5G Network Implementation for Autonomous Mobile Robots in Manufacturing Fields

Shuhao Liang and Ramiro Ramirez

Abstract— Autonomous Mobile Robots are popular facilities in manufacturing fields today but require a wireless network connection to back-end applications. The low latency and high bandwidth for massive connectivity are crucial issues in intelligent manufacturing since intelligent features require more computing resources with higher operating efficiency. This study compares the WiF6, 5G with multi-access edge computing (MEC), and 5G without MEC to verify the response delay from the different computation resources. The experiment performed the data throughput measurement of video and audio of a high-definition camera to evaluate the latency. Camera (CCTV) is commonly used in AMR to detect objects in its peripheral environment, and it committed the most bandwidth in the mobile operation of AMR. The measurement results reveal that the best latency of video and audio are 123 ms and 13.85 ms via the WiFi 6 network. The data transmission routes through the 5G with MEC and without 5G resulted in a more significant delay. Consequently, the latency can be unsatisfaction in the manufacturing field when the AMRs tend to reach farther away applications or computation resources with the current network. In summary, the results show that the current 5G network applied in the experiment had constrained by the mobile network operator (MNO). In further works, we propose a network simulation tool, GNS3, and illustrate a topology for combining practical and hypothetical data analysis.

Index Terms—5G, AMR, URLLC, mMTC, GNS3, MNO, SDN, NFV, network slicing

I. INTRODUCTION

The industrials have started deploying more brilliant mobile Equipment to connect various processes in workshops, factories, and manufacturing fields to improve productivity and efficiency since the introduction of Industry 4.0 in 2013. As time passed, the mobile equipment quantities increased, and the communication demands were also escalating simultaneously. Most AGVs, automated guided vehicles deployed earlier in the logistic at production lines or depots, have been gradually upgrading to AMRs, autonomous mobile robots, for more brilliant feasibility and flexibility. Moreover, AGVs or AMRs should not be individual islands in manufacturing fields that need a proficiency network to acquire information to interact and cooperate with others.

Intelligent manufacturing fields need new network technologies to cope with the tremendous data transmission demands and respond to rapid operation changes. Emmanuel Oyekanlu et al. (2020) reveal the communication need for the AGVs and AMRs fleet management with the 5G network in intelligent manufacturing environments[1]. 5G network is committed to wireless data transmission in manufacturing and can achieve ultra-reliable low latency communication (URLLC) and massive machine type communication (mMTC) criteria, which is currently the most promising one. AMRs usually require more computing sources and communicate with the peripheral facilities more frequently than AGVs to develop better autonomy. Therefore, the network should commit to low latency, reliability, and massive connectivity.

The early 5G network deployments started in New York City, Boston, Chicago, Washington, D.C., and many major cities in the United States in 2019 [2]. These successful 5G network deployment stories leave the impression to the public that the 5G network is capable and ready for any applications, including consumer and industrial areas in current. The criteria of the 5G network for applications in the industrial area could be much more critical, complicated, and challenging than consumer applications. For example, 5G network outages in gaming applications for the individual consumer can be less costly than factory production line losses due to communication interruptions such as equipment damage, material loss, and overall loss of production stoppages in factories.

This article reviews the recent development of AMRs and 5G network technology to notify the issues when implementing the network. The communication protocols for AMRs and revising of the robot operating system (ROS) reflect the changes in communication and operation. Further, the constraints on the regulations and mobile network operators (MNOs) in deployment have limited the performance of the 5G networks, although the technology capability can achieve more than the current configuration. The current 5G technology status and architecture reviews can provide essential information for planning a private industrial network.

The experimental section illustrated a simple architecture of the factory scene, demonstrating the communication measurement and actual data transmission in operation. The measurement of latency adopted the camera's video and audio transmission since they dominated the most bandwidth on AMR rather than others. The 5G network deployment in the manufacturing field, network architecture, communication facilities, and MEC testbed main components are addressed briefly.

The measurement of the latency between WiFi 6, 5G with MEC, and 5G bypass MEC shows that WiFi 6 has the best latency among others. The results can only explain that the local network with WiFi 6 protocol can perform better but cannot represent the capabilities of the 5G network due to the constraints on network configuration and authorization from MNO.

In conclusion, the ARM communication latency in video and audio transmission achieved 205 ms and 33.7 ms in the 5G network with MEC. That represents the capability of the current 5G network to reach the application within the MEC.

Shuhao Liang is with the Industry 4.0 Implemenation Center, National Taiwan University of Science and Technology, 106335 Taipei, Taiwan. (email: shuhaoliang@mail.ntust.edu.tw). Ramiro Ramirez is with the National Taipei Univeristy of Technoogy, 106344 Taipei, Taiwan (email: t109379402@ntut.edu.tw)

II. Technology Overview

AMRs have become popular facilities in intelligent manufacturing environments since the raised of Industry 4.0. Although most AMRs can operate independently with their perception components for location positioning and obstacle avoidance, they still need to acquire the mission instruction and peripheral information to collaborate with other entities in factory operation. AMR communication, robot operating system upgrade issue, current communication network, 5G New Radio core technology, and network configuration constraints on the MNO are the majority of issues in the deployment for engaging intelligent manufacturing. The following sub-sections, AMR communication, O.S. upgrade issues, current network and applications, 5G N.R. and core, constraints on MNO, and digital-twin generation depict essential information and perspectives in a 5G and ARM implementation project.

A. AMRs communication

AMRs communication includes two portions: the interconnection wired network with inter modules in AMRs, and the other wireless communication to an intra-private industrial network or Internet. Both wired and wireless networks should be able to support the traffic requirement with feasibility and reliability. Most of the time, the network in AMRs discussed is related to the communication protocol among models, like controller area network, CAN, and data flow analysis [3]. The network architecture has been recognized and well-developed in most industrial applications.

Nevertheless, the 5G communication bandwidth demand regards their application and computing resources allocating in edge or cloud. Mobilized facilities like AMRs can only rely on wireless networks that could encounter signal attenuation and radio interference. Rodriguez et al. (2021) illustrated the integration of 5G technology in the control of autonomous mobile robots [4]. The study indicates that 5G technology provides reliable AMRs fleet management control and supports the migration of the AMRs onboard routeplanning to the edge cloud. Thus, AMRs communication should consider robot interconnection, fleet management via wireless networks, like 5G or WiFi 6, and edge cloud computing arrangement.

B. O.S. upgrade issues

The most popular Open Robotics Operation System, ROS, is widely adopted for relevant robotics research or practical application projects in academic and industrial fields. The ROS2 is the successor of the ROS system [5]. As mentioned above, the extension of the ROS system should increase network communication capabilities and cloud computing for the implemented AMRs and interact with other AMRs and facilities on data synchronization, aggregation, and analysis. Diverse communication like 5G and WiFi 6 could be embedded protocols in ROS in the future for faster response.

C. Current network and applications

5G network might consist of different types of radio cells to engage the various communication need and energy efficiency for different transmission distances and operation fields. Radio stations or cells are classified into the metro cell, micro cell, pico cell, and femtocell regarding their radio coverage range, as Figure 1 shows [6]. Small-Cell networks are heterogeneous networks comprising different Radio Access Technologies (RAT), including WiFi, GSM, UMTS/HSPA, and LTE/LTE-A.

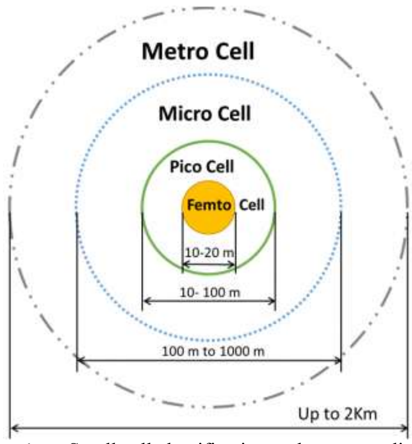

Figure 1. Small cell classification and coverage distance

The current network used to combine macro cells and small cell provides flexible deployment and configuration for homes, enterprises, and metropolitan. Typical small cells connect to 5G N.R. stations to approach the 5G core, and there are two types of small cells: indoor and outdoor[7]. The small indoor cells use in smart factories, classrooms, and spaces with many wireless signal barriers and interference sources. In the same manner, the outdoor type small cell provides better signals service for the outdoor environment like sports stadiums, transportation, and smart cities in most urban areas.

Intelligent manufacturing in 5G network deployment should consider the cost-effective and high performance with a modular concept, which provides the indoor radio system with flexibility.

D. 5G N.R. and Core

5G boosts some of the LTE key performance indicators to a new horizon: capacity, latency, energy efficiency, spectral efficiency, and reliability [8]. 5G end-to-end communication commits to low latency and massive Machine-Type-Communication, and the 5G core technology brings new network features, such as software-defined network (SDN), network function virtualization (NFV), and network slicing. The mobile network operator can offer a dedicated network with the required QoE (quality of user experience) by tenants with these new methods. For specific services, the user equipment might request the application located on the distributed unit (D.U.) and centralized unit (C.U.) [9].

In this study, the experimental works conduct video and audio data transmission via WiFi 6, 5G with MEC, and 5G without MEC to represent the latency among the AMR and local link computing source (laptop), edge computing (MEC), and cloud (D.U. or C.U.). Moreover, the simulation software constructing a 5G network topology depicts the essential elements for large-scale AMR deployment planning.

E. Constraints on MNO – private 5G network

5G networks change the conventional business model of MNO due to the 5G end-to-end connection concept [10]. The mobile network operators would provide internet connectivity, highly sophisticated infrastructure services (Infrastructure-as-a-Service, IaaS), differentiated feature sets, and optional configurations for the customers.

The new model allows the tenants (site owners, e.g., stadium or factory, power gaming users, contents creator, enterprises, etc.) to build their networks upon the mobile operator's infrastructure to optimize their specific use cases. MNO and tenants should become partners in the service development or provide higher authorization to the tenants. Three new business models are 1. No control model. 2. Limited control model. 3. Extended control model. The first and second models give the third party no control or limited control over deployed network services and functions. The last model, the extended model, provides the tenants or third-party designs, configures, deploys, and controls their network functions and services.

Most industries could have experience in essential network management and operations but lack professionals on the new technical solutions built on with 5G network. MNO can share the data center, infrastructure (switches, routers, firewalls), and even virtual network functions in a private 5G network project. Also, there are many challenges in customized 5G and beyond private networks with Integrated URLLC, eMBB, mMTC, and Positioning for industrial verticals (Guo et al., 2022) [11]. However, MNOs must consider the security of the overall 5G network and provide training courses for the current industrial tenants to corporate on the 5G private network.

F. Digital-Twins generation

Digital tools across the design and manufacturing process bring manufacturing technology into the digital-twin generation. The manufacturing system becomes part of a networked ecosystem that provides accumulated manufacturing data for analyzing and generating insight into customer, market, and supplier information.

The topics and technologies mentioned can be valuable references when planning an intelligent manufacturing field. The new intelligent manufacturing with AMRs should link with the data beyond the essential manufacturing information, including e-business, customer service, and supplier logistics so that it can master and respond to customer decisions, needs, and values.

The following methods and experiments section presents the 5G network implementation circumstance for reaching different computation sources. The 5G network architecture refers to the network infrastructure at the Industry 4.0 Implementation Center, National Taiwan University of Science and Technology.

III. METHODS AND EXPERIMENTS

The network facilitated a manufacturing field with AMR that might include data generation equipment and the 5G network facilities. The data generation equipment is the camera (or CCTV) on the AMR to transmit data to the backhaul. The primary network facilities contain Multi-Access Edge Computing and network switches. In experiments, there are three routes for AMR to access backhaul resources located at the local computation, edge computation, and cloud service (D.U.) in the experiment. The AMR connects to Laptop, MEC, and cloud via the WiFi 6, 5G via with MEC), and 5G (without MES), respectively, as Figure 2 shows.

MEC (multi-edge computing) engages the 5G gNB new radio station to screen the data for the internet or intranet (workshop internal). The switch connects all entities in the network and provides the data flow control without moderating function under one Gigabyte connection speed. In practical operation, the AMR connects to the 4G LTE/5G small cell, conveying data to the application server and 5G gNB via optical fiber and Ethernet. The application server programs give the AMR commands and supervise the whole operation via the network. The anticipate response delay is approximately 10 ms for crucial operations.

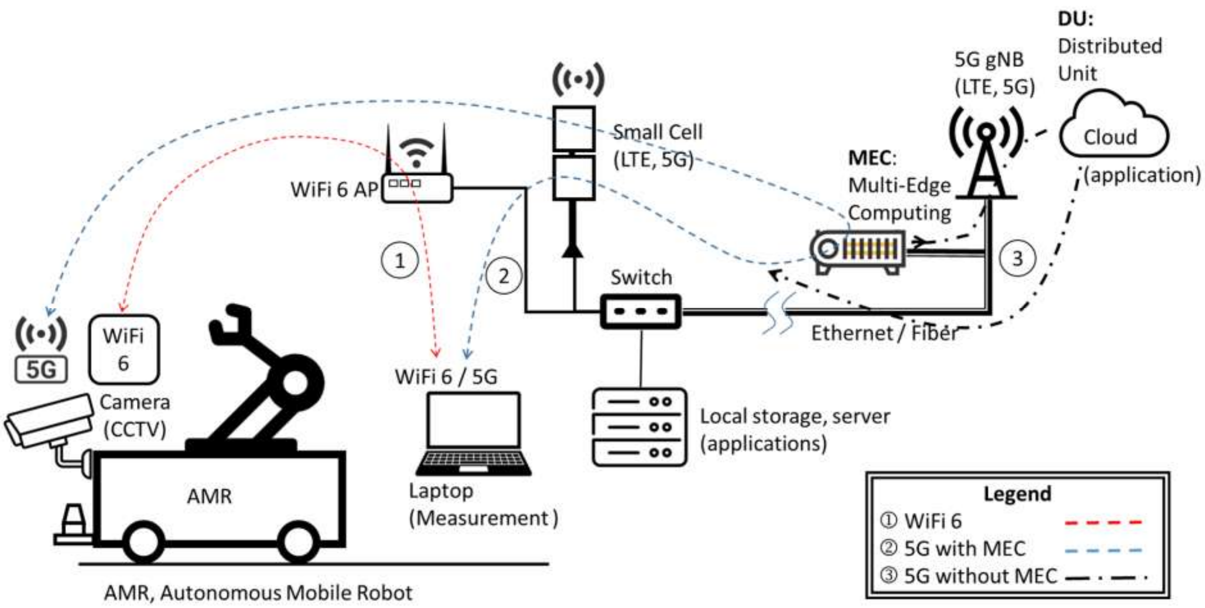

Figure 2. 5G network schematic in the manufacturing field with AMR

The first route, WiFi 6, passes video and audio segments to the laptop which installed the measurement software. The second route, 5G with MEC, transmits the same segments to the laptop vis the loop to MEC, emulating the access to the service at MEC. The third route, 5G without MEC, represents the approach to cloud service.

The non-standalone (NSA) network, 5G/4G LTE, could not achieve the URLLC latency, like 10 ms, at the field. This issue is prominent in the 5G standalone (S.A.) network [12], and the private industry 5G network can be more feasible than a public network. Therefore, experimental communication was conducted to know the actual data transmission capability with the current network.

A. Data generation

An ultra-high-definition CCTV unit on the AMR transmits video and audio data to the testing host, laptop with WiFi, and 5G protocols. This setup performs end-to-end communication, and the measurement adopted the three wireless routes: WiFi, 5G with MEC, and 5G without MEC.

This study focuses on Real-Time Streaming services. A local server has been set up to achieve this, hosting the required software for streaming purposes. Ubuntu (20.04) has been selected as the server's operating system to provide server capabilities, which includes Nginx, an open-source web-server software application.

Real-Time Messaging Protocol (RTMP) conducts real-time communication, a dedicated media stream module included in Nginx. Signal transmission via broadcast relies on Open-Broadcaster Software (OBS), an open-source software that integrates with Nginx-RTMP; both Nginx and OBS run in Docker. Finally, server performance can be evaluated using IPERF3, an open-source network performance evaluation tool. IPERF3 can generate data streams to measure the throughput of the public or private network. The data streams can contain either Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) packages—the MEC testbed main components are listed in Table I.

TABLE I. MEC TESTBED MAIN COMPONENTS

Application	Software	License
Operating System	*Ubuntu 20.04*	*GNU*
Real-time Server	*Nginx-RTMP*	*BSD-2-Clause*
Broadcasting tool	*Open-Broadcaster-Software (OBS)*	*GLPv2*
Container storage	*Docker*	*Free/Paid*
Performance testing	*IPERF3*	*BSD*

B. 5G network facility

The main components of the 5G network deployed at the Industry 4.0 Implementation Center as the Figure 3 shows. The user equipment (U.E.), like AMR at our experiment, connects 5G next generation Node B unit (gNB) via 5G small cells. Software-Defined Networks (SDN) and Bypass switches are used to direct the request to MEC and the local server, which provides the service and application, or app-arch the service on the Internet, like cloud service.

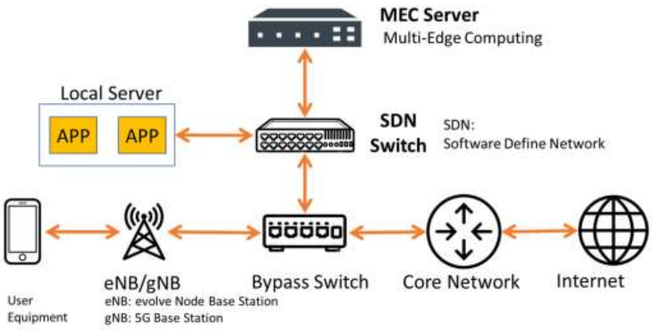

Figure 3. 5G network at Industry 4.0 Implementation Center.

Wireless Equipment, WiFi 6 and MiFi 5G [13] construct the wireless networks to conduct the data transmission in the test. The 5G small cell links the 5G gNB via optical fiber to approach cloud services. Table II. lists the wireless Equipment used for the experiment.

TABLE II. WIRELESS EQUIPMENT

Application	Manufacturer	Model
WiFi 6 Access Point	*Netgear*	*AX6000*
5G Hotspot	*APAL*	*5G Mi-Fi*
5G Small Cell	*Ericsson*	-

1) Multi-Access Edge Computing (MEC)

Multi-Access Edge Computing enables edge collection and processing of data from the U.E. When the data can be processed near the U.E., latency tends to decrease. The 5G with MEC route represents the service conducted at the local server. On the other hand, the 5G without the MEC route performs the service in the cloud via the bypass switch.

2) Network Switches

The experiment uses two physical network switching devices, Juniper EX3400 and CISCO 2960, as Table III shows. SDN and Bypass functions run their program at the Juniper EX3400, the main run in the intranet. The switch CISCO 2960 connects the campus network for access to internet service.

TABLE III. NETWORK SWITCHING DEVICES

Application	Manufacturer	Model
SDN Bypass Switch	*Juniper*	*EX3400*
Switch	*CISCO*	*2960*

IV. RESULTS

The measurement is mainly divided into two communication types: video segments and audio segments. The latency measure regarding WiFi, MiFi(5G), and MiFi (5G, without MEC) is recorded as Table IV shows. Referring to Figure 2, the WiFi 6 has less hop than Mi-Fi 5G or Mi-Fi 5G without MEC. The Mi-Fi 5G without MEC needs to access the Internet, which takes more hops to complete the data forwarding. Further, the

Mi-Fi 5G (without MEC) could roam among the base stations.

TABLE IV. RESPONSE LATENCY AT DIFFERENT ROUTES

Comm. Type	WiFi 6 (802.11ax)	Mi-Fi 5G (with MEC)	Mi-Fi 5G (without MEC)
Video segment	*123 ms*	*205 ms*	*244 ms*
Audio segment	*13.85 ms*	*33.7 ms*	*45.6 ms*

The route of Mi-Fi 5G with MEC processed the application at the local server, but the latency is doubled mainly to the result via WiFi 6. The video and audio latency via the WiFi 6 route is 123 ms and 13.85 ms, respectively, which eliminates the processing delay caused by the 5G MEC. Therefore, the 5G network facilities in the current network architecture increased the latency by about 82 ms and 19.85 ms at video and audio transmission.

Comparing the response latency between Mi-Fi 5G with MEC and without MEC, the latency difference is about 33 ms and 11.9 ms in video and audio. The difference did not contain application processing, only passing through the 5G core network at 5G MNOs.

In conclusion, the video/audio segments pass through the intranet via WiFi 6 can satisfy the application latency up to 123 ms at the approximate 2.5 Gbps data transmission rate. We cannot access the SDN and MEC servers due to the lack of authentication from MNO in the experiment. Due to the licensed network should consider higher security criteria, most MNOs would not provide authentication for accessing 5G facilities.

Tenants and Telco should have a collaborative platform to bridge the demand and customize network design by access authorization. Constructing topology and scanning actual data throughput in the network can be the first step for tenants.

We have built a briefing network to represent the practical topology in our workshop. Using open-source network tools such as GNS3 [14], mininet (MEC) [15], and network surveillance tools like Wireshark [16] can configure the network topology by setting the fundamental factors on the Cisco switch (2960) and Fortinet firewall (Forti-81E) for emulating the current data flow, as Fig 3. shown.

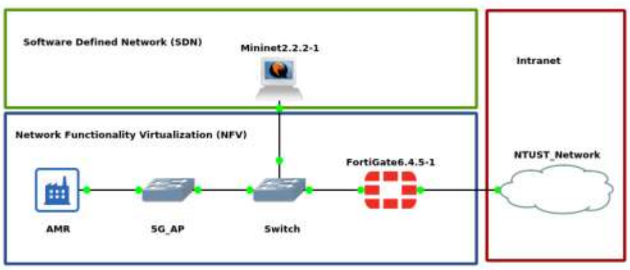

Figure 4. The network architecture of the Industry 4.0 center

With these simulation tools, tenants can design a dedicated network coup with network functions. The Telco can customize the network based on the design and simulation results as a reference to achieve the goal of customers on QoE.

V. CONCLUSION

The 5G network can provide broader bandwidth and faster network connection speed. Still, many constraints remain for industrial venues, including technical and regulatory issues. The 5G network implementation has been accomplished without anticipation in response time due to a lack of authentication on network configuration. Last, a topology was built to study the data flow in the 5G network, which can be extended for o a large-scale AMR deployment design.

ACKNOWLEDGMENT

This work received financial support from the Center for Cyber-Physical System Innovation, the featured areas research center program within the higher education sprout project framework of the Ministry of Education, Taiwan.

REFERENCES

[1] E. A. Oyekanlu et al., "A Review of Recent Advances in Automated Guided Vehicle Technologies: Integration Challenges and Research Areas for 5G-Based Smart Manufacturing Applications," in IEEE Access, vol. 8, pp. 202312-202353, 2020, doi: 10.1109/ACCESS.2020.3035729.
[2] Verizon, When was 5G introduced? https://www.verizon.com/about/our-company/5g/when-was-5g-introduced . Accessed on: Jul 15, 2022.
[3] Valter Silva, José A. Fonseca, Urbano Nunes, Rodrigo Maia, Communications requirements for autonomous mobile robots: analysis and examples, IFAC Proceedings Volumes, Volume 38, Issue 2, 2005, Pages 91-98, ISBN 9783902661012, https://doi.org/10.3182/20051114-2-MX-3901.00014 .
[4] Rodriguez, Ignacio, Rasmus Suhr Mogensen, Andreas Fink, Taus Raunholt, Søren Markussen, Per Hartmann Christensen, Gilberto Berardinelli, Preben Mogensen, Casper Schou, and Ole Madsen. (2021). "An Experimental Framework for 5G Wireless System Integration into Industry 4.0 Applications" Energies 14, no. 15: 4444. https://doi.org/10.3390/en14154444.
[5] ROS.org. Changes between ROS 1 and ROS 2. http://design.ros2.org/articles/changes.html. Accessed on: Sep 15, 2022.
[6] A. S. Bhosle, "Emerging trends in small-cell technology," 2017 IEEE International Conference on Electrical, Instrumentation and Communication Engineering (ICEICE), 2017, pp. 1-4, doi: 10.1109/ICEICE.2017.8191847.
[7] Ericsson.com. Small Cells. Available: https://www.ericsson.com/en/small-cells , Accessed on: Sep 15, 2022.
[8] Devaki Chandramouli, Rainer Liebhart, Juh Pirskanen. (2019). 5G for the connected world. New Jersey, USA. John Wiley & Sons Ltd.
[9] 5GWorldPro.com. (2023, March 10). What is C.U. and D.U. in 5G? 5G Training and 5G Certification. Retrieved May 1, 2023, from https://www.5gworldpro.com/5g-knowledge/what-is-cu-and-du-in-5g.html
[10] Husain, Syed S., Athul Prasad, Andreas Kunz, JaeSeung Song, Adrian Buckley, and Emmanouil Pateromichelakis. (2021). End-to-End Mobile Communications: Evolution to 5G. 1st ed. New York: McGraw Hill. https://www.accessengineeringlibrary.com/content/book/9781260460254
[11] Guo, S., Lu, B., Wen, M., Dang, S., & Saeed, N. (2022). Customized 5G and Beyond Private Networks with Integrated URLLC, eMBB, mMTC, and Positioning for Industrial Verticals. IEEE Communications Standards Magazine, 6(1), 52–57. https://doi.org/10.1109/mcomstd.0001.2100041
[12] 3GPP TS 23.501, 5G; System Architecture for the 5G System (5GS), 3GPP TS 23.501 version 16.6.0 Release 16. Available online: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3144. Accessed on: Jun 13, 2022.
[13] MiFi https://www.apaltec.com/mifi/. Accessed on: Jul 15, 2022.
[14] GNS3, Getting Started with GNS3 Available online: https://docs.gns3.com/docs/. Accessed on: Jun 22, 2022.
[15] Mininet, An Instant Virtual Network http://mininet.org/. Accessed on: Jul 15, 2022.

[16] Wireshark, Internet Protocol Family. Available online: https://wiki.wireshark.org/InternetProtocolFamily. Accessed on: Jun 22, 2022.

Shuhao Liang received his M.S. degree in the Department of Mechanical Engineering from the National Taiwan University of Science and Technology, Taipei, Taiwan, in 2000 and his Ph.D. degree in the Department of Engineering and System Science from National Tsing Hua University, Hsinchu, Taiwan, in 2006. He is currently a project assistant professor with the Industry 4.0 Implementation Center at the National Taiwan University of Science and Technology, Taipei, Taiwan. His current research interests and publications are in the Internet of Things, automation, 5G network, and robotics applications.

Ramiro Ramirez received the M.S. degree in the Department of Industry Management from the National Taiwan University of Science and Technology, Location, in 2020. He is currently a doctoral student at the National Taipei University of Technology, Taipei, Taiwan. His current research interests and publications are in the Internet of things, automation, 5G network, and robotics applications.