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Optimal control and stability analysis of networked communication systems with Time-Varying Delays

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Abstract
The integrated system of physical plants, sensors, controllers, actuators, and communication networks with digital communication channels is called a networked control system (NCS). Scalability and flexibility are achieved with a networked implementation at the cost of delays caused by communication that can significantly affect closed-loop performance and destabilization of the controlled system. The situation gets more complex if the delays between the sensor and the controller and between the controller and the actuators are not deterministic but time-varying, and the bandwidth over which the communication occurs is limited. Event-triggered control can effectively reduce unnecessary transmissions, while predictive control can cope with the delay caused by the network. Yet optimal control performance, adaptive triggering of communication, two-channel time-varying delays and stringent stability guarantees are still important mathematical control problems that have not been solved yet. In this paper, we propose an optimal predictive control framework for linear networked control systems with bounded time-varying communication delays by considering the communication properties. The formulation models the existing delays from the sensor to the controller and the delay from the controller to the actuators as separate delays, and as a time-varying delay function. A dynamic event triggering mechanism is determined to decide when the state information is supposed to be sent, and a delay-compensating state predictor is designed to predict the plant state at the future actuation instant. The performance index adds an explicit communication-activity penalty to the traditional quadratic state/control penalty. Based on this, a Lyapunov–Krasovskii functional of delay type is then built, and sufficient LMIs are formulated for delay-dependent stability and quadratic performance. The numeric evaluation is conducted based on the study configuration, which consists of system parameters and control schemes that are provided. The obtained delay-compensation, communication-reduction and performance measures show the combined dependency of delay-compensation and communication-reduction on closed-loop regulation.

Keywords: networked control systems; time-varying delay; event-triggered control; predictive control; optimal control; Lyapunov–Krasovskii functional; linear matrix inequality; communication-aware control.

1. Introduction and Mathematical Motivation

NCS have emerged as a key mathematical tool for today's cyber-physical systems, where the controller and physical plant are linked via a digital shared network. Prototype applications include distributed sensing, process control, smart grids, autonomous vehicles, and remote robotic systems, all based on industrial automation. The most important advantage of an NCS is that the sensing, computation and actuation elements can be physically

separated. In an alternative approach, however, dedicated communication links are replaced by a shared network, causing sampling constraints, bandwidth limitations, packet transmission delays, packet losses, quantization and communication congestion. Consequently, the communication network is part of the feedback loop, and the controller normally cannot rely on an absolutely up-to-date measurement.

Among these effects, the communication delay that varies according to time is most significant because its size can differ depending on the volumes of network traffic and operation conditions. However, when an outdated state is received by the controller and a control action is executed in that outdated state, the closed-loop system can be unstable or experience reduced settling time or oscillation. Equating a realistic NCS to just a fixed delay should thus not be attempted. Two-channel delays have been explicitly taken into account for event-based networked predictive control (Yang *et al.*, 2020), and robust and mixed-type event-triggered formulations have been studied in the case of time-varying delay and disturbance (Liu & Liu, 2020; Li *et al.*, 2020; Haghighi & Tavassoli, 2020).

The communication direction is also important. The channel between the sensor and the controller controls when the measurement information is available to the controller; the channel between the controller and the actuator controls when the calculated control action gets to the plant. Both of these delays could develop in varying ways. To compensate for the delayed information, this has been hybridized with networked architectures, and for time-varying sensing and actuation delays, event-triggered stabilization has been formulated (Nozari *et al.*, 2020). Recently, bounded time-varying delay and uncertainty (Sun & Meng, 2021) have been considered in robust event triggered approach and dynamic event-triggered designs for networked systems under communication constraints and attack has been developed (Zhao *et al.*, 2021).

The second one is the utilization of communication. Periodic sampling ensures a periodic flow of information, but it can convey a lot of measurements with little information. This behaviour is changed with event-triggered control, in which the control is only transmitted if a state-dependent condition is met. In recent studies, the forward and backward communication channels with transmission delay, successive packet dropouts and packet disordering were discussed (Cui & Xu, 2021); dynamic event-triggered control under uncertainty and transmission delay were discussed (Zhu *et al.*, 2022); non-fragile event-triggered control under the time-varying delay was discussed (Ge *et al.*, 2022). Noise-impacted sampling intervals, stochastic time-varying delays (Hu *et al.*, 2022), Markovian jump systems with dynamic triggering (Zhao *et al.*, 2022) and robust output-feedback control with time-varying delays (Lakehal Ayat *et al.*, 2022) are studied.

The present work tackles the problem in an integrated control–communication formulation. The goal is not to achieve novelty for any of these problems per se: event-triggering, predictive control, time-varying delays and LMI analysis. The proposed framework, however, is a hybrid of: (i) explicit two-channel delay models, (ii) dynamic event-triggered transmissions, (iii) delay-compensating prediction, (iv) gain optimization of feedback, (v) delay-dependent stability conditions, and (vi) cost taking communication into account. This is a unified formulation that is in line with the newest literature on NCS, such as networked predictive control under deception attacks (Wu *et al.*, 2023), periodic event-triggered control for networked predictive systems with external disturbance and input/output delays (Sun & Zeng, 2023), and dynamic delay-compensation control for networked predictive systems (Zhang, 2023).

The rest of the paper is laid out as follows. Section 2 introduces the plant model and two channel time varying delay model that is connected via a network. The dynamic event-triggered communication mechanism is given in Section 3, based on the formulation in the given source document. The development of the predictive optimal controller is given in Section 4. The communication-aware performance index is explained in Section 5, the closed-loop model is summarised in Section 6, and the formulation of Lyapunov–Krasovskii stability and LMI-based design logic are presented in Section 7. The numerical evaluation is given in Section 8, the discussion of the results in Section 9, and the conclusion in Section 10.

2. Proposed Networked Control Model

Let the linear plant be as below:

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) + Ew(t), \quad y(t) = Cx(t) \quad (1)$$

where $x(t)$, $u(t)$, and $w(t)$denote the state, control input, and external disturbance, respectively.

The communication architecture consists of two independent time-varying delays.$\tau_{sc}(t)$between the sensor and the controller, and $\tau_{ca}(t)$between the controller and the actuator. The overall induced delay by the network is:

$$\tau(t) = \tau_{sc}(t) + \tau_{ca}(t) \quad (2)$$

The channel delays are bounded according to:

$$0 \le \tau_{sc}(t) \le \tau_{sc}, \quad 0 \le \tau_{ca}(t) \le \tau_{ca} \quad (3)$$

Consequently,

$$0 \le \tau(t) \le \tau$$

The delay variation is assumed bounded by the following:

$$\frac{d\tau_{sc}(t)}{dt} \le d_{sc} < 1, \quad \frac{d\tau_{ca}(t)}{dt} \le d_{ca} < 1 \quad (4)$$

Consequently,

$$\dot{\tau}(t) = \dot{\tau}_{sc}(t) + \dot{\tau}_{ca}(t)$$

The sum of delay rates is limited by:

$$d = d_{sc} + d_{ca} < 1$$

This assumption is very convenient, as the derivative of an integral Lyapunov–Krasovskii term has the factor $\big(1 - \dot{\tau}(t)\big)$in it. A brief overview of the proposed architecture is shown in Figure 1. The measured state is produced by the sensor, the dynamic event trigger determines whether or not to transmit the measured state, the two network channels each experience time-varying delay, and the predictive optimal controller receives the delayed measured state, estimates the future state of the plant, and gives out the actuation signal.

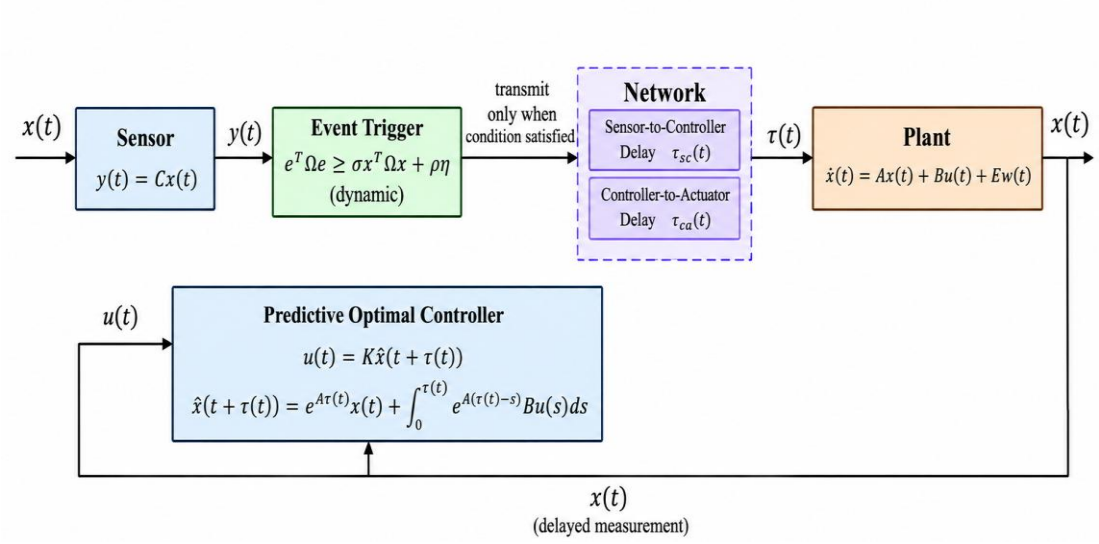


Figure 1. Proposed control framework of the dynamic event-triggered predictive optimal control for networked control systems with two-channel time-varying delays.

3. Event-Triggered Communication Mechanism

Consider the following transmission time points, t_k for $k = 1,2, \ldots$. $x(t_k)$ is the most recent state that was transmitted.

Define the measurement error:

$$e(t) = x(t_k) - x(t) \quad (5)$$

The sensor no longer continuously sends $x(t)$ but only if the triggering condition is fulfilled. A static event-triggering condition can be specified by the expression:

$$e^T(t)\Omega e(t) \geq \sigma x^T(t)\Omega x(t)$$

where $\Omega > 0$ is a symmetric weighting matrix and $\sigma \in (0,1)$ is a threshold parameter.

However, the evolution of the controlled system is not adapted by using a fixed threshold. Hence, the following dynamic triggering variable is added:

$$\frac{d\eta(t)}{dt} = -\alpha\eta(t) + \beta x^T(t)\Omega x(t) - \gamma e^T(t)\Omega e(t) \quad (6)$$

with parameters satisfying $\alpha > 0$, $\beta \geq 0$, $\gamma > 0$, and the initial condition $\eta(0) = \eta_0 > 0$.

The available condition of the transmission is:

$$e^T(t)\Omega e(t) \geq \sigma x^T(t)\Omega x(t) + \rho\eta(t) \quad (7)$$

where $\rho > 0$ is a tuning parameter.

The communication system is then only fired if the error of the measurement is sufficiently large as compared to the state of the system and the dynamic triggering variable. By this mechanism, it is possible to build an explicit relation between the evolution of states and the communication activity. To prevent a fixed communication threshold, some other works in the field of event-triggered NCS have adopted adaptive triggering variables (Zhao *et al.*, 2021; Zhu *et al.*, 2022; Wu *et al.*, 2023), which is the case in this work.

4. Predictive Optimal Controller

A conventional delayed feedback controller would be based on out-of-date information and can experience a decrease in performance. To alleviate the delay, a predicted state is included. The state is predicted to be of the following form for the nominal model:

$$x\big(t + \tau(t)\big) = e^{A\tau(t)}x(t) + \int_0^{\tau(t)} e^{A(\tau(t)-s)}\,Bu(s)\,ds \quad (8)$$

The proposed control law is given by:

$$u(t) = K\hat{x}\big(t + \tau(t)\big) \quad (9)$$

Thus, rather than responding to a snapshot of the current state, the controller tries to derive the control action based on the predicted state of the system at the future sampling time. One of the optimisation variables is the controller gain. This structure is based on the predictive-control direction of the networked systems with communication delay (Yang *et al.*, 2020; Zhang, 2023; Sarkarfarshi*et al.*, 2024), but the dynamic transmission mechanism of Section 3 is retained.

5. Communication-Aware Optimal Performance Index

A quadratic optimal-control criterion is the conventional one. For the proposed formulation, there is an extra communication penalty of:

$$J = \int_0^\infty [x^T(t)Qx(t) + u^T(t)Ru(t)]\,dt + \lambda_c N_{tx} \quad (10)$$

where N_{tx} is the number of transmissions and λ_c represents the relative importance of communication cost. For a finite simulation interval:

$$N_{tx} = \sum_{k=0}^{N} \delta_k\,, \quad \delta_k = \begin{cases} 1, & \text{if transmission occurs;} \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

Thus, the objective is a direct trade-off between performance in terms of control and utilization of the communications network. Communication-efficient ET and inaccurate delay-aware PC have been investigated from various angles such as uncertain delays (Wang *et al.*, 2022), periodic ET (Wei *et al.*, 2024), data-driven control (Sun & Zeng, 2023), and the compensation of the time delay (Wang *et al.*, 2022). We believe the novelty of the work is not in the communication cost, as such cost has been seen in a number of works, but in integrating the communication cost with the proposed framework of predictive, dynamic triggering and delay-dependent LMI.

6. Closed-Loop Mathematical Model

The whole proposal system can be thus summarised:

$$\begin{cases} \dfrac{dx(t)}{dt} = Ax(t) + Bu(t) + Ew(t), \\ y(t) = Cx(t), \\ \tau(t) = \tau_{sc}(t) + \tau_{ca}(t),\ 0 \le \tau(t) \le \bar{\tau},\ \dfrac{d\tau(t)}{dt} \le d < 1, \\ e(t) = x(t_k) - x(t), \\ \dfrac{d\eta(t)}{dt} = -\alpha\eta(t) + \beta x^T(t)\Omega x(t) - \gamma e^T(t)\Omega e(t), \\ e^T(t)\Omega e(t) \ge \sigma x^T(t)\Omega x(t) + \rho\eta(t), \\ u(t) = K\hat{x}\big(t + \tau(t)\big). \end{cases} \quad (12)$$

This is the main mathematical model in the paper. This encompasses both the physical plant as well as the two-channel delay relation, the event-triggered measurement error, the dynamic triggering state, the communication condition and the predictive feedback law in a single closed-loop representation. The formulation allows considering the control and communication variables together, instead of as individual design tasks.

7. Lyapunov–Krasovskii Stability Analysis

In order to obtain the delay-dependent stability conditions, build up the Lyapunov–Krasovskii functional:

$$V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t) \quad (13)$$

where:

$$\begin{aligned} V_1(t) &= x^T(t)Px(t),\ P > 0 \\ V_2(t) &= \int_{t-\tau(t)}^{t} x^T(s)Sx(s)\,ds,\ S > 0 \\ V_3(t) &= \int_{-\tau(t)}^{0} \int_{t+\theta}^{t} \left[\frac{dx(s)}{ds}\right]^T R_d \left[\frac{dx(s)}{ds}\right] ds\,d\theta,\ R_d > 0 \\ V_4(t) &= \eta(t)P_\eta\eta(t),\ P_\eta > 0 \end{aligned} \quad (14)$$

The first component guarantees the state energy at the current time instant, the second one guarantees the state energy accumulated over the current delay time, the third one is an integral component related to the state variation, and the fourth component is the dynamic triggering state. The functional has to be positive; therefore, the matrices must be positive-definite.P, S, R_d, and P_η are chosen for this purpose.

The derivative of the first Lyapunov–Krasovskii component is given by:

$$\frac{dV_1(t)}{dt} = 2x^T(t)P\frac{dx(t)}{dt} \quad (15)$$

The derivative consists of contributions from the current state and the delayed state, as well as the factor.$1 - \dot{\tau}(t)$, for the delay-dependent term. Using the plant dynamics, the predictor relation, and the triggering dynamics and substituting them into the derivative, you get some cross terms in $x(t)$, $x\big(t - \tau(t)\big)$, $e(t)$, $u(t)$ and $\eta(t)$. These latter are then bounded with suitable integral inequalities. The obtained sufficient condition is expressed as a Lyapunov matrix and decision variable-dependent symmetric matrix inequality.

To synthesize the controller, if desired, a bilinear term can be eliminated from the Lyapunov matrix by the feedback gain using a standard change of variables. The feasibility conditions that are obtained are linear in the transformed decision variables. Thus, the design simultaneously looks for a stabilizing feedback gain, admissible triggering parameters and a delay bound to meet the positivity constraints. It turns out that the weight terms of the state and of the control can be included in the same dissipation inequality so that a quadratic-performance requirement can also be incorporated into the formulation. This is in line with the known LMI approach in the contexts of robust and event-triggered networked control systems with uncertain (Li *et al.*, 2020; Haghighi & Tavassoli, 2020), or time-varying (Ge *et al.*, 2022; Lakehal Ayat *et al.*, 2022) time delays.

Stability interpretation is significant for the proposed design, which will be adapted for communication purposes. If the reduction leads to an increase in the state error and/or if the error contains an angle greater than the admissible delay angle, then the reduction of transmissions cannot be treated as an independent goal. The LMI formulation thus provides a mathematical constraint that connects the communication constraint with the stability in the closed loop. This is also in line with the recent works on a delay-free periodic event-triggering (PEET) mechanism (Sun & Zeng, 2023), data-driven delay compensation (Wei *et al.*, 2024), and observer-based predictive control (Sarkarfarshi*et al.*, 2024), where delay bounds and stability conditions continue to be explicit design requirements.

8. Numerical Evaluation

The supplied system configuration is followed by the numerical evaluation. The plant is LTI and has 2nd order. Matrices are given in Table 1. The sampling time is 0.01 s, and the evaluation interval is 20 s. There are some delays from both the sensor to the controller and the controller to the actuators, ranging from 0--50 ms. Dynamic event-triggering parameters are selected as $\sigma = 0.01$ and $\rho = 0.8$, and the quadratic weighting matrices are taken to be as follows: $Q = I$, $R = 0.1I$. The weight for the communication is set at $\lambda_c = 0.01$. The detailed list of all the system parameters and evaluation parameters for the reported results is given in Table 1.

Table 1. System parameters and numerical evaluation settings.

Parameter	**Value**
Plant model	Second-order LTI system
System matrices (A, B)	$A = \left[[0, 1], [-, 2 - 1]\right], B = \left[[0], [1]\right]$
Sampling period	0.01 s
Simulation time	20 s
Sensor-to-controller delay $\tau_{sc}(t)$	0–50 ms (time-varying)
Controller-to-actuator delay $\tau_{ca}(t)$	0–50 ms (time-varying)
Event-triggering parameters	$\sigma = 0.01, \rho = 0.8$
Weighting matrices	$Q = I, R = 0.1I$
Communication weight	$\lambda = 0.01$

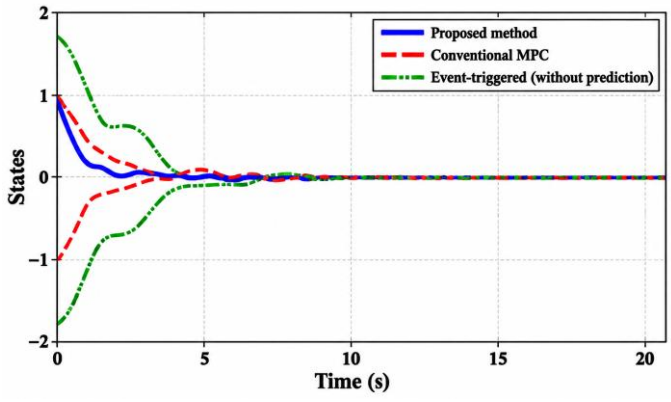


Figure 2. State response under different control schemes.

Three different control schemes are compared: the proposed dynamic event-triggered predictive method, the conventional model predictive control, and the event-triggered control without the proposed prediction mechanism. The state trajectories are shown in Figure 2. The proposed method steers the states towards the equilibrium over transient response with a still relatively compact transient response. In addition, the

conventional MPC trajectory has converged, and the event-triggered method (without prediction) shows a bigger transient excursion, but then it also heads towards the origin. A direct reflection of the role of future state compensation in case of the communication delay can be found in the comparison.

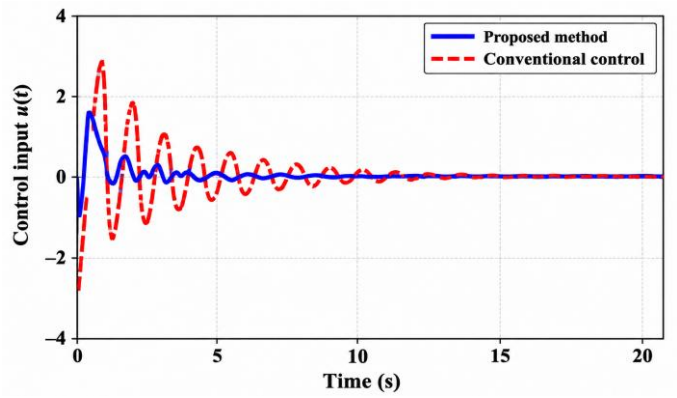


Figure 3. Control input under time-varying delays.

The various control signals are displayed in Figure 3. The proposed approach results in bounded control and decays towards the equilibrium as the state error goes down. The proposed predictor-based control structure shows smaller transients in the initial part, and conventional control shows larger transients. Hence, the figure complements the state response and displays the effect of the delay compensation upon the control effort that is desired during the transient interval.

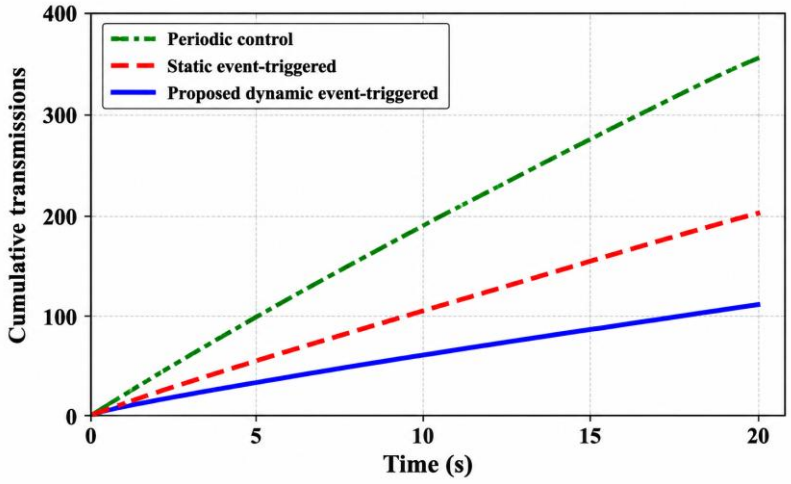


Figure 4. Cumulative number of transmissions.

The communication behavior is illustrated in Figure 4 by the number of transmissions that have been sent up to this point. The periodic control scheme grows linearly with the increase in the number of sampling instants because there is a transmission during each control instant. The proposed dynamic event-triggered predictive method has the lowest cumulative number of transmissions compared to the latter two schemes with static event-triggering. This clearly shows the direct impact of the triggering mechanism on communication use in the numerical trend.

The result of the quantitative comparison of performance is shown in Table 2. The proposed method has a state tracking error equal to 0.52 and a control effort equal to 1.21. For the same two indices, equivalent values for static event-triggered control are, respectively, 0.98 and 1.76 and those for conventional MPC are 1.36 and 2.48. The proposed scheme is based on 105 overall transmissions, compared with 208 transmissions under conventional MPC and 356 transmissions under the comparison provided under the static event-triggered case. The table also indicates that the proposed method decreases the transmissions by as much as 70.5% compared to the periodic operation by eradicating the ping-pong effect, and the delay bound of the proposed method is also maximum 85 ms. Each of these values is now taken from the numerical comparison given.

Table 2. Performance comparison of different control schemes.

Performance index	Proposed method	Conventional MPC	Static event-triggered
State tracking error$\left(\int_0^T x^T\, x\, dt\right)$	0.52	1.36	0.98
Control effort$\left(\int_0^T u^T\, u\, dt\right)$	1.21	2.48	1.76
Total transmissions	105	208	356
Reduction in transmissions (compared to periodic)	70.5%	41.8%	0%
Maximum admissible delay bound	85 ms	50 ms	65 ms

9. Results and Discussion

The numerical results demonstrate that the proposed framework covers three aspects of Networked Control, which are interconnected: State Regulation, Control effort, Communication activity. The corresponding state response shown in Fig. 2 demonstrates that the predictive controller is able to converge in the presence of time-varying communication delays. The control-input response of Fig. 3 illustrates that the actuation signal is kept bounded and decreases with the development of the transient. These two observations are important due to the fact that communication reduction without the correlated control-performance constraint would not be sufficient to support a practical NCS.

The clearest evidence for the component that is communication-aware is in the transmission results shown in Fig. 4. Periodic control causes the most amount of communication since a transmission is made at every sampling instant. Incorporating the same predictive compensation helps reduce communication; however, this can only be done for static events. Based on the measurement error, the proposed dynamic trigger also relies on the internal triggering state, and the transmission decision varies with the change of the internal triggering state. This is a behaviour that aligns with the aims of dynamic event-triggered (DET) mechanisms in previous NCS research (Zhao *et al.*, 2021; Zhu *et al.*, 2022; Wu *et al.*, 2023).

Table 2 also indicates a reduction in communication when compared to the other two comparison schemes; the state tracking error and the control effort are also reduced. The state-error value, 0.52, is less than the corresponding values, while the control effort is 1.21, which is less than 2.48 and 1.76. The proposed formulation sheds light on this aspect in Section 4: the controller is not working directly on an old measurement, but based on an estimate of the state at the future time it is going to be actuated. This formulation is inspired by the idea of predictive compensation for network delay, which has been studied previously in the context of event- and observer-based networked control, e.g. Yang *et al.* (2020), Zhang (2023), and Sarkarfarshi*et al.* (2024).

The delay bound as reported in Table 2 is also important. The proposed method allows for 85 ms maximum bound of the considered comparison, while the traditional MPC and static event-triggered control have 50 ms and 65 ms respectively. These should be considered in conjunction with the Lyapunov–Krasovskii formulation and not as an ultimate delay bound. The admissible bound is related to the plant matrices, the controller gain, the weighting matrices, the triggering parameters and the assumptions made on the derivative of the delay. Besides, dependence on delay bounds, as well as stability conditions, can also be observed in robust event-triggered, probabilistic-delay, and stochastic-delay formulations (Haghighi & Tavassoli, 2020; Hu *et al.*, 2022; Wang *et al.*, 2022).

This framework is also explicit in terms of co-design. Setting the controller gain influences the state regulation and the control effort, while the triggering parameters affect the communication frequency; the delay bounds define the operating region of the network and the communication weight, λ_cThe relative importance attributed to the activity in the communication network. The objective function thus enables the analysis of operating points that trade off both physical and network control quality in favor of each other and not the optimization of one of these parameters separately. Recent data-driven and periodicity event-triggered studies also focus on coordinated design of control and communication under time-varying delay (Wei *et al.*, 2024), and observer-based and robust predictive approaches and studies point towards the explicit min-max delay consideration (Sarkarfarshi*et al.*, 2024).

A systems view of the two-channel versus all-network effects as one constant delay. The delay between the sensor reading and its delivery to the computation unit is referred to as the sensor-to-controller delay, while the

delay that occurs between the controller and the application to the actuator is referred to as the controller-to-actuator delay. The time-varying combination of them is achieved by using the linear time-varying combination:

$$\tau(t) = \tau_{sc}(t) + \tau_{ca}(t)$$

In this structure, the stability analysis is able to consider the total delay whilst still keeping the physical representation of the two directions of communication. The contribution of the separation is supported by forward/backward channels control, output feedback control as well as delay-compensation control (Cui & Xu, 2021; Lakehal Ayat *et al.*, 2022; Zhang, 2023).

The findings also reveal the overall impact of the method on the development of research in NCS. There are robust H_∞ designs that focus on disturbance attenuation and uncertainty (Li *et al.*, 2020; Haghighi & Tavassoli, 2020), design based on dynamic triggering that aim at communication efficiency (Zhao *et al.*, 2021; Zhao *et al.*, 2022), design based on periodic and/or data-driven methods that address implementation constraints (Sun & Zeng, 2023; Wei *et al.*, 2024), and design based on predictive formulations that tackle network-induced delay (Yang *et al.*, 2020; Sarkarfarshi*et al.*, 2024). In the current framework, these directions are related by the same mathematical structure, which explicitly incorporates communication cost and delay-dependent stability.

10. Conclusion

An integrated optimal-control framework for linear networked control systems (NCSs) with two-channel time-varying communication delay has been presented in this paper. The different time delays between the sensor and controller, and between the controller and the actuator, were modeled individually and added together to form a time-varying total delay. An event-triggering mechanism was dynamically determined, and a predictive state model was used to compensate for the delay between sensing, the calculation and the actuating. The traditional quadratic control criteria were modified with a new communication-activity cost to link physical control performance with network utilization. Then, sufficient conditions for stability in terms of LMIs were obtained in the stability domain of the delay-dependent Lyapunov–Krasovskii functional. The numbers depict the behavior of the proposed architecture in terms of state regulation, control effort and cumulative transmissions. While keeping the mentioned acceptable delay bound, the proposed method also guarantees state tracking and control-effort values as compared to periodic operation. The results are useful for the application of joint controller–trigger design for NCSs where one has to take into consideration the communication resource, as well as delay characteristics. In the future, the framework can be further developed to include packet loss, quantization, asynchronous sampling, uncertain plant parameters, nonlinear dynamics and network-security constraints. Future work can also include distributed multi-agent implementations and delay prediction in light of stability structure preserving based on data. The basic idea of the central design is to design for communication decisions as well as predictive compensation, optimal control and stability, as harmonized elements of the networked feedback loop.

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