Sampling-Induced Dynamics in Networked Control Systems with Stochastic Delay

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Abstract: This paper investigates the impact of stochastic communication delay on networked control systems under discrete-time implementation. While classical analysis typically models delay as constant or weakly time-varying, practical communication infrastructures introduce stochastic jitter and asynchronous updates that can fundamentally alter the observed closed-loop behavior. A hardware-in-the-loop (HIL) architecture based on TCP/WebSocket communication is employed to reproduce realistic network effects, while an equivalent discrete-time simulation framework is used for systematic analysis and reproducibility. The results show that stochastic delay does not merely degrade performance, but induces non-exponential transients, irregular oscillations, and deviations from classical linear time-invariant (LTI) dynamics, even for a linear plant under proportional feedback. A central finding of this work is the strong interaction between delay variability and sampling resolution. Coarse sampling may artificially mask instability by smoothing delay fluctuations, whereas finer sampling reveals instability under identical delay conditions. Moreover, the discretization of stochastic delay is shown to generate structured transient-like responses, indicating that sampling actively reshapes the effective system dynamics. These findings suggest that stochastic delay should not be treated solely as a disturbance, but as a dynamic mechanism intrinsically coupled to discretization and implementation effects.

Keywords: Networked control systems; Stochastic delay; Jitter; Sampling effects; Time-varying systems; Communication-induced dynamics

1. INTRODUCTION

Networked Control Systems (NCS) have become a fundamental paradigm in modern control applications, including teleoperation, robotics, and IoT-based automation systems. In such systems, the control loop is closed over a communication network, introducing non-idealities such as delays, packet loss, and jitter.

Classical control theory typically assumes either negligible delay or constant time-delay models. However, practical implementations exhibit stochastic and time-varying delays, especially when communication is implemented over packet-based or web-based infrastructures.

The challenges associated with network-induced delays in control systems have been extensively studied over the past decades. Early foundational works, such as Zhang et al. (2001), established that even small communication delays may significantly affect closed-loop stability, particularly in fast dynamic systems. A comprehensive survey by Hespanha et al. (2007) highlighted that networked control systems must explicitly account for delays, packet drops, and asynchronous sampling, emphasizing that classical control assumptions are no longer valid in such contexts.

Subsequent research has focused on stability analysis of time-delay systems using Lyapunov-based methods. In particular, Fridman (2014) provides a rigorous theoretical framework for systems with constant and time-varying delays, while Seuret and Gouaisbaut (2013) introduced improved integral inequalities that reduce conservatism in stability conditions.

More recent research has extended classical delay analysis toward stochastic and time-varying communication models, emphasizing the impact of jitter, asynchronous sampling, and communication uncertainty on closed-loop stability and performance Liu et al. (2019a,b); Mishra et al. (2020); Bengtsson and Wik (2022). Despite these advances, many existing approaches rely on strong probabilistic assumptions or computationally intensive formulations, while experimental validation under realistic communication infrastructures remains relatively limited.

Despite these advances, several limitations remain. Many existing approaches rely on strong assumptions, such as known delay distributions, probabilistic channel models, or structured packet loss processes. Furthermore, they often introduce significant computational burden or architectural complexity, which may hinder real-time implementation. More importantly, experimental validation under realistic network conditions – particularly in web-based or TCP-driven environments – remains relatively limited.

In particular, there is a lack of studies that explicitly quantify how stochastic delay variability affects the effective closed-loop dynamics of classical controllers when implemented over non-deterministic communication infrastructures. To the best of our knowledge, few works simultaneously address stochastic delay effects in real-time implementations while maintaining low

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implementation complexity and avoiding strong probabilistic assumptions.

The present work addresses this gap by focusing on the experimental characterization of stochastic delay effects in real-time control systems, where such assumptions are not directly available or may not hold. The proposed approach departs from model-heavy stochastic formulations and instead emphasizes a practical and experimentally grounded perspective.

Specifically, the work is motivated by a hardware-in-the-loop (HIL) experimental setup in which a Matlab/Simulink controller interacts in real time with a remote plant emulator implemented in JavaScript via WebSocket communication. This architecture inherently introduces time-varying communication delay, stochastic jitter, asynchronous sampling, and non-deterministic feedback timing, leading to degradation of stability margins not captured by classical linear time-invariant models.

The impact of stochastic delay in this TCP/WebSocket-based HIL framework is systematically investigated, with particular relevance to robotic and remote control applications where network-induced jitter is unavoidable.

The main contributions of this paper are as follows:

- A real-time HIL framework for reproducing stochastic communication delay and jitter in networked control systems;
- An experimentally grounded discrete-time analysis of stochastic delay effects under asynchronous sampling;
- The identification of emergent transient-like dynamics induced by the interaction between delay variability and sampling resolution;
- Experimental evidence that coarse discretization may mask instability under stochastic delay conditions.

In contrast to existing works that rely on probabilistic models or computationally intensive control strategies, the proposed approach provides a low-complexity and experimentally validated framework for understanding and designing control systems under realistic network conditions.

The remainder of this paper is organized as follows. Section 2 presents the problem formulation, introducing a discrete-time model of the networked control system that explicitly captures stochastic delay, jitter, and asynchronous sampling effects. Section 3 describes the proposed hardware-in-the-loop experimental architecture. Sections 4 and 5 present the experimental setup, experimental results and analysis. Finally, Section 6 concludes the paper and discusses future research directions.

2. PROBLEM FORMULATION

Consider a continuous-time linear time-invariant (LTI) plant given by

$$\dot{x}(t) = Ax(t) + Bu(t) \ , \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state vector and $u(t) \in \mathbb{R}^m$ is the control input.

In a standard digital control implementation, the system is sampled with a fixed sampling period T_s, and the control signal is updated synchronously. However, in a networked control system (NCS), the feedback loop is closed over a communication network, introducing non-idealities such as time-varying delay, jitter, and asynchronous updates.

In this work, we consider a networked architecture in which the controller and the plant are physically separated and communicate via a TCP/WebSocket-based protocol. As a result, the control loop is affected by a stochastic communication delay, denoted by τ_k, which varies at each sampling instant.

Let t_k denote the k-th sampling instant at the controller side. Due to network effects, the control input u_k computed at time t_k is applied to the plant at time

$$t_k^a = t_k + \tau_k \ , \tag{2}$$

where τ_k is a stochastic, time-varying delay.

Similarly, the measured output is transmitted back to the controller with an additional delay, which may differ from the forward channel delay, resulting in an overall asynchronous feedback loop.

To capture these effects, we adopt a discrete-time representation with variable delay. Assuming zero-order hold (ZOH) actuation, the state evolution can be described as

$$x_{k+1} = \Phi x_k + \Gamma(\tau_k) u_{k-d_k} \ , \tag{3}$$

where $\Phi = e^{AT_s}$ and $\Gamma(\tau_k)$ depends on the effective delay within the sampling interval. The integer d_k represents the number of sampling periods corresponding to the delay τ_k, i.e.,

$$d_k = \left\lfloor \frac{\tau_k}{T_s} \right\rfloor \ . \tag{4}$$

The presence of τ_k introduces two key effects:

- *Variable input delay*: the control action is applied with a time shift that varies at each step;
- *Sampling asynchrony*: the controller operates on outdated or irregularly spaced measurements.

In contrast to classical time-delay systems, the delay τ_k is not assumed to follow a known distribution, nor is it bounded by a deterministic model. Instead, it is treated as an experimentally observed stochastic process arising from the communication infrastructure.

The control law is assumed to be a simple proportional feedback controller

$$u_k = -Kx_k \ , \tag{5}$$

where K is a constant gain matrix designed without explicit compensation for delay variability.

Under these conditions, the closed-loop system becomes a stochastic, time-varying system, whose stability and performance depend not only on the controller gains but also on the statistical properties of the delay sequence $\{\tau_k\}$.

The objective of this work is to experimentally characterize how stochastic delay affects the closed-loop dynamics, and to identify regions in the controller parameter space where stability is preserved or lost as a function of delay variability.

3. SYSTEM DESCRIPTION AND MODELING

3.1 Networked Control Architecture

The considered system is a networked control architecture in which the controller and the plant are physically decoupled and communicate over a TCP/WebSocket-based network. The controller is implemented in Matlab/Simulink, while the plant is emulated remotely using a JavaScript-based environment.

The communication between both entities is established through a bidirectional client-server protocol, introducing non-deterministic transmission delays, variable sampling intervals, and asynchronous data exchange. This architecture reflects realistic scenarios found in teleoperation systems, remote robotics, and cloud-based control applications.

Preliminary observations were obtained using the real-time WebSocket-based implementation. However, for systematic analysis and reproducibility, an equivalent simulation framework was employed, preserving the key communication-induced effects.

At each control cycle, the controller computes a control signal based on the most recently received state measurement and transmits it to the plant through the network. Due to communication latency, the control signal is not applied instantaneously, resulting in a time-varying actuation delay. Similarly, sensor measurements are affected by transmission delay before reaching the controller.

3.2 Communication and Delay Modeling

Let τ_k^{sc} and τ_k^{ca} denote the sensor-to-controller and controller-to-actuator delays at the k-th iteration, respectively. The total round-trip delay is therefore time-varying and given by

$$\tau_k = \tau_k^{sc} + \tau_k^{ca} \; . \tag{6}$$

In practical implementations over TCP/WebSocket protocols, these delays are influenced by factors such as network congestion, buffering mechanisms, operating system scheduling, and asynchronous message handling. As a result, τ_k exhibits stochastic variability and cannot be accurately described by a deterministic or stationary probabilistic model.

In this work, the delay is treated as an experimentally observed quantity, measured in real time during system operation. This approach avoids imposing restrictive assumptions on its statistical properties and allows direct characterization of its impact on control performance.

3.3 Discrete-Time Representation

To analyze the system behavior, a discrete-time model is adopted. Let t_k denote the sampling instants at the controller side. Due to asynchronous communication, the measurement available at time t_k corresponds to a delayed state of the plant.

Assuming zero-order hold actuation, the system can be described as

$$x_{k+1} = \Phi x_k + \Gamma(\tau_k) u_{k-d_k} \; , \tag{7}$$

where $\Phi = e^{AT_s}$, $\Gamma(\tau_k)$ captures the effect of partial input application within the sampling interval, and d_k represents the discrete delay associated with τ_k.

Control Law The control input is defined as a state-feedback law of the form

$$u_k = -K x_k \; , \tag{8}$$

where K is a constant gain matrix designed based on the nominal delay-free model of the plant.

It is important to emphasize that the controller is intentionally restricted to a proportional structure, leading to a non-zero steady-state error. This is not a limitation, but a deliberate modeling choice aimed at isolating the impact of stochastic communication delay on the system dynamics.

The controller is intentionally restricted to a proportional structure in order to isolate the effects of stochastic communication delay on the closed-loop dynamics. More sophisticated compensation strategies could partially mask the phenomena under investigation by introducing additional dynamical mechanisms. Therefore, the objective of this work is not optimal tracking performance, but the experimental characterization of delay-induced effects under realistic communication conditions. The formulation is general and can represent a wide class of controllers, including linear state-feedback laws and approximations of more complex control strategies implemented in discrete time. In this work, no explicit compensation for communication-induced delay is included in the control design.

In the presence of stochastic delay, both the state measurement used to compute u_k and the application of the control signal are affected by time-varying latency. These effects introduce phase lag and modify the effective closed-loop dynamics, potentially leading to performance degradation and instability.

Under these conditions, the closed-loop system becomes time-varying and driven by stochastic delay, with behavior that depends jointly on the controller parameters and the communication-induced delay variability.

This modeling framework serves as the basis for interpreting the experimental results presented in the following section.

Plant Model Used in Experiments For the purpose of experimental validation, a second-order discrete-time plant is considered as a representative benchmark. The model is obtained via zero-order hold discretization and is given by

$$G(z) = \frac{0.2924z + 0.2671}{z^2 - 1.676z + 0.763} \; . \tag{9}$$

This model captures the dominant dynamics of a torsional system configuration and serves as a simplified yet representative case for analyzing the impact of stochastic delay on closed-loop behavior.

The use of a low-order linear model is intentional, as it allows isolating the effects of communication-induced delay without additional complexities arising from higher-order or nonlinear dynamics.

4. EXPERIMENTAL SETUP

The experimental platform reproduces a realistic networked control scenario composed of: (i) a Matlab/Simulink controller, (ii) a TCP/WebSocket communication bridge, and (iii) a remote JavaScript-based plant emulator. It consists of three main components: (i) a controller implemented in matlab/simulink, (ii) a communication interface based on a TCP/WebSocket bridge, and (iii) a remote plant emulator implemented in JavaScript.

The controller runs in real time using a fixed sampling period and communicates with the remote plant through a custom S-function interface. This interface handles data serialization, transmission, and reception over the network.

The communication layer is implemented using a Node.js-based server acting as an intermediary between Simulink and the plant emulator. Messages are exchanged asynchronously using the WebSocket protocol, introducing non-deterministic delays and jitter.

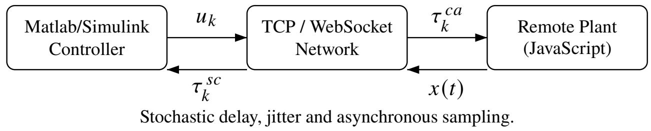

Figure 1. Networked control system architecture with bidirectional communication over a TCP/WebSocket network. The sensor-to-controller (τ_k^{sc}) and controller-to-actuator (τ_k^{ca}) delays are stochastic and time-varying.

The plant emulator executes the system dynamics and returns state measurements to the controller. Due to the asynchronous nature of the communication, the timing of control updates and measurements is not synchronized, resulting in variable effective sampling intervals.

To enable detailed analysis, timestamps are recorded at each stage of the communication process, allowing the measurement of round-trip delay, jitter, and timing irregularities. This data is used to correlate network behavior with closed-loop performance.

Experiments are conducted under different network conditions, including varying levels of induced delay and jitter. The controller gains are systematically varied to evaluate the impact of communication uncertainty on stability and performance.

This setup provides a flexible and reproducible framework for analyzing the effects of stochastic delay in networked control systems under realistic operating conditions.

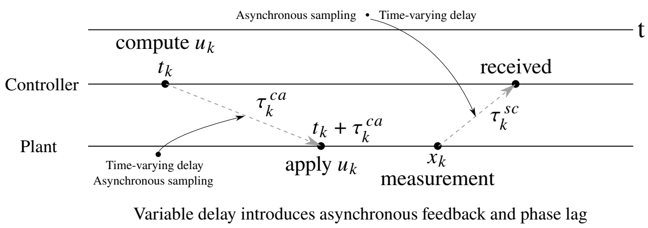

Figure 2. Illustration of stochastic delay in the control loop. The control signal u_k computed at time t_k is applied at the plant after a time-varying delay τ_k^{ca}, while measurements are received with delay τ_k^{sc}, resulting in asynchronous feedback and effective phase lag.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The impact of stochastic communication delay on the closed-loop system was evaluated under different configurations, including constant delay, time-varying delay (jitter), and different sampling resolutions.

Figure 3 compares the closed-loop responses under three conditions: nominal (delay-free), constant delay, and stochastic delay. While the nominal system exhibits a standard oscillatory convergence, the introduction of delay significantly degrades performance, increasing the settling time and altering the transient dynamics. When stochastic delay is introduced, the system behavior changes qualitatively, exhibiting irregular oscillations and a non-exponential decay profile.

The reference step is applied at $t = 0.2$ s to improve visualization of the transient response, and importantly, while the steady-state behavior remains consistent with classical predictions, the transient response is profoundly reshaped by stochastic delay.

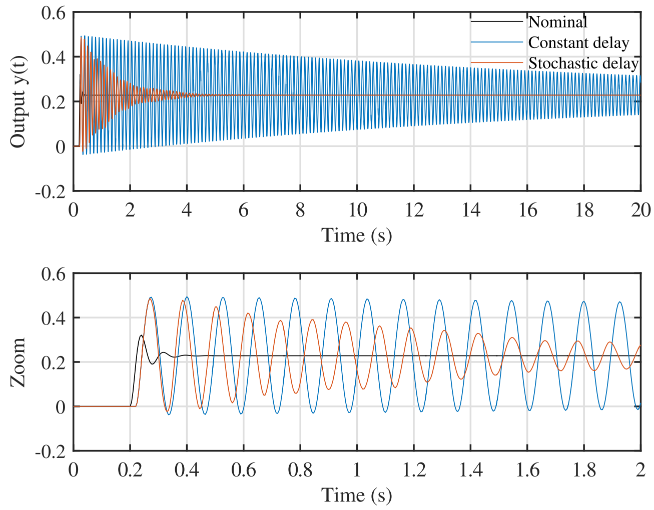

Figure 3. Closed-loop response under nominal, constant delay, and stochastic delay conditions. The top plot shows the full response over 20 s, while the bottom plot provides a zoom of the initial transient. The stochastic delay case exhibits irregular oscillations and deviation from exponential convergence.

To better understand this phenomenon, the discrepancy between the true plant output and the delayed measurement was analyzed, defined as

$$e(t) = y_{\text{true}}(t) - y_{\text{delayed}}(t) \ . \tag{10}$$

The resulting error signal, shown in Figure 4, does not follow a classical exponentially decaying pattern, indicating that the system can no longer be accurately described as linear time-invariant (LTI). Instead, the time-varying delay induces a stochastic modulation of the system dynamics, leading to time-varying phase distortions and amplitude fluctuations. The centered error representation reveals that stochastic delay introduces persistent fluctuations that are not captured by classical linear time-invariant models.

The statistical properties of this effect are illustrated in Figure 5, where the histogram of the error signal reveals a significant dispersion, confirming that the delay variability introduces uncertainty in the perceived system state.

To further quantify the impact of stochastic delay, the energy of the error signal is analyzed through its root-mean-square (RMS) envelope (Fig. 6). Interestingly, both constant-delay and stochastic-delay cases tend to converge toward similar asymptotic RMS levels, despite exhibiting substantially different transient dynamics. This suggests that the interaction between stochastic delay and sampling may induce an effective statistical equilibrium in the closed-loop error energy. Moreover, finer sampling resolutions reveal structured transient envelopes and persistent oscillatory modulations that become largely masked under coarser discretization.

Although a rigorous theoretical interpretation is beyond the scope of the present work, these observations strongly suggest that stochastic delay combined with discrete-time implementation may generate emergent statistical dynamics not captured by conventional LTI formulations. In particular, the convergence toward similar asymptotic RMS levels despite markedly different transient responses indicates that the interaction between

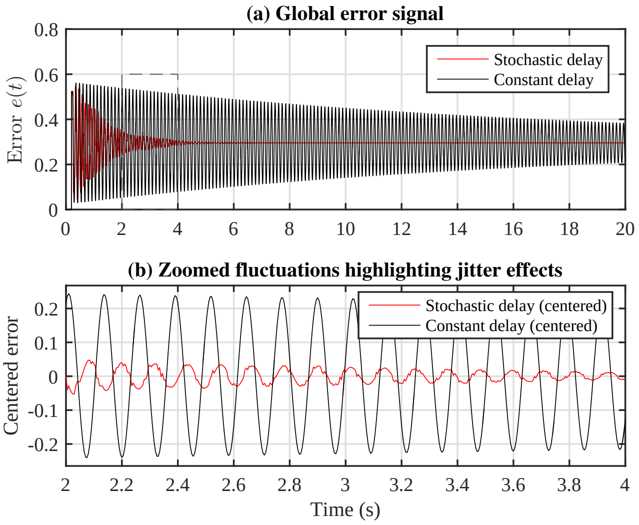

Figure 4. Error signal under constant and stochastic delay conditions. (a) Global behavior over the full simulation horizon. (b) Zoomed view in the interval $[2, 4]$ s, with centered signals to highlight high-frequency fluctuations. While constant delay produces smooth and predictable behavior, stochastic delay introduces irregular variations, revealing the departure from classical LTI dynamics.

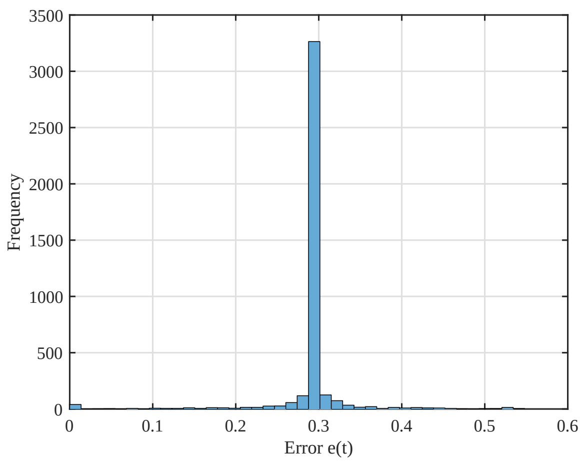

Figure 5. Distribution of the error signal under stochastic delay. The wide dispersion confirms the uncertainty introduced by delay variability.

sampling and delay variability may induce an effective statistical regime in the closed-loop dynamics.

A key result of this work is illustrated in Fig 7, where the same system is simulated using different fixed integration steps. When a coarse sampling period ($T_s = 0.02$ s) is adopted, the system appears to remain stable under stochastic delay conditions. However, reducing the sampling period to $T_s = 0.005$ s reveals a clear loss of stability under the same delay characteristics.

This apparent contradiction is not due to a change in the underlying system dynamics, but rather to the interaction between sampling resolution and the stochastic nature of the delay. Coarser sampling effectively introduces an implicit quantization and smoothing of the delay signal, attenuating its variability and partially masking its impact on the closed-loop behavior. In contrast, finer sampling captures a richer temporal structure of the delay, exposing high-frequency variations that significantly affect stability.

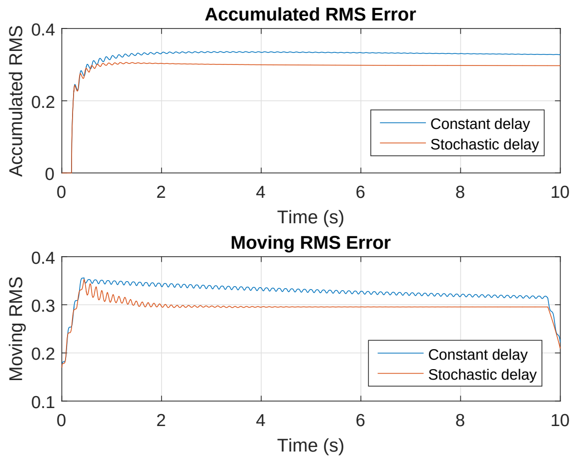

Figure 6. Accumulated and moving RMS analysis of the error signal under constant and stochastic delay conditions. Despite markedly different transient behaviors, both cases tend toward similar asymptotic RMS levels, suggesting the emergence of an effective statistical equilibrium in the closed-loop error dynamics. Fine sampling resolution reveals persistent oscillatory modulations and structured transient envelopes that are largely masked under coarser discretization.

To further elucidate this phenomenon, Fig 7 also presents the difference between delay realizations obtained under the two sampling resolutions. Remarkably, this difference signal exhibits an oscillatory behavior with a decaying envelope, resembling the transient response of a dynamical system, despite originating purely from a stochastic process. This indicates that the discretization of stochastic delay is not neutral, but instead induces emergent dynamics that can alter the observed system behavior.

These results demonstrate that sampling resolution plays a critical role in the analysis of networked control systems, and may lead to misleading conclusions if not properly accounted for. In particular, coarse discretization may artificially suggest stability by masking delay variability, while finer discretization reveals the true sensitivity of the system to stochastic delay.

This demonstrates that the interaction between sampling resolution and delay variability plays a critical role in the observed system behavior. In particular, coarse discretization introduces an implicit quantization of the delay, which may artificially attenuate the effect of jitter and mask instability.

These results highlight that stochastic delay not only degrades performance but fundamentally alters the structure of the closed-loop dynamics. Even for a simple linear plant and a basic feedback controller, the presence of time-varying delay leads to behavior that cannot be captured by classical LTI analysis.

The findings emphasize the need for control design methodologies that explicitly account for delay variability and its interaction with sampling and implementation constraints.

Beyond performance degradation, the results suggest that stochastic delay combined with discretization acts as a struc-

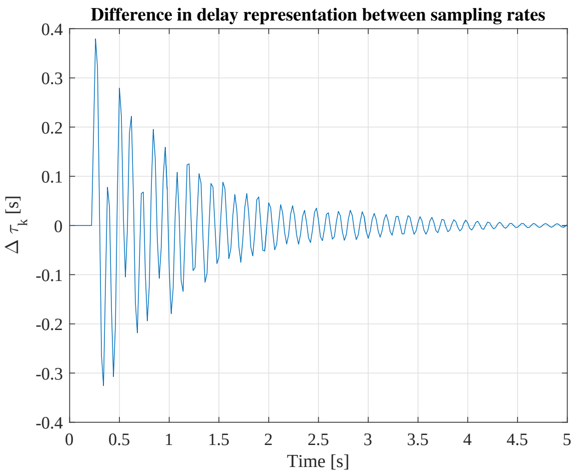

Figure 7. Comparison of system behavior under different sampling resolutions and corresponding delay difference signal. While the system appears stable for $T_s = 0.02$ s, instability is revealed for $T_s = 0.005$ s under identical stochastic delay conditions. The difference between the delay realizations exhibits an oscillatory transient-like behavior, highlighting that sampling resolution alters the perceived structure of stochastic delay and may introduce emergent dynamics.

tural mechanism capable of reshaping the effective closed-loop dynamics. This indicates that delay variability and sampling effects should be treated as intrinsic dynamical components rather than secondary implementation artifacts.

6. CONCLUSION

This paper investigated the impact of stochastic communication delay on networked control systems using a combined experimental and simulation-based framework.

The results demonstrate that time-varying delay and jitter do not merely degrade closed-loop performance, but fundamentally alter the structure of the observed system dynamics. Even in the case of a linear plant controlled by a simple proportional feedback law, the presence of stochastic delay leads to non-exponential transient behavior, irregular oscillations, and deviations from classical linear time-invariant (LTI) predictions.

A central contribution of this work is the identification of a strong interaction between delay variability and sampling resolution. It was shown that coarse sampling may mask instability by implicitly smoothing delay variations, while finer sampling reveals the full impact of stochastic delay, including the emergence of instability under otherwise identical conditions.

Furthermore, the analysis of delay realizations across different sampling resolutions revealed that the discretization of stochastic delay is not neutral. Instead, it can induce structured, transient-like dynamics, indicating that part of the observed system behavior may originate from the interaction between sampling and delay, rather than from the underlying plant dynamics alone.

These findings indicate that communication timing and sampling effects must be treated as intrinsic components of the closed-loop dynamics. Consequently, classical delay-free and purely LTI-based assumptions may become insufficient in realistic networked implementations.

Future work will focus on the development of control design methodologies that explicitly account for stochastic delay and its interaction with sampling effects, as well as on the extension of the present framework to nonlinear systems and real-world networked platforms.

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