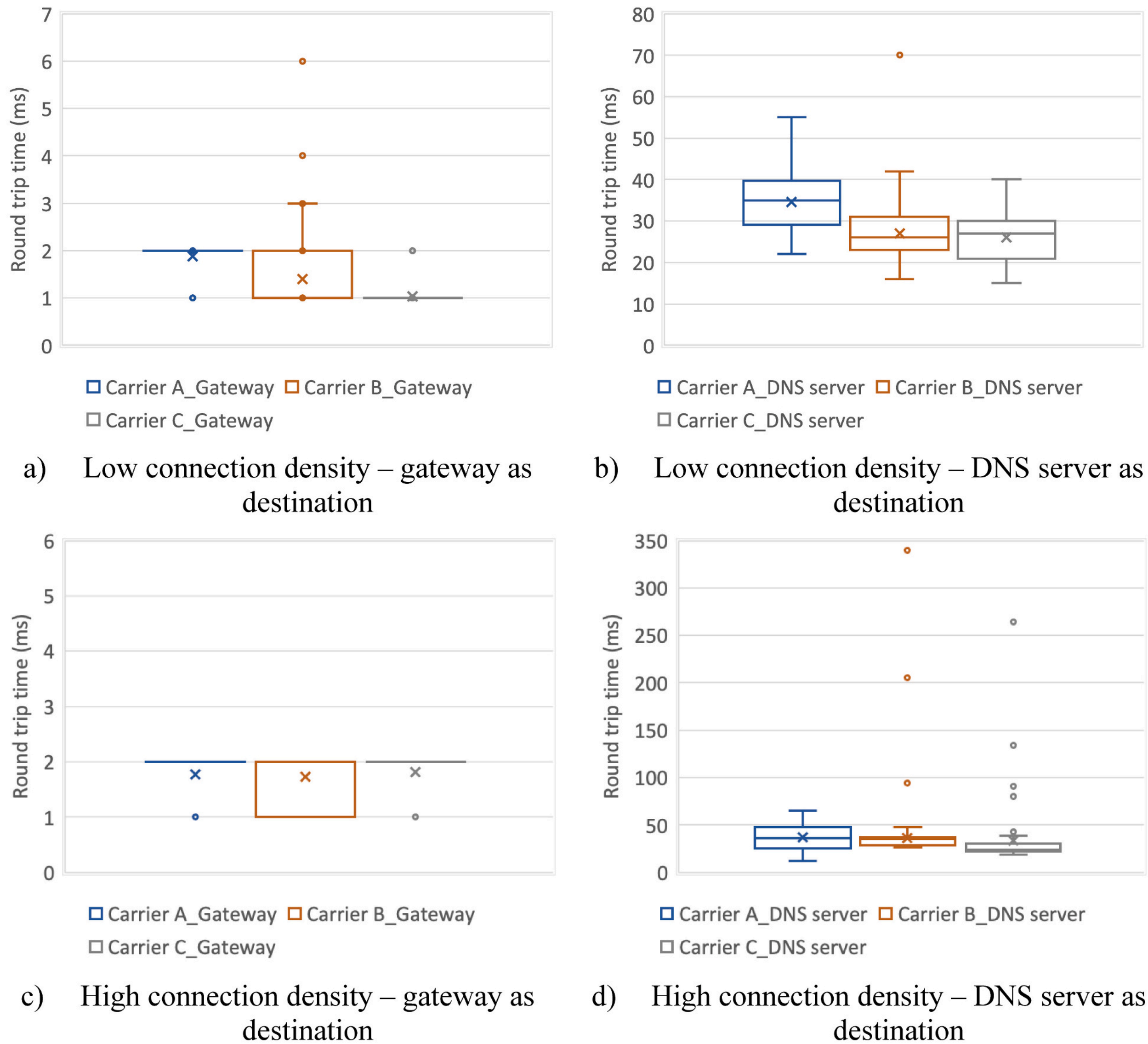



**Fig. 10.** Distribution of delay in 5G network.

**Table 2**
Statistical 5G network characteristics under different conditions.

| Network condition | Destination | Carrier | Packet loss rate | Mean round-trip time (ms) | Max. round-trip time (ms) | Round-trip time > 500 ms |
|---|---|---|---|---|---|---|
| High connection density | Gateway | Carrier A | 0 | 1.8 | 2 | 0 |
| | Gateway | Carrier B | 0 | 1.7 | 2 | 0 |
| | Gateway | Carrier C | 0 | 1.8 | 2 | 0 |
| | DNS server | Carrier A | 0 | 37.3 | 65 | 0 |
| | DNS server | Carrier B | 1% | 36.2 | 340 | 0 |
| | DNS server | Carrier C | 0.5% | 33.4 | 1130 | 0.5% |
| Low connection density | Gateway | Carrier A | 0 | 1.9 | 2 | 0 |
| | Gateway | Carrier B | 0 | 1.4 | 6 | 0 |
| | Gateway | Carrier C | 0 | 1.0 | 2 | 0 |
| | DNS server | Carrier A | 0 | 34.6 | 55 | 0 |
| | DNS server | Carrier B | 0 | 27.1 | 70 | 0 |
| | DNS server | Carrier C | 0.5% | 26.1 | 40 | 0 |

employing the conventional DDC architecture. At the setpoint of 50 °C, the controlled variable can be stabilized at the setpoint with the error of 0.32 K. At lower setpoint, controlled variable is more fluctuating, showing that the network has some slight impact on the control performance. The standard deviation and oscillation range have slightly increase compared that employing conventional DDC architecture. The standard deviations have increased by 0.52 K and 0.36 K in the cases with set-points of 45 °C and 43 °C, respectively. The oscillation range has also increased by 1.45 K and 1.26 K in these two cases, respectively.

Fig. 13 shows the same test results when employing the cellular network-based IIoT architecture under the "high connection density" condition. Table 5 shows the same control performance indicators. Due

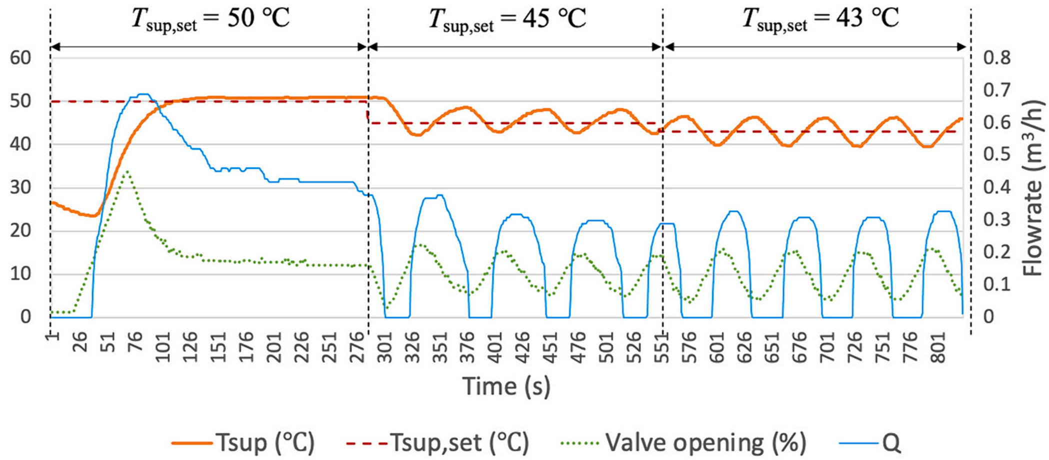



**Fig. 11.** Major control and system variables when control loop employing the conventional DDC architecture.

**Table 3**
Indicators of the control performance employed the conventional DDC architecture.

| | $T_{sup,set} = 50\ ^\circ C$ | $T_{sup,set} = 45\ ^\circ C$ | $T_{sup,set} = 43\ ^\circ C$ |
|---|---|---|---|
| Overshoot | 0.9 K (1.8%) | – | – |
| Peak value (°C) | 50.9 | – | – |
| Peak time(s) | 124 | – | – |
| Settling time (±5%, s) | 73 | – | – |
| Steady value (°C) | 50.9 | – | – |
| Standard deviation (Last 60s, K) | 0.04 | 1.88 | 2.33 |
| Steady-state error (K) | 0.92 | – | – |
| Oscillation range (K) | – | 5.5 | 6.8 |

to the impact of high connection density, there are 2 network-introduced packet losses and 111 active packet losses. The longest continuous packet loss period during the test involves 5 packets and all of them are active packet loss. It can be seen that, even the network condition degraded, the control performance has not been significantly affected. The control performance indicators at setpoint of 50 °C are almost the same as that under the "low connection density" condition. The peak time and settling time are slightly longer. At the setpoints of 45 °C and 43 °C, the standard deviation and oscillation range have experienced very small increase due to the increase of network delay. The standard deviation increases by 1.7% (0.04 K) and 10.4% (0.28 K) at 45 °C and 43 °C, respectively. The oscillation range increases by 3.6% (0.25 K) and 1.7% (0.14 K) at 45 °C and 43 °C, respectively.

The distributions of the time cost in these two control tests are shown in Fig. 14. The statistics of data exchange are shown in Table 6. It is worth mentioning that such statistics are obtained at the application layer. It includes the time of data transmission in the network and the time of data processing in the IoT controller. It can be seen that the time cost is significantly higher than the delay solely introduced by networks. The mean time cost in the test under the high connection density condition (305 ms) is slightly higher than that under the low connection density condition (223 ms). Such increased time cost is acceptable for the control requirements. However, the maximum time cost can be seen a significant increase with the increase of active packet loss rate in the test under the high connection density condition. It could be attributed to the increase of connection density, which leads to a much higher and more unstable network transmission delay. However, even with such degradation, the control performances are acceptable under both two

**Table 4**
Control performance indicators when employing the cellular network-based IIoT architecture - "low connection density" condition.

| | $T_{sup,set} = 50\ ^\circ C$ | $T_{sup,set} = 45\ ^\circ C$ | $T_{sup,set} = 43\ ^\circ C$ |
|---|---|---|---|
| Overshoot | 1.3 K (2.6%) | – | – |
| Peak value (°C) | 51.3 | – | – |
| Peak time(s) | 114 | – | – |
| Settling time (±5%, s) | 76 | – | – |
| Steady value (°C) | 50.3 | – | – |
| Standard deviation (Last 60s, K) | 0.22 | 2.40 | 2.69 |
| Steady-state error (K) | 0.32 | – | – |
| Oscillation range (K) | – | 6.95 | 8.06 |

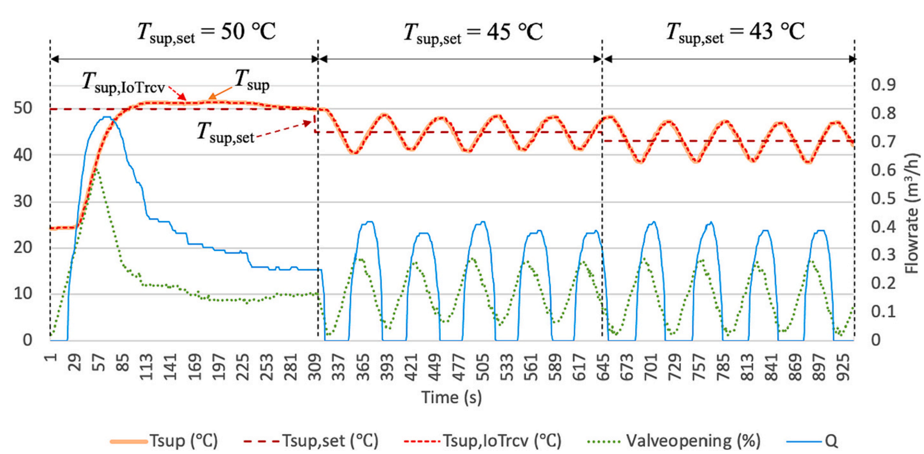



**Fig. 12.** Major control and system variables when control loop employing cellular network-based IIoT architecture - "low connection density" condition.

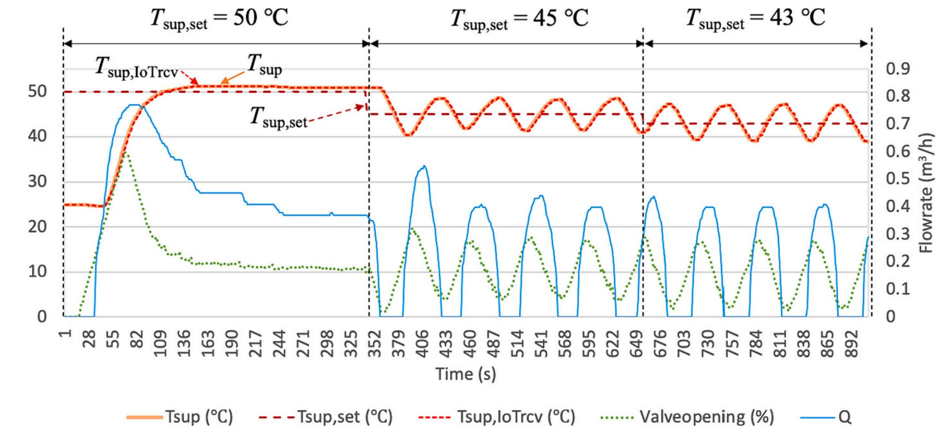



**Fig. 13.** Major control and system variables when control loop employing cellular network-based IIoT architecture - "high connection density" condition.

**Table 5**
Control performance indicators when employing the cellular network-based IIoT architecture - "high connection density" condition.

| | $T_{sup,set}$ = 50 °C | $T_{sup,set}$ = 45 °C | $T_{sup,set}$ = 43 °C |
|---|---|---|---|
| Overshoot | 1.1 K (2.2%) | – | |
| Peak value (°C) | 51.1 | – | |
| Peak time(s) | 161 | – | |
| Settling time (±5%, s) | 93 | – | |
| Steady value (°C) | 50.9 | – | |
| Standard deviation (Last 60s, K) | 0.03 | 2.44 | 2.97 |
| Steady-state error (K) | 0.85 | – | |
| Oscillation range (K) | – | 7.2 | 8.2 |

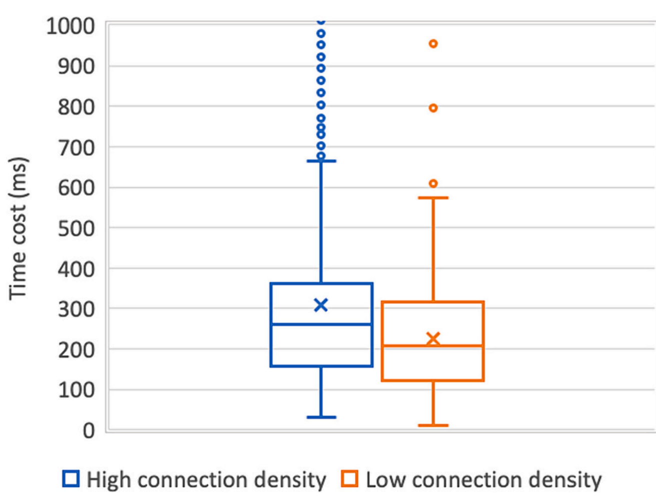



**Fig. 14.** Distribution of time cost of two control tests.

**Table 6**
Statistics of data exchange under different conditions of two control tests.

| | High connection density | Low connection density |
|---|---|---|
| Packet loss rate | 0.02% | 0.03% |
| Active packet loss | 111 | 0 |
| Mean time cost (ms) | 305 | 223 |
| Max. time cost (ms) | 3326 | 955 |

conditions.

## 4. Discussion and prospective applications of enhanced 5G networks

In future buildings with deep penetration of IoT technologies, the network performance is an essential and critical issue. Currently, the BA system relies on the various networks with various cable connections at different levels of BA systems. The heterogeneous network structure limits the flexibility of the BA systems. With the deep penetration of IoT technologies in future buildings, many functions (e.g., management, monitoring, supervisory control, field-level control) will be implemented by smart IoT devices. The connection among these devices will rely on the wireless network. With a powerful unified wireless network, the entire system might no longer need a complicated hieratical physical structure with extensive wiring. Many system operation data or parameters can be directly exchanged among the smart devices without network gateways. For the management in commercial applications, an address table along with the management software could be useful for the large-scale field-level control. In the large-scale practical applications, the topology management of large-scale control and involved devices could be done by the graph structure. Specific device ID and device feature could be allocated to each smart device. The management software could establish the control topology, assign decision-making tasks by use the specific device ID. Besides, the overall deployment cost could be significantly reduced comparing to the deployment of a conventional hierarchical structure BA system. The setting and modifications of BA systems can be done in a plug-and-play manner, making the systems more flexible.

To facilitate wider applications of IoT technologies in buildings, the deployment of a low-latency, high-reliability wireless network is a fundamental concern. However, the layout in buildings can be complicated. The building structures, e.g., walls and doors, can be the obstacles of signal transmission. Those can significantly degrade the network quality. The interference from other electric devices may also affect the network performance. Thus, it could be a difficult task for engineers to deploy such high-quality networks in buildings to meet the requirements of networked control implemented by smart IoT devices. The carriers of cellular network may use their advanced communication technologies to provide a high-performance network in a "network-as-service" manner, or called "mobile network operator rule" mode [38], for buildings. In this manner, an easy-deployment and high-quality network for future smart buildings can be expected.

From the test results, it can be observed that the increase of network density cannot be an ignorable factor concerning the network performance. In this study, as a prototype of future building service system, only two smart IoT devices are involved in the field-level control using the cellular network. During the normal operation period of the building (i.e., "high connection density" condition), the network delay and packet loss rate is increased and the control performance is slightly degraded. Although the degradation is minor, the network capacity and interaction of these connected smart IoT devices need to be considered seriously, as the density of building service devices associated to BA systems could be high. Since the feasibility and capability are approved in this study, the further simulation can be considered to extensively analyze the specific impacts of networks.

The modes of 5G networks need to be considered also. As shown in Fig. 15, the facilities of 5G-SA mode are dedicated for 5G network usage with 5G core network ("5GC" in Fig. 15). In the 5G-NSA mode, the signal of network control (dash line in Fig. 15) relies on the facilities of 4G LTE network (evolved packet core, "EPC" in Fig. 15). End-user devices connected to 5G-NSA networks need to maintain dual connections, i.e., 4G LTE and 5G connection. The quality of each connection directly affects the network performance. This study attempts to use the 5G-NSA network to implement the control task. During the test, the connection of 5G-NSA is not stable, and the network frequently changes between 4G and 5G. Such unsatisfactory network leads to the poor control performance, even worse than that employing the 4G network.

The 5G-SA network shows great potentials to be applied in future smart buildings. The well-known features of 5G networks, such as ultra-reliable, low-latency, and massive connection support, have high possibility of fulfilling the requirements of building process control tasks. Even this test does not fully utilize some advantages of the 5G network, the basic performance of 5G network is tested and shows satisfactory results. The 5G-SA network performance is not obviously affected by the increased network connections, i.e., in "high connection density" condition. Meanwhile, many quality-of-service (QoS) guarantee methods, e.g., QoS-aware scheduling [40], middleware [41], could be used to improve the real-time performance. However, if the networked control is not implemented in a dedicated network, the data traffic of control tasks might be affected by the other applications using such QoS-aware protocols. The theoretical network capacity, i.e., 1 million per square kilometer, shows great potential to be applied in the building sector [36]. The 5G feature of network slicing also can be expected. It is means that a dedicated network can be sliced virtually from the public 5G cellular network for specific applications. The network management concerning the scalability could be much easier. In the building sector, a dedicated network slice can be built for some time-critical applications (e.g., field-level control), to meet the high requirements of network performance without being interfered by other network users. It can be expected the 5G network, with its full features fulfilled, could have better performance based on the results of tests adopting industrial configured 4G network.

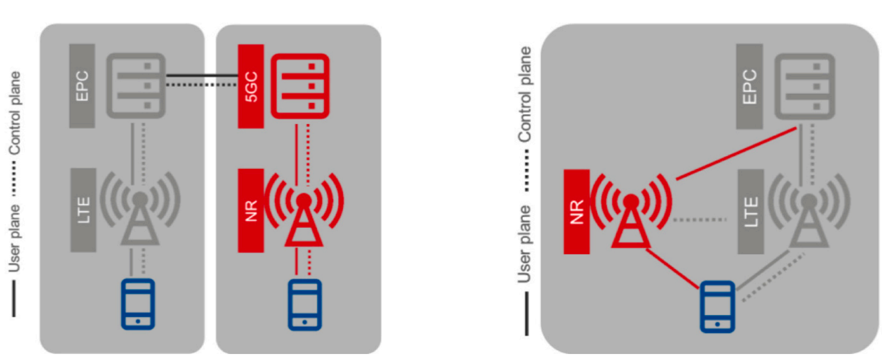
## 5. Conclusion

To provide an effective control architecture for building automation systems in future smart buildings with more penetration of IoT technologies, this study proposes a cellular network-based IIoT architecture and experimentally investigates the applicability and performance of using IIoT technologies and cellular network for time-critical building control tasks. A typical time-critical control task in buildings, AHU supply air temperature control, is selected for the validation tests. The prototype of smart field-level devices integrated with the cellular network-enabled IoT controller is developed and used to implement the field-level control. The performance of advanced cellular networks, i.e., 4G LTE network and 5G network, are tested. The 4G LTE cellular network is specially configured to fit such IIoT control application and applied in the control system using the proposed architecture. The control performance of the control system using the proposed cellular network-based IIoT architecture under different network conditions is compared with that using the conventional DDC architecture. Based on the experimental test results and analyses, the main conclusions can be made as follows:

- o The proposed IIoT architecture shows good capability of applying to the building time critical control tasks. The process control performance using proposed IIoT architecture is similar to that using conventional DDC architecture. The smart field-level device, i.e., valve embedded with the cellular network enabled IoT controller, has enough capacity to collect data from the cellular network and conduct the local process control.
- o The experimental test results show that the 4G cellular network is capable to support the process control tasks with acceptable control performance in smart buildings. With the increasing of the connection density, the network performance is slightly affected by the increased delay and packet loss rate. This issue needs to be considered seriously in the real buildings with massive connections of field-level devices and more interference.
- o The 5G-standalone network shows attractive performance in the conditions concerned for performing time-critical control tasks in buildings. The delay and packet loss rate are only very slightly affected by the increased connection density.

## CRediT authorship contribution statement

**Xinyue Li:** Writing – original draft, Software, Methodology, Investigation, Data curation. **Shengwei Wang:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Jiannong Cao:** Supervision, Project administration, Funding acquisition.




A: 5G-SA mode structure B: 5G-NSA mode structure

**Fig. 15.** Structures of 5G-SA and 5G-NSA mode [39].

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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