

An Integrated 5G-TSN Framework for Networked Control in Factory Automation

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Abstract—Modern industrial automation requires integrating Ethernet and wireless communication technologies to effectively control physical processes that can change rapidly. This paper presents a 5G-TSN integration framework for wireless networked control systems with fast dynamics. The demonstration is carried out in an indoor factory scenario modeled through the OMNeT++ simulation platform. The factory setup involves Ethernet-based TSN and 5G networks. A linear inverted pendulum on a cart serves as a plant controlled by a TSN device connected to a 5G network. The plant relies on 5G user equipment to exchange sensing and actuation data with the remote controller. The proposed quality-of-service mapping enables high-priority traffic flows with latencies below the 2-ms sampling period in over 99.98% of cases. Less than 0.02% of control and sensing messages arrive after their deadlines and are discarded. Notably, extensive Monte Carlo simulations show that the plant remains stable in the closed loop over the integrated 5G-TSN network.

Index Terms—Networked control systems, system analysis and design, wireless communication, Ethernet, 5G, QoS, reliability.

I. INTRODUCTION

Wireless networked control systems (WNCS) hold immense significance in various fields, including industrial automation, intelligent transportation, smart grids, and telesurgery, as highlighted in [1]–[3]. Their mission-critical applications have garnered substantial attention from both industry and academia. Estimation and control over unreliable links are pivotal research areas in WNCS, as discussed in [1], [3], and [4], along with the references therein. However, mission-critical systems encounter several challenges, such as strict requirements for reliability, latency, energy efficiency, cost, interoperability, coexistence, security, and privacy.

A typical factory floor creates dense propagation environments with significant interference. This presents a major challenge for implementing control strategies, over wireless networks, demanding careful attention to meet control-application-level requirements such as reliability and stability [5]. To ensure reliability and low latency, industrial automation starts adopting time-sensitive networking (TSN) standards [6]–[8], which focus on zero congestion loss and bounded latency for time-sensitive traffic. These standards use per-traffic class scheduling and shaping, resource reservation, preemption, and replication strategies. Low latency is achieved through scheduling in IEEE 802.1Qbv and shaping in 802.1Qcr, with traffic shaping options including time-schedule-based, credit-based, and asynchronous methods. Tim-

ing guarantees come from resource reservation (802.1Qcc) or frame preemption (802.1Qbu). Reliability is supported by frame replication and elimination (IEEE 802.1CB), with bridge functions defined in IEEE 802.1Q. These Ethernet standards are being adapted to wireless, with 3GPP Release 16 adding support for TSN via quality of service (QoS) mapping.

Most modern industrial automation scenarios use both Ethernet and wireless communication. We developed a simulation testbed supporting multiple traffic flows over an integrated 5G-TSN network for an indoor factory floor conforming to 3GPP 38.901 specifications. It uses the OMNeT++, INET, and Simu5G libraries along with a QoS-aware simulation framework, 5GTQ [9], as detailed in Section III. This testbed helps assess closed-loop WNCS dynamics, supporting feasibility analyses and integrated communication-control design.

In this paper, we demonstrate the feasibility of wireless networked control for industrial systems with rapid dynamics using an integrated Ethernet-based TSN and 5G solution. To the best of our knowledge, this is the first paper to jointly address control and communication challenges in WNCS with integrated 5G-TSN networks.

The main *contributions* of this paper include:

- developing a simulation testbed for WNCS that utilize an integrated 5G-TSN network on an indoor factory floor, adhering to 3GPP 38.901 specifications;
- analyzing communication delays and message dropouts through extensive Monte Carlo simulations to assess control-application communication reliability;
- demonstrating closed-loop control for fast industrial systems over 5G-TSN with an inverted pendulum on a cart, using a 2 ms sampling period.

The *related work* on 5G-TSN integration, its applications in industrial automation, and simulation and hardware testbeds is thoroughly covered by dedicated surveys, [10]–[12]. [10] surveys wireless TSN, detailing 5G-based architectures, testbeds, and applications, with a focus on synchronization, latency, reliability, traffic scheduling, and resource allocation. All the simulation testbeds listed in [10] rely on OMNeT++, with the latest ones, [9] and [13], using INET and Simu5G model libraries. Our WNCS simulation testbed builds on the QoS-aware framework of [9], adding an indoor factory floor environment, extending QoS mapping to control-application traffic,

and implementing application-layer logic. [11] reviews literature on 5G-TSN integration, highlighting emerging trends, technical requirements, and areas where current research can be improved. It acknowledges OMNeT++ as a leading simulation framework for performance assessment. This finding is corroborated by [12], which surveys open-source 5G-TSN simulation tools, software components, and hardware options available for integrating these components. Finally, [14] and [15] propose alternative algorithms for 5G-TSN data flow QoS mapping.

The rest of this paper is *organized* as follows. Section II introduces the WNCS integrated with 5G-TSN communication. Section III describes the simulation testbed architecture and setup. Section IV presents the simulation results, and Section V concludes the paper.

II. INTEGRATED 5G-TSN WNCS ARCHITECTURE

The primary challenge in designing WNCS lies in the intricate interplay between the communication and control subsystems, as discussed in [1] and [5]. Each controlled system, also known as a plant, typically processes continuous signals that necessitate quantization and sampling for digital transmission over a communication network. The appropriate sampling method and its fundamental features, such as the sampling period or level-crossing thresholds, depend on the plant characteristics and impose strict constraints on suitable communication technology. For instance, the inverted pendulum stabilization problem may require time-triggered sampling with short sampling periods of 1–6 ms, depending on the plant parameters, such as the length and mass of the vertical rod, as well as the specific controller implementation [16]. Legacy industrial wireless communication standards, including IEEE 802.15.4e low-latency deterministic network (LLDN), WirelessHART, ISA100.11a, and Zigbee PRO 2015, do not support sampling periods shorter than 10 ms [5]. Consequently, an integrated 5G-TSN communication solution emerges as an attractive option for industrial control of systems exhibiting rapid dynamics.

Fig. 1 shows a WNCS architecture integrated with 5G-TSN communication. The 5G user equipment (UE) connects the physical system, which includes a plant along with its sensors and actuators, at the application layer to a controller on a TSN-enabled device within an Ethernet-based network. The network-side TSN translator (NW-TT), situated within the user plane function (UPF), handles translation and QoS mapping between TSN and 5G data streams. The plant sensing link transmits sensor data (e.g., y_k) from the 5G UE to the 5G base station (gNB), which then forwards it to the UPF and ultimately to the TSN device hosting the plant control application. The sensor message handler (SMH) sends sensor data to the controller at a set time. In the simplest implementation, the SMH resets an internal buffer to zero at the start of its sampling period (T_s) and waits for a specific period (τ_s) for new data. At the end of the waiting period, the SMH sends its buffer content to the controller, effectively discarding outdated data, as illustrated in Fig. 2. At time step k , $\gamma_k = 1$

indicates the arrival of new sensor data within τ_s ; otherwise, $\gamma_k = 0$. The output-feedback controller in Fig. 1 addresses the linear-quadratic-Gaussian (LQG) problem by integrating a Kalman filter in its current estimator form—depicted by the system state estimator and estimator dynamics blocks—with a linear-quadratic regulator (LQR), shown by the state feedback block. The plant actuation link transmits control commands (e.g., $\hat{u}_k$) from the output-feedback controller on a TSN device to the UPF, gNB, and ultimately to the 5G UE of the physical system. Similar to the SMH, the plant control message handler (CMH) delivers control commands to the actuators at a set time. The CMH resets its internal buffer to zero at the start of the sampling period and waits for a specific duration (τ_c) for a new command to arrive. At the end of this waiting period, the CMH sends its buffer contents to the actuators, effectively clearing outdated commands. $\delta_k = 1$ indicates the reception of a new control command within τ_c ; otherwise, $\delta_k = 0$. The output-feedback controller needs to know if its latest control command has been received promptly by the actuators. The plant actuation acknowledgment link provides this information. If an acknowledgment does not arrive within the specified time interval (τ_a), the acknowledgment message handler (AMH) assumes the control command has been lost and reports it to the state estimator ($\alpha_k = 0$). Otherwise, the AMH provides the state estimator with the result of the control message transmission δ_k .

Fig. 2 shows an example of information flow in a WNCS timing diagram. Full black arrows denote messages transmitted through the integrated 5G-TSN communication network, whereas thinner gray arrows illustrate information exchange within the local application. The plant control components are in gray, while the UE physical system components are in black. In the top left corner, x_k indicates the plant state at discrete time k . The discrete-time index k increases by one after each sampling period T_s . Sensors measure the plant state as $y_k = Cx_k + v_k$, where C is the system output matrix, and v_k is white Gaussian measurement noise with variance Σ_v . The thin gray vertical line indicates that the measurement time is much shorter than the sampling time and can be ignored. The UE transmits y_k to the TSN device over the sensing link, shown by the thick black arrow. The message is received within τ_s , so $\gamma_k = 1$ and the received measurement is $\hat{y}_k = y_k$. Subsequently, the state estimator performs the update step employing the predicted system state, $\bar{x}_k$, and the received measurement: $\hat{x}_k = \bar{x}_k + M(\hat{y}_k - C\bar{x}_k)$, where M represents the innovation gain matrix. The LQR computes the control input to actuators as $\hat{u}_k = -K\hat{x}_k$, where K is the feedback gain matrix. The control input is sent to the state estimator for state prediction and transmitted as a message over the actuation link. This message is received within τ_c , so $\delta_k = 1$, and the actuators' input is $u_k = \hat{u}_k$. This input affects the plant state as $x_{k+1} = Ax_k + Bu_k + Gw_k$, where A , B , and G are the system state, input, and process noise matrices, respectively, while w_k is white Gaussian measurement noise with variance Σ_w . The result of the control message

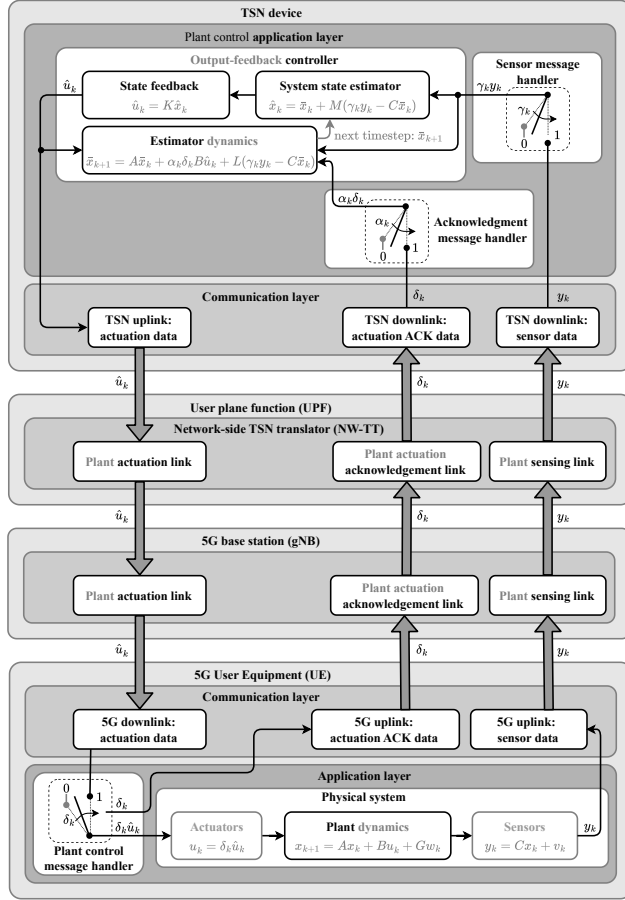


Fig. 1. A WNCS architecture integrated with 5G-TSN communication.

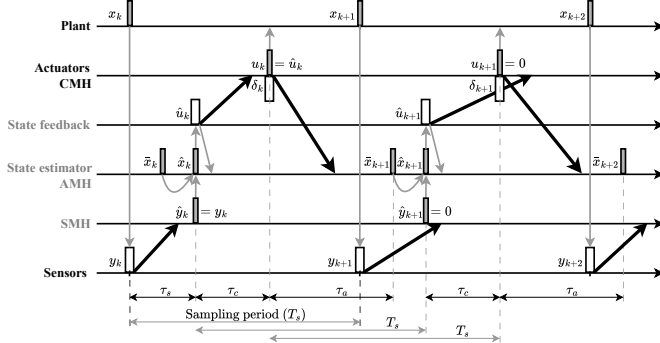


Fig. 2. A WNCS timing diagram.

transmission, $\delta_k = 1$, is sent back to the state estimator via the acknowledgment link. This acknowledgment is received within τ_a , so $\alpha_k = 1$. At this point, the state estimator has all the necessary information to carry out the prediction step as $\bar{x}_{k+1} = A\bar{x}_k + \alpha_k \delta_k B \hat{u}_k + L(\gamma_k y_k - C\bar{x}_k)$, where L is the Kalman filter gain. The procedure is reiterated for the subsequent discrete time $k + 1$. In the example illustrated in Fig. 2, the sensing measurement message y_{k+1} is received with a delay exceeding τ_s , resulting in $\gamma_{k+1} = 0$. Consequently, the message content is discarded by the SMH, and, therefore, $\hat{y}_{k+1} = 0$. Since the control input message $\hat{u}_{k+1}$ exceeds τ_c , CMH discards it, resulting in $\delta_{k+1} = 0$.

We note that any sensing, control, and acknowledgment message may be discarded due to excessive delay, resulting in eight different transmission outcome combinations possible at each discrete time step k , depending on the values of γ_k , δ_k , and α_k . The asymptotic gain matrices for the LQG controller are obtained as follows. $K = (B^T X B + R)^{-1} B^T X A$, where $R \succ 0$ is a positive-definite input weighting matrix, X is the solution to the discrete-time algebraic Riccati equation (DARE) $X = A^T X A - A^T X B (B^T X B + R)^{-1} B^T X A + Q$, and $Q \succeq 0$ is a positive-semidefinite state weighting matrix. Furthermore, ^{T} represents the matrix transpose, and $^{-1}$ indicates the matrix inverse. Then, $L = A Y C^T (C Y C^T + \Sigma_v)^{-1}$, and $M = Y C^T (C Y C^T + \Sigma_v)^{-1}$, where Y is the solution to the DARE $Y = A Y A^T - A Y C^T (C Y C^T + \Sigma_v)^{-1} C Y A^T + \Sigma_w$.

The traditional LQG controller outlined above disregards the statistical properties of stochastic processes $\{\gamma_k\}$, $\{\delta_k\}$, and $\{\alpha_k\}$. This shortcoming could result in subpar performance or even instability [17], [18]. Knowing the expected values of $\{\gamma_k\}$, $\{\delta_k\}$, and $\{\alpha_k\}$ and their dependence on the wireless channel state enables the design of advanced WNCS systems [17], [19], [20]. The subsequent section outlines the architecture of the simulation testbed and its configuration, which aims to derive the statistical properties of pertinent stochastic processes within an integrated 5G-TSN communication network supporting wireless networked control.

III. SIMULATION TESTBED ARCHITECTURE AND SETUP

The simulation testbed uses the OMNeT++ discrete-event simulation library [21], combined with the INET and Simu5G model libraries [22]. The INET model library supports the Internet stack, especially the user datagram protocol (UDP) and Internet protocol (IP) in both versions 4 and 6, as well as wired and wireless link layer protocols like Ethernet and IEEE 802.11. It also includes custom mobility models and QoS architectures. The Simu5G model library allows for simulating 5G New Radio (NR) data plane deployments from end to end, including all protocol layers. The physical layer (PHY) interacts with the channel models that follow the 3GPP 38.901 specification [23]. The testbed uses the QoS-aware 5G-TSN simulation framework (SGTQ, [9]) for 5G-TSN translation. It performs QoS mapping between TSN and 5G traffic by aligning the TSN priority code point (PCP) classifier with the 5G QoS identifier (5GQI) and offers 5G QoS-aware priority scheduling. These functionalities are offered at the 5G service data adaptation protocol (SDAP) sublayer. Our testbed currently uses OMNeT++ 6.0.3, INET 4.5, and Simu5G 1.2.2. The following subsections provide our implementation details.

A. Indoor Factory Floor Scenario

Our indoor factory floor (InF) measures 120 m by 60 m and conforms to 3GPP 38.901. 18 gNBs are placed every 20 m, 10 m from the wall [23, Table 7.8-7]. The Simu5G channel model is extended to InF with a sparse clutter and low base station height (InF-SL) as in [23]. Table I summarizes the changes made to the Simu5G LteRealisticChannelModel module.

TABLE I
INF-SL IMPLEMENTATION

Method	Parameter Reference
computePathLoss	[23, Table 7.4.1-1]
computeLosProbability	[23, Table 7.4.2-1]
computeShadowing	[23, Table 7.2-4]

B. Network and Traffic Model with QoS Mapping over 5G

Fig. 3 shows the network topology. A relevant section of the TSN over Ethernet network is displayed in the top-right corner, including two TSN devices, a plant controller, and a material-handling device. Both are connected to a TSN switch, which is linked to a 5G UPF that performs the NW-TT. Although the UPF connects to all the gNBs located in the InF, only one gNB provides connectivity to two UEs, supporting a plant and a material-handling vehicle. Traffic from other gNBs is not included in this setup, as the main focus is on 5G-TSN integration. The traffic routes considered in this setting connect the plant controller to the plant and the material-handling device to the vehicle. The traffic model includes plant control, supervision, and best-effort traffic from the plant controller to the plant, as well as material supervision and best-effort traffic from the material-handling device to the vehicle. Additionally, sensor reporting and actuation acknowledgment traffic flow from the plant to the plant controller. Table II outlines the QoS mapping for each traffic flow, with QoS characteristics detailed in the current stable release of the relevant 3GPP technical specification [24, Table 5.7.4-1]. Due to their criticality, the plant control data flow has the highest 5GQI and PCP values, closely followed by actuation acknowledgment and sensor reporting. This mapping is tailored to a specific application. Future research could explore a more systematic analysis of mapping options across different applications and traffic loads.

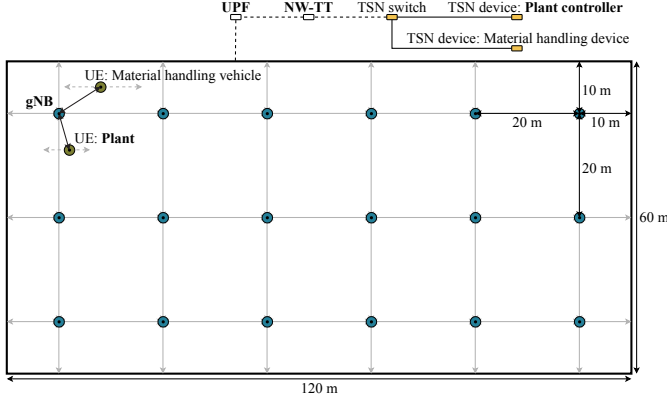


Fig. 3. Network topology diagram.

C. Plant Model and Parameters

We analyze a linearized model of an inverted pendulum on a cart [25]. The plant's state ξ_k includes the linear displacement of the cart, the pendulum angle, and their derivatives. Only the position of the cart and the pendulum angle are measured by sensors. From [26, Sec. 4.3.4] and [27], the dynamics of a

TABLE II
TRAFFIC FLOW QoS MAPPING

Flow	QoS Mapping	
	PCP	5GQI
Best effort	0	5
Material supervision	4	74
Plant supervision	5	80
Actuation acknowledgment	6	82
Sensor reporting	6	82
Plant control	7	86

discrete-time system with an input delay $\tau_i = \tau_s + \tau_c \leq T_s$ are given by $\xi_{k+1} = A_1 \xi_k + B_1 u_{k-1} + B_2 u_k + w_k$, where A_1 , B_1 , and B_2 are constant matrices. Under the zero-order hold, these matrices are defined by the constant continuous-time system's state and input matrices, Γ and Ψ . For any time interval λ , let $\mathcal{A}(\lambda) = e^{\Gamma\lambda}$ and $\mathcal{B}(\lambda) = \int_0^\lambda e^{\Gamma\varsigma} d\varsigma \Psi$. Then, $A_1 = \mathcal{A}(T_s)$, $B_1 = \mathcal{A}(T_s - \tau_i) \mathcal{B}(\tau_i)$, and $B_2 = \mathcal{B}(T_s - \tau_i)$. To obtain the system's dynamics in the standard state-space form described in Section II, we use the following augmented system:

$$x_k = \begin{bmatrix} \xi_k \\ u_{k-1} \end{bmatrix}, \quad A = \begin{bmatrix} A_1 & B_1 \\ 0 & 0 \end{bmatrix}, \quad B = \begin{bmatrix} B_2 \\ I \end{bmatrix}, \quad G = \begin{bmatrix} I \\ 0 \end{bmatrix},$$

where I is the identity matrix of the appropriate size.

For the inverted pendulum on a cart linearized around the unstable equilibrium, the system parameters are as follows.

$$\Gamma = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 2.2643 & -15.8866 & -0.0073 \\ 0 & 27.8203 & -36.6044 & -0.0896 \end{bmatrix}, \quad \Psi = \begin{bmatrix} 0 \\ 0 \\ 2.2772 \\ 5.2470 \end{bmatrix},$$

$T_s = 2$ ms, $\Sigma_w = 10^{-6}(I_5 - e_5^\top e_5)$, and $\Sigma_v = 4 \cdot 10^{-4} I_2$, where I_n is the identity matrix of size n , e_i is the i th column vector of the standard basis of the Euclidean space of dimension 5.

IV. RESULTS AND DISCUSSIONS

We ran 1600 Monte Carlo simulations of 60 s each, collecting 30000 data points per run, totaling 48 million data points. We used a global simulation time as an ideal clock to establish the baseline delay for each link. Future work could explore the effects of time synchronization.

A. Communication delay analysis

Fig. 4 shows the relative occurrence of sensing, actuation, and acknowledgment delays across all simulations. All sensor messages arrive within 5.2 ms, 99.98% of which have a delay of less than 0.841 ms. 99.9975% of actuation messages arrive within 0.285 ms, 99.9998% within 0.660 ms, and 99.9999% within 1.035 ms, while the remaining 0.0001% are lost. All acknowledgment messages are received within 6.898 ms. Of these, 99.9667% have a delay under 0.593 ms, and 99.9848% are under 1.461 ms.

B. Message dropout analysis

As outlined in Section II, SMH, CMH, and AMH discard late messages based on thresholds τ_s , τ_c , and τ_a , which must be shorter than the sampling period T_s , so that $\tau_s + \tau_c < T_s$,

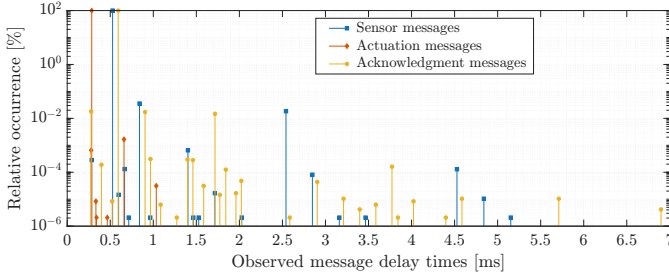


Fig. 4. Message delay distribution across all simulations for the relevant links.

and $\tau_c + \tau_a < T_s$. We set $\tau_s = 0.841$ ms, $\tau_c = 0.285$ ms, and $\tau_a = 1.461$ ms to satisfy these constraints, based on the observed message delay distributions shown in Fig. 4. Fig. 5 shows the number of discarded and lost messages over sensing, actuation, and control links in each Monte Carlo simulation.

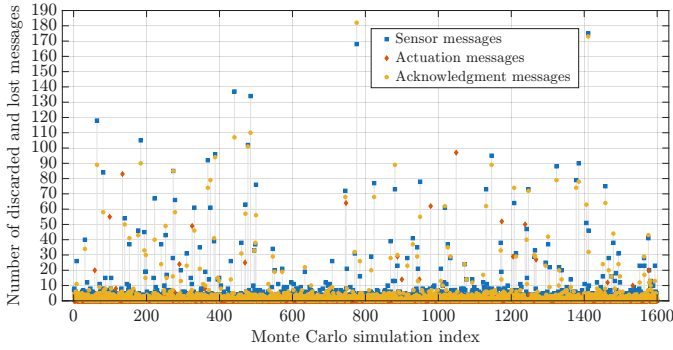


Fig. 5. Message dropout counts for each simulation.

Table III shows the message dropout correlation coefficients: the sensing and acknowledgment links exhibit a weak but significant correlation of 0.048. A possible explanation for this weak correlation is that the sensing and acknowledgment links share the same 5G data plane uplink and experience similar channel conditions, whereas the actuation link is a downlink.

TABLE III
MESSAGE DROPOUT CORRELATION BETWEEN LINK PAIRS

Link	Sensing	Actuation	Acknowledgment
Sensing	1	0.017785	0.048132
Actuation	0.017785	1	0.000736
Acknowledgment	0.048132	0.000736	1

Our simulations show that the actuation link is the most reliable, with the quickest response times and the lowest message loss rate. It fully meets the C class of service requirements for time-sensitive applications (latency below 1 ms and reliability above 99.999%, [28]). The sensing and application-layer acknowledgment links only meet the class B requirements for time-sensitive applications (which demand 10–1 ms latency and reliability of 99.9–99.99%), and they also exhibit correlated message loss. As shown in Section II, both sensing and acknowledgment information are necessary for the remote system state estimation (in the prediction step), indicating that neither acknowledgment nor sensing link

dynamics should be considered ideal because of the significant message losses and delays they cause.

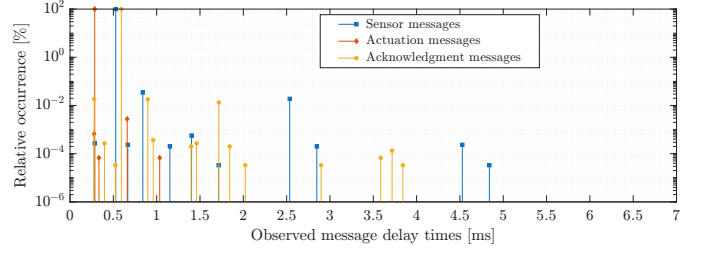


Fig. 6. Message delay distribution across the first 100 simulations.

As a final remark, we note that the thresholds τ_s , τ_c , and τ_a for SMH, CMH, and AMH are derived from the message delay distributions shown in Fig. 4. In real-world scenarios, these distributions are typically unknown in advance. In practice, the thresholds are set in a data-driven manner: initial values are established during a brief measurement phase and then adjusted using operational data. Fig. 6 shows the relative occurrence of sensing, actuation, and acknowledgment delays across the first 100 simulations. It reports that 99.9799% of observed sensor messages arrive within 0.841 ms. 99.9969% of actuation messages arrive within 0.285 ms, and 99.9861% of acknowledgment messages have a delay of less than 1.461 ms. Consequently, $\tau_s = 0.841$ ms, $\tau_c = 0.285$ ms, and $\tau_a = 1.461$ ms can be confidently determined in the given setting, even with a short measurement campaign collecting just 100 min of operational data. The threshold selection criterion is straightforward: choose values that minimize delay and maximize cumulative relative occurrence, subject to the sampling period constraint. This criterion balances two conflicting objectives: reducing delays and limiting the number of discarded messages.

C. Closed-loop system dynamics

For any suitable integer i , let $x_i(k)$, $y_i(k)$, and $\hat{x}_i(k)$ denote the i th component of the system state, output, and estimated state at time k , respectively. Figs. 7 and 8 show how their first two components change over time, as seen in the 776th and 1049th simulations. As specified in Section III-C, the first two components indicate the linear displacement of the cart and the pendulum angle. Similar to those in Figs. 7 and 8, all the closed-loop system dynamics remain stable despite process and measurement noises, as well as sensing, actuation, and acknowledgment message dropouts, which were most severe in the 776th and 1049th simulations.

V. CONCLUSION

This paper presented a WNCs simulation testbed designed to support industrial applications and cross-layer optimization. The testbed allowed us to analyze the end-to-end communication delay in the closed-loop control of an inverted pendulum on a cart within an indoor factory environment, involving mixed traffic over an integrated 5G-TSN network. We found evidence of message dropout correlation over sensing and acknowledgment uplinks, which is often overlooked in the

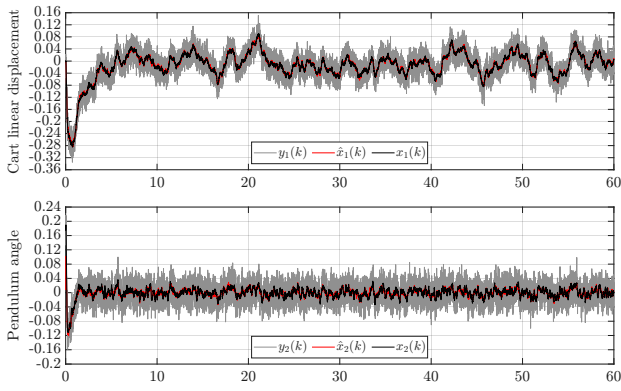


Fig. 7. System output, estimated state, and true state (776th simulation)

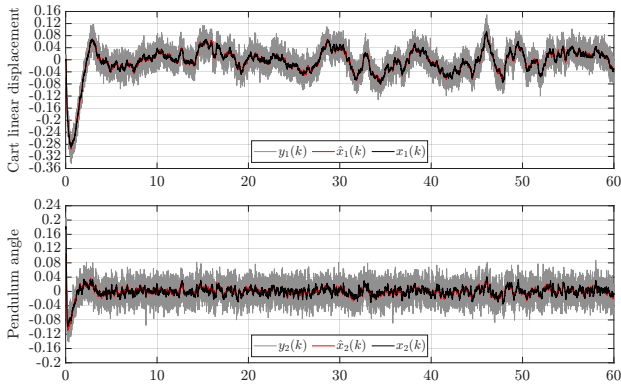


Fig. 8. System output, estimated state, and true state (1049th simulation)

WNCS literature. Nonetheless, the closed-loop system dynamics remained stable under traditional LQG control, thanks to timely message delivery in over 99.98% of cases. Future work could explore more advanced cross-layer designs for integrated ultra-reliable low-latency communication services. Additional efforts could focus on automating configuration, batch execution, and analysis to improve the testbed's usability before releasing its source code.

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