A 5G-enabled Digital Twin Architecture for Real-time Monitoring and Event-driven Control: Experimental Network Performance Study

Pradujthep Maneechay[1*], Tuangyot Supeekit[1], Thanakorn Naenna[1], Eakkachai Warinsiriruk[1], Orrawadee Ruenrom[2], Mananya Paksaksri[3]

[1]Department of Industrial Engineering, Smart Industrial Engineering Program, Faculty of Engineering Mahidol University, Nakhon Pathom, Thailand
[2]Department of Business Transformation - East, Advanced Info Service Public Company Limited Bangkok, Thailand
[3]Smart Factory Division, Thai German Institute, Chonburi, Thailand
**Bell090943@gmail.com*

Keywords: Digital Twin, AIS 5G, Remote Monitoring, Node-Red, Network Latency

Abstract

This paper presents the design and performance evaluation of a remote monitoring-and-control Digital Twin system operated over the AIS 5G network. System performance was assessed under three bandwidth scenarios Local (Wi-Fi), 5G limited to 1 Mbps, and 5G limited to 10 Mbps by comparing latency and practical usability, while controlling the measurement conditions using Ping round-trip time (RTT) with a 32-byte payload (N = 100) in each scenario. The results show 0% packet loss across all cases, indicating reliable packet delivery; however, real-world usability differed clearly due to variations in latency and effective performance. In particular, the 5G 10 Mbps condition achieved an average latency of 61 ms, meeting the minimum practical requirement for initial real-time Digital Twin operation. Overall, the findings suggest that AIS 5G with a 10 Mbps bandwidth limit is sufficient to support baseline real-time monitoring and control for a Digital Twin deployment.

1 Introduction

Modern automation often adopts Digital Twin technology by first developing a centralised dashboard for real-time monitoring of machine and production-process data [1]-[3]. Shop-floor signals from sensors, PLCs, and industrial machines are collected through standard protocols such as Modbus and sent to a central processing layer [2], [4]. This layer formats, validates, and stores data, commonly in a time-series database, before visualisation. The dashboard acts as a system-status window, enabling users to monitor machine states, cycle counts, alarms, critical parameters, and historical trends, as well as configure alert thresholds for abnormal conditions. Beyond visibility, dashboard-based Digital Twins improve traceability through time-stamped logs, audit trails, and root-cause analysis, while providing data for trend evaluation, including downtime, response time, and overall performance efficiency [2], [5], [6].

At an advanced stage, Digital Twins can integrate workflow automation to support event-driven control and AI-assisted decisions, including abnormal-event screening, execution verification, and response prioritisation [5], [7]. This is important for remote 5G operation, where latency and throughput directly affect responsiveness and interaction continuity [8], [9].

In this research context, the Digital Twin is not merely a visualisation screen; it functions as a supervisory layer that provides real-time device status visibility, supported by logging and traceability for audit and root-cause analysis. When integrated with automation, the system can enforce “safety rules” and “quality criteria” before issuing commands to physical equipment, thereby reducing human error and preventing inappropriate operations. Furthermore, incorporating AI into the Digital Twin helps transform raw data into decision-oriented information for example, summarising key events, generating explainable alerts, and recommending appropriate actions making remote control more reliable and scalable for real-world field deployment.

This paper presents the design and experimental evaluation of a Digital Twin system capable of remote monitoring and control. The system leverages 5G network connectivity and adopts Node-RED on Cloud as the integration platform to enable connectivity, communication, and data management between the physical system and the Digital Twin.

2 Methodology

This research focuses on the design and experimental evaluation of Phase 2 of the proposed Physical-Agentic AI framework, which involves the integration of the physical system with a Digital Twin for real-time remote control and status monitoring over the 5G network. As illustrated in Fig. 1, the overall framework consists of two phases: Phase 1 represents the Agentic AI layer for multi-modal interaction, identity authorization, prescription validation, and flexible commanding, while Phase 2 represents the Physical AI layer for cobot operation and Digital Twin monitoring. However, the scope of this paper is limited to Phase 2, where the physical system is connected to the Digital Twin to evaluate remote monitoring and control performance. The user interface is designed to provide operational situational awareness through two complementary views: a 3D model viewer for spatial understanding and a dashboard for tracking system status, operational continuity, and readiness for real-world deployment.

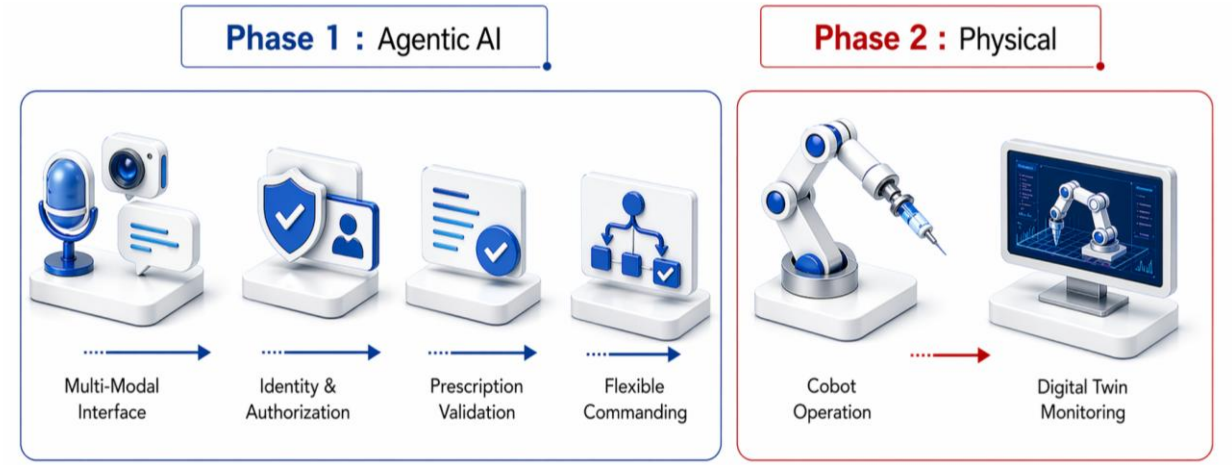

Fig.1 Shows the overview proposed Physical-Agentic AI workflow and Digital Twin integration.

Building on the Phase 1 Physical-Agentic AI system, which was structured as a multi-agent architecture, this study investigated automated workflow development by introducing a Master Agent and four specialized agents. Each agent was assigned distinct sub-tasks based on module expertise to improve correctness and precision, and to reduce human error during the operation of the cobot and the chemotherapy drug compounding machine. In Phase 2, the focus shifted to developing a Digital Twin, with Node-RED serving as the integration of middleware between the physical system and the core Agentic AI. Operationally, the Agentic AI issues control commands as API requests to Node-RED, which then translates and formats the commands to match the interfaces of the compounding equipment and the cobot before forwarding them to the physical system via the Modbus TCP protocol. In addition, Node-RED collects operational status and telemetry feedback from the physical layer to continuously update the Digital Twin, enabling bidirectional communication and supporting reliable remote monitoring and supervision.

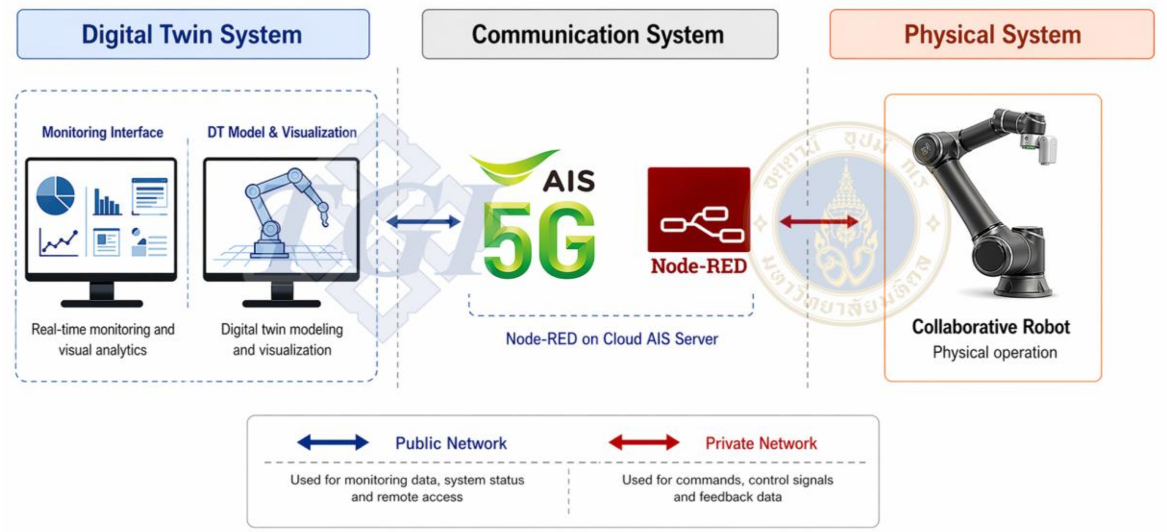

Fig.2 Digital Twin Demonstration for 5G-Enabled Global by AIS 5G.

Figure 2 shows the system architecture developed for long-distance Digital Twin monitoring and control over the 5G network. The architecture links three main components: the Digital Twin system, the cloud-based communication system, and the physical cobot system. In the experiment, the physical collaborative robot was installed at Mahidol University, Salaya campus, while the remote operator accessed the monitoring and control interface from the Thai German Institute (TGI), Chonburi, located approximately 110 km away. Node-RED on Cloud was used as the communication and integration layer to exchange data between the physical system and the Digital Twin interface. The public network supported remote access, system monitoring, status visualisation, and 3D model display, allowing the operator to observe the robot condition in real time. In contrast, the private 5G network was used for transmitting control commands and feedback data between the operator and the physical device. To evaluate communication performance, three operating conditions were compared: local connection, 5G private network limited to 1 Mbps, and 5G private network limited to 10 Mbps. These conditions were selected to assess latency, data transmission stability, and the practical feasibility of remote Digital Twin operation over long-distance network infrastructure for future industrial and medical automation applications in Thailand.

2.1 Network Latency Evaluation for Remote Digital Twin Operation over 5G

This experiment was designed to evaluate the effect of network conditions on Digital Twin communication performance by measuring round-trip time (RTT). The main independent variable was the communication scenario, which consisted of three conditions: a local Wi-Fi connection without bandwidth limitation, a 5G private network limited to 1 Mbps, and a 5G private network limited to 10 Mbps. To ensure a fair comparison, the same client machine, target destination, latency measurement method, and payload size were used in all tests. The dependent variable was the measured Ping RTT, which represents the time required for a data packet to travel from the client to the target and return to the client. A 32-byte payload was applied for every measurement, and each scenario was repeated for 100 samples to obtain sufficient data for latency analysis. Test ID T1 represented local-network testing at Mahidol University, while T2 and T3 represented long-distance 5G testing from TGI under 1 Mbps and 10 Mbps bandwidth constraints, respectively. These variables were selected to identify communication limitations that may affect real-time monitoring, remote control, visualisation response, and practical usability of the Digital Twin system. The complete experimental conditions and controlled variables are shown in Table 1.

Table 1 Experimental conditions for Ping RTT latency measurements.

Test ID	Scenario	Link/Network	Limited Speed	Latency type	Payload (Bytes)	Samples (N)
T1	Local	Local Wi-Fi	No Limit	Ping RTT	32	100
T2	5G 1 Mbps	5G	1 Mbps	Ping RTT	32	100
T3	5G 10 Mbps	5G	10 Mbps	Ping RTT	32	100

After the experimental conditions had been defined, the RTT results were analysed to determine how network type and bandwidth limitation affected the responsiveness of the Digital Twin system. T1 was used as the baseline condition because it represented local communication through Wi-Fi without bandwidth restriction. In contrast, T2 and T3 represented remote communication through the 5G private network with bandwidth limits of 1 Mbps and 10 Mbps, respectively. By keeping the payload size, target endpoint, latency type, and number of samples constant, the comparison mainly reflected the influence of the network condition rather than other external factors. This controlled setup allowed the study to evaluate whether the 5G connection could support practical Digital Twin operation, especially for real-time monitoring, command transmission, visualisation feedback, and remote control. The results obtained from these scenarios were therefore used to assess communication reliability and operational feasibility.

3 Results

To evaluate how network constraints affect the use of a Digital Twin for remote monitoring and control, RTT latency was measured using the ping method under three communication scenarios: Local Wi-Fi, 5G limited to 1 Mbps, and 5G limited to 10 Mbps. The same measurement configuration was applied in all scenarios, including a 32-byte payload, 100 transmitted packets, and the same target endpoint, to minimise external variation and support a fair comparison. The collected data were used to assess average latency, packet loss, and the practical effect of each network condition on system responsiveness. These indicators are important because delayed feedback or unstable communication may directly affect monitoring accuracy, command response, and operator confidence during remote operation. The results are summarised in Table 2.

Table 2 Latency performance and observed usability of the Digital Twin across network scenarios.

Test ID	Scenario	Payload (Bytes)	Packets Sent (N)	Average RTT (ms)	Packet Loss (%)	Observed usability
T1	Local	32	100	1	0	The system works well on local Wi-Fi but loses communication and control outside Wi-Fi coverage.
T2	5G 1 Mbps	32	100	355	0	The system can be controlled and monitored remotely, but noticeable latency causes delayed and less responsive operation. In addition, 3D visualisation data cannot be reliably retrieved from the server under this network condition.
T3	5G 10 Mbps	32	100	61	0	Remote control and monitoring are smooth with no noticeable latency, and 3D visualisation data is fully retrieved and displayed from the server.

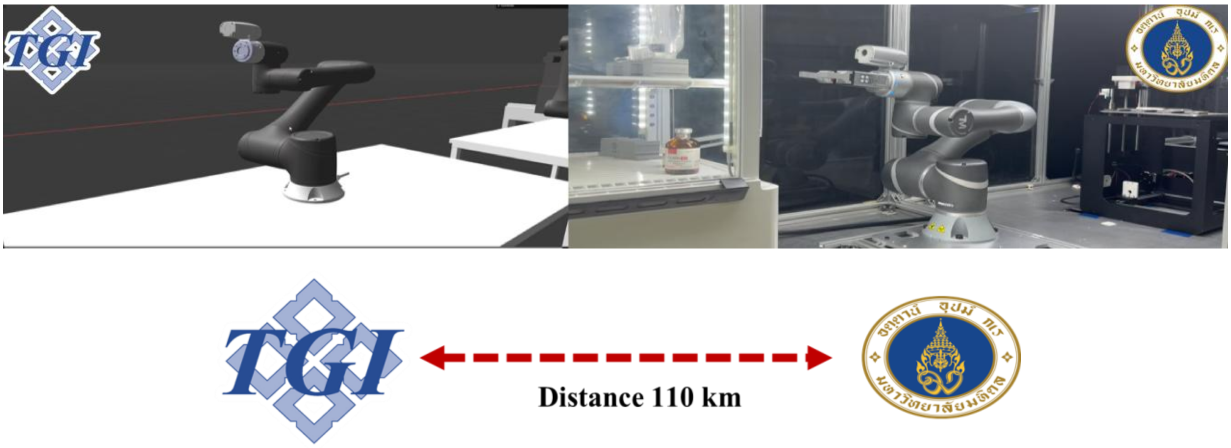

Fig.3 Remote Digital Twin monitoring and control test over a 110 km distance.

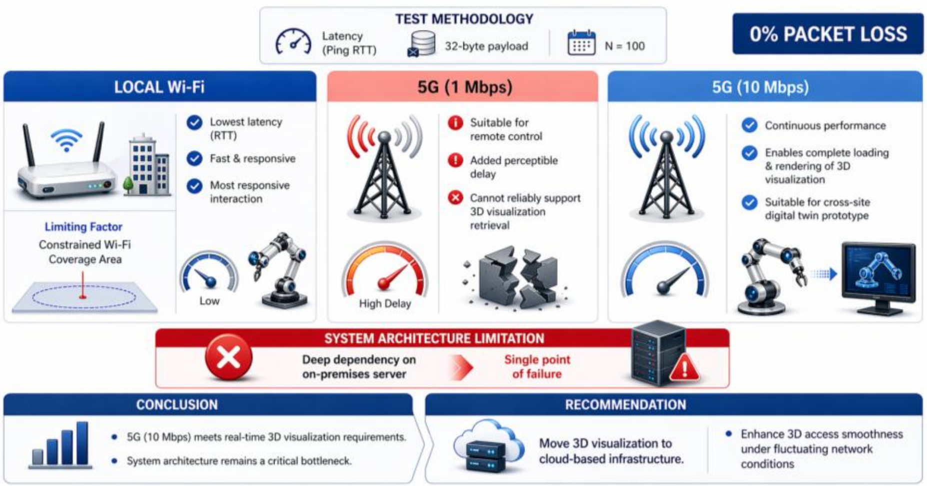

Fig.4 Summary of Digital Twin remote monitoring and control performance over local Wi-Fi and 5G networks.

Table 2 reports the latency test results (Ping RTT, 32-byte payload, 100 samples) and highlights how network performance directly affects the usability of the monitoring- and control functions. The remote test configuration is illustrated in Fig. 3, where the Digital Twin system was used to monitor and control the physical robot system across a distance of approximately 110 km. All scenarios achieved 0% packet loss, indicating stable communication in terms of packet delivery. However, practical usability is primarily governed by latency and by the network's effective data-transfer capability in each condition. In T1 (Local Wi-Fi), the system exhibited a very low average RTT (~1 ms), enabling fast and accurate control with smooth responsiveness, which is well suited for on-site operation within Wi-Fi coverage. A key limitation, however, is the dependence on local coverage; once outside the Wi-Fi range, communication and control are no longer available, making cross-site operation impractical. Under T2 (5G limited to 1 Mbps), the system still supported remote control and monitoring with no packet loss, but the delay became visibly noticeable (average RTT in the order of 355 ms), leading to less continuous interaction particularly for tasks requiring real-time responsiveness. Moreover, the system failed to retrieve 3D visualisation content from the server, suggesting that the bottleneck was not latency alone but also insufficient throughput for transmitting 3D model data. In contrast, T3 (5G limited to 10 Mbps) delivered substantially improved performance, maintaining 0% packet loss with an average RTT of approximately 61 ms. This enabled smoother and more continuous remote operation and allowed complete loading and rendering of 3D visualisation from the server. A visual summary of these network-performance differences, including the practical limitations and recommended system improvement, is presented in Fig. 4. Overall, the results indicate that sufficient 5G bandwidth significantly improves readiness for practical cross-site Digital Twin operation, whereas a 1 Mbps constraint remains technically functional but clearly degrades responsiveness and visualisation capability.

4 Discussion

Although the results indicate that AIS 5G limited to 10 Mbps is sufficient for real-time Digital Twin monitoring and control, the primary limitation remains on the server side. The current system relies on an on-premises server at Mahidol University to maintain device connectivity and continuously provide 3D visualisation services, creating a single point of failure. If the server experiences issues, such as power outages or network disruptions, the Digital Twin operation will be interrupted immediately, even when the user-side network remains available.

To improve stability and ensure more continuous operation, a practical approach is to migrate the 3D visualisation module and the associated 3D model files to the cloud. This reduces dependency on a single local server, enables access from anywhere, and can improve 3D model loading performance by leveraging cloud infrastructure, which helps mitigate pipeline bottlenecks especially under constrained network conditions. In summary, while 5G at 10 Mbps is adequate at the prototype level, achieving long-term reliability and scalability for real-world deployment would benefit from adopting cloud-based 3D visualisation to enhance continuity, robustness, and overall user experience.

5 Conclusion

This study evaluates network performance for monitoring- and control functions and Digital Twin operation by comparing latency (Ping RTT, 32-byte payload, 100 samples) across three scenarios: Local Wi-Fi, 5G limited to 1 Mbps, and 5G limited to 10 Mbps. Although all conditions achieved 0% packet loss, the practical user experience differed significantly due to variations in latency and throughput. Local Wi-Fi delivered the lowest RTT and the most responsive interaction, but its usability is constrained to the Wi-Fi coverage area. The 5G 1 Mbps condition remained functional for remote control, yet introduced perceptible delay and could not reliably support 3D visualisation retrieval. In contrast, 5G 10 Mbps provided sufficiently continuous performance for remote controlling and monitoring and enabled complete loading and rendering of 3D visualisation from the server, making it suitable for cross-site Digital Twin operation at the prototype level. However, the key limitation is not the network alone but the system architecture, which still depends on an on-premises server as a single point of failure. Therefore, the study concludes that 5G at 10 Mbps represents a practical minimum requirement for initial real-world Digital Twin deployment, while improved stability and availability would benefit from migrating the 3D visualisation module to a cloud-based infrastructure to reduce single-point-of-failure risk and enhance 3D access smoothness under fluctuating network conditions.

6 Acknowledgements

We would like to express our sincere gratitude to Advanced Info Service Public Company Limited (AIS) and the Thai German Institute (TGI) for supporting the equipment and resources necessary for conducting this research, as well as for facilitating system testing and operation. Their support was essential to the successful completion of this study.

7 References

[1] Iliuţă, M.-E., Moisescu, M.-A., Pop, E., et al.: 'Digital Twin-A Review of the Evolution from Concept to Technology and Its Analytical Perspectives on Applications in Various Fields', Applied Sciences, 2024, 14, (13), article 5454

[2] Calderón, D., Folgado, F.J., González, I., et al.: 'Implementation and Experimental Application of Industrial IoT Architecture Using Automation and IoT Hardware/Software', Sensors, 2024, 24, (24), article 8074

[3] Daraba, D., Pop, F., Daraba, C.: 'Digital Twin Used in Real-Time Monitoring of Operations Performed on CNC

Technological Equipment', Applied Sciences, 2024, 14, (22), article 10088

[4] Kiangala, K.S., Wang, Z.: 'An inceptive approach for designing simple digital twins and industrial metaverse process frameworks for small manufacturing I5.0 environments using Node-RED', International Journal of Advanced Manufacturing Technology, 2025, 140, pp. 2245-2268

[5] Dai, D., Zhao, B., Yu, Z., et al.: 'Generative and Predictive AI for Digital Twin Systems in Manufacturing', Frontiers in Artificial Intelligence, 2025, 8, article 1655470

[6] Wakili, A., Bakkali, S., Ibrahim, I.A.: 'A digital twin-enhanced cybersecurity framework for IoT in healthcare: Applications in Industry 4.0', Telematics and Informatics Reports, 2025, 20, article 100254

[7] Stavropoulos, P., Papacharalampopoulos, A., Sabatakakis, K., et al.: 'Metamodelling of Manufacturing Processes and Automation Workflows towards Designing and Operating Digital Twins', Applied Sciences, 2023, 13, (3), article 1945

[8] Mertes, M., Weckesser, J., Pechmann, A., et al.: 'Machine-Integrated 5G Connectivity: Experimental Evaluation of a Private 5G Standalone Network for Manufacturing Applications', CIRP Journal of Manufacturing Science and Technology, 2024

[9] O'Brien, W., Dooley, A., Penica, M., et al.: 'Performance benchmarking of private 5G networks', Computer Networks, 2025, 272, article 111693