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Dynamic Wireless QoS Analysis for Real-Time Control in URLLC

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***Abstract*—One of the major goals of *ultra-reliable and low-latency communication* (URLLC) is to enable real-time wireless control systems. However, it is challenging to use URLLC throughout the control process since a huge amount of wireless resource is needed to maintain the rigorous *quality-of-service* (QoS) in URLLC, i.e, ultra reliability and low latency. In this paper, our goal is to discuss that whether the extreme high QoS in URLLC leads to better control performance than low QoS during the control process. This is expected to provide a guideline on the usage of the URLLC throughout the control process dynamically. Specifically, we first investigate the relationship between the URLLC QoS and control performance. Then, we discuss the effect of different communication QoS on the control performance. Our results show that the rigorous QoS in URLLC and a low QoS can be used dynamically throughout the control process with high system performance.**

I. INTRODUCTION

As an important communication scenario in the coming *fifth generation* (5G) cellular networks, *ultra-reliable and low-latency communication* (URLLC) is treated as an enabler for the real-time wireless control systems. In such a system, rigorous *quality-of-service* (QoS) is needed to guarantee the real-time requirement, where a huge amount of wireless resource should be available [1]–[7]. For example, the authors in [7] jointly optimized uplink and downlink bandwidth to minimize the total bandwidth required to guarantee the overall packet loss and *end-to-end* (E2E) delay. From their discussion, we can obtain that the wireless resource consumption in URLLC is extreme large, which impedes the usage of URLLC in real-time wireless control systems especially when the device is powered by battery. Thus, it is very important to investigate whether the rigorous QoS in URLLC is necessary and can be replaced by low QoS dynamically throughout the control process to maintain the control performance.

In fact, the transmission time delay and packet loss in control systems have been extensively studied [8]–[11], where most of them adopt *medium access control* (MAC) protocol to model the time delay and packet loss. Furthermore, some other research has been done to deal with the time delay and packet loss since they are pernicious for the control systems [12] [13]. From their discussion, the large transmission time delay and packet loss result in larger control performance loss than small ones. However, that whether the large time delay and packet loss are always more harmful to the control performance than the small ones throughout the control process is not discussed. This is also very important for the wireless communications since large time delay and packet loss can significantly reduce the resource consumption.

In this paper, we adopt a communication-control co-design method to investigate the effect of different time delay and packet loss on the control performance dynamically throughout the control process. By the co-design, the dynamic plant state update can be observed using different QoSs belonging two levels in control process, where we can find out when the low QoS outperforms the high QoS in terms of control performance. To analyze the reason for the observation, we propose a converting method to convert the plant state update requirement into the requirement on the communication QoS, where we can proof that low communication QoS can be used to obtain better control performance than high QoS at certain points when the plant state returns to the pre-set state. Note that we use rigorous QoS[1] in URLLC to represent the high QoS and the QoS in *long-term-evolution* (LTE) represents the low QoS adopted in this paper.

In the rest of this paper, we present the system model in Section II. In Section III, we analyze the plant state update with different communication QoS. In Section IV, we provide simulations to illustrate the performance of our analysis. Section V concludes the paper.

II. SYSTEM MODEL WITH LATENCY AND RELIABILITY

In this section, we present the real-time wireless control model with communication time delay and reliability. As shown in Fig. 1, we consider the inverted pendulum as an example to illustrate the control system. Here, the control loop consists of sampling at the sensor, the current state estimation at the remote controller, linear state feedback at the controller, control input at the actuator, and the state update at the plant, periodically. We assume that the imperfect wireless network is adopted between the sensor and the controller, which means that the uplink data experiences time delay and packet loss. Furthermore, perfect wireless network is adopted by the downlink from the BS to the plant[2]. Then, the continuous control function is given by a linear differential equation as [9]

$$d\mathbf{x}(t) = \mathbf{A}\mathbf{x}(t)dt + \mathbf{B}u(t)dt + d\mathbf{n}(t), \tag{1}$$

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[1] In the rest of this paper, we assume that the QoS consists of transmission time delay and packet loss.

[2] Note that the case that downlink experiences imperfect communication can be discussed using the same method in this paper.

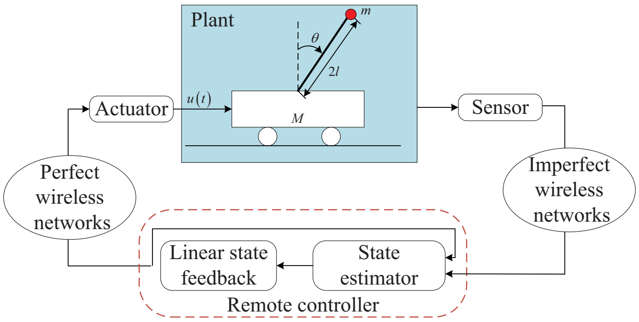

Fig. 1. Wireless control system model.

where $\mathbf{x}(t)$ is the state, $u(t)$ is the control input, and $\mathbf{n}(t)$ is the disturbance caused by additive white gaussian noise (AWGN) with zero mean and variance $\mathbf{R}$. In addition, $\mathbf{A}$ and $\mathbf{B}$ represent the system parameter matrices.

In the inverted pendulum example, we have $\mathbf{x}(t) = (c_t, \dot{c}_t, \theta_t, \dot{\theta}_t)$, where c_t represents the cart's position, $\dot{c}_t$ represents the cart's velocity, θ_t represents the pendulum's angle, and $\dot{\theta}_t$ represents the pendulum's angular velocity. The expression of $\mathbf{A}$ and $\mathbf{B}$ consists of the pendulum length $2l$, the inertia of the pendulum Ψ, the friction of the cart r, the gravitational acceleration g, the mass of the pendulum m, and the mass of the cart M. Thus, $\mathbf{A}$ and $\mathbf{B}$ can be expression as follows, respectively,

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{-(\Psi+ml^2)r}{\Psi(M+m)+Mml^2} & \frac{m^2gl^2}{\Psi(M+m)+Mml^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{-mlr}{\Psi(M+m)+Mml^2} & \frac{mgl(M+m)}{\Psi(M+m)+Mml^2} & 0 \end{pmatrix} \tag{2}$$

and

$$B = \begin{pmatrix} 0 \\ \frac{(\Psi+ml^2)r}{I(M+m)+Mml^2} \\ 0 \\ \frac{ml}{\Psi(M+m)+Mml^2} \end{pmatrix}. \tag{3}$$

To obtain the discrete time control model, we assume that s_n represents the sample period at time index n, which consists of the wireless transmission time delay d_n and an idle period $\bar{s}_n$. Their relationship can be expressed as

$$s_n = \bar{s}_n + d_n, \tag{4}$$

where $n = 1, 2, \cdots, N$ represents the sampling time index in the control process. In addition, u_n^c represents the linear state feedback parameter and is calculated once the sample data arrives at the controller. u_n^a represents the control input at the actuator and is executed as soon as the state feedback arrives at the actuator. We have $u_n^a = u_n^c \triangleq u_n$ since the communication from the BS to the actuator is perfect. Then, the discrete time control model with time delay d_n can be obtained as

$$\mathbf{x}_{n+1} = \mathbf{\Omega}_n \mathbf{x}_n + \mathbf{\Phi}_0^n u_n + \mathbf{\Phi}_1^n u_{n-1} + \mathbf{n}_n, \tag{5}$$

where $\mathbf{\Omega}_n = e^{\mathbf{A} s_n}$, $\mathbf{\Phi}_0^n = \left(\int_0^{\bar{s}_n} e^{\mathbf{A}_n t} dt\right) \cdot \mathbf{B}_n$, and $\mathbf{\Phi}_1^n = \left(\int_{\bar{s}_n}^{s_n} e^{\mathbf{A}_n t} dt\right) \cdot \mathbf{B}_n$.

Assuming $\xi_n = (\mathbf{x}_n^T \quad u_{n-1})^T$ is the generalized state, then the control function in (5) can be rewritten as

$$\xi_{n+1} = \mathbf{\Omega}_d \xi_n + \mathbf{\Phi}_d u_n + \bar{\mathbf{n}}_n, \tag{6}$$

where $\bar{\mathbf{n}}_n = (\mathbf{n}_n^T \quad 0)^T$ and $\mathbf{\Phi}_d = \begin{pmatrix} \mathbf{\Phi}_0^n \\ \mathbf{I} \end{pmatrix}$. We assume $\mathbf{\Omega}_n = \mathbf{\Omega}$. Then, we have $\mathbf{\Omega}_d = \begin{pmatrix} \mathbf{\Omega} & \mathbf{\Phi}_1^n \\ 0 & 0 \end{pmatrix}$.

Considering the packet loss, we have $\Pr\{\alpha_n = 1\} = \Pr\{\varepsilon_n \geq \varepsilon_{th}\}$ and $\Pr\{\alpha_n = 0\} = \Pr\{\varepsilon_n < \varepsilon_{th}\}$, where "1" means that the packet is successfully transmitted and the control is under close loop, and "0" means that the packet is lost and the control is under open loop. In addition, we assume that the state estimator is perfect, and then a linear feedback $u_n = \Theta \xi_n$ is used, where Θ is calculated by the method in [9]. Then, we have the close-loop system in (6) can be rewritten as

$$\xi_{n+1} = \begin{cases} (\mathbf{\Omega}_d + \mathbf{\Phi}_d \Theta)\xi_n + \bar{\mathbf{n}}_n, & \text{if } \alpha_n = 1 \\ \mathbf{\Omega}_d \xi_n + \bar{\mathbf{n}}_n, & \text{if } \alpha_n = 0, \end{cases} \tag{7}$$

which can be rewritten in a general way as

$$\xi_{n+1} = \begin{cases} \mathbf{\Omega}_{e_1} \xi_n + \bar{\mathbf{n}}_n, & \text{if } \alpha_n = 1 \\ \mathbf{\Omega}_{e_0} \xi_n + \bar{\mathbf{n}}_n, & \text{if } \alpha_n = 0, \end{cases} \tag{8}$$

where $\mathbf{\Omega}_{e_1} = \mathbf{\Omega}_d + \mathbf{\Phi}_d \Theta$ is the parameter of the control system with time delay when the packet is successfully transmitted, and $\mathbf{\Omega}_{e_0} = \mathbf{\Omega}_d$ is the parameter of the control system with time delay when the packet transmission is failed.

In the above discussion, we have presented the communication and control co-design model where communication time delay and packet loss have been modeled into real-time wireless control systems. In the following of this paper, we discuss our proposed method to obtain the effect of different communication QoSs on the control performance.

III. DYNAMIC QOS ANALYSIS

Our goal is to analyze the effect of different communication QoSs on the control performance. Thus, in the following of this section, we first give an example to show the plant state update with different communication QoSs. Then, we analyze the effect of them theoretically.

A. Example

To show the effect of different communication QoSs on the control performance, we use the plant state at each time index n to represent the instantaneous control performance, which is represented by the state norm $\bar{\mathbf{x}}_k = ||\mathbf{x}_k||_2$. The example that the plant state update when communication QoS is different is shown in Fig. 2, where the sampling period is 100 ms and other simulation parameters are the same as those in Section IV.

From the figure, the plant state update with high QoS is more smooth than that with low QoS, which leads to smaller state change. Thus, the high QoS has advantage over the low QoS when the plant state increase from the initial state and returns to the pre-set state before n is less than 5, i.e., $n < 5$. On the contrary, the low QoS has advantage over the high QoS

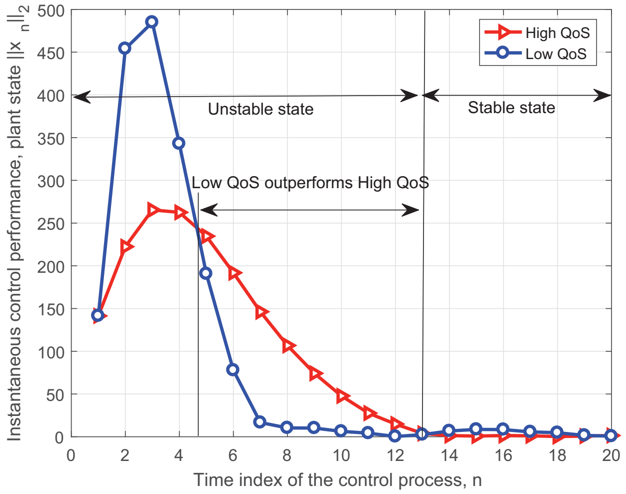

Fig. 2. An example shows the plant state update when communication QoS is different.

when the plant state returns to the pre-set state, i.e., $5 \leq n \leq 13$. When the state is stable, i.e., $n > 13$, the instantaneous control performance of the low QoS approximates to the high QoS. In summary, high QoS can be adopted in the control process dynamically to obtain better control performance and reduce the communication consumption.

B. *Theoretical Analysis*

To analyze the phenomenon in the above example, we consider Lyapunov-like cost function for the plant, which can be expressed as [14]

$$\Delta(\xi) = \xi^T \mathbf{U} \xi. \tag{9}$$

Here, $\mathbf{U}$ is a given positive definite matrix. The Lyapunov-like cost function is a instantaneous control cost, where these functions should decrease at given rates $\rho < 1$ for the close loop during the control process. Note that small ρ means that the plant state updates smoothly, which can guarantee good control performance [14]. For any possible value of the current plant states ξ_n, the Lyapunov-like cost function needs to satisfy

$$\mathbb{E}[V(\xi_{n+1})|\xi_n] \leq \rho\Delta(\xi_n) + Tr(\mathbf{U}W) \tag{10}$$

where $\mathbb{E}[\cdot]$ represents the expectation operator.

From (8), we can obtain the relationship between the communication and control as [14]

$$\begin{aligned}\mathbb{E}[V(\xi_{n+1})|\xi_n] = {} & \Pr\{\alpha_n = 1\}\xi_n^T \mathbf{\Omega}_{e_1}^T \mathbf{U} \mathbf{\Omega}_{e_1} \xi_n \\ & + \Pr\{\alpha_n = 0\}\xi_n^T \mathbf{\Omega}_{e_0}^T \mathbf{Q} \mathbf{\Omega}_{e_0} \xi_n \\ & + Tr(\mathbf{U}W).\end{aligned} \tag{11}$$

Then, for $\xi_n \neq 0$, we can obtain

$$\Pr\{\alpha_n = 1\} \geq \frac{\xi_n^T(\mathbf{\Omega}_{e_0}^T \mathbf{U}_m \mathbf{\Omega}_{e_0} - \rho_m \mathbf{U})\xi_n}{\xi_n^T(\mathbf{\Omega}_{e_0}^T \mathbf{U} \mathbf{\Omega}_{e_0} - \mathbf{\Omega}_{e_1}^T \mathbf{Q} \mathbf{\Omega}_{e_1})\xi_n}, \tag{12}$$

which means that the lower bound of the successful transmission probability can be obtained from the control performance. In other words, the upper bound of the control performance is bounded by the successful transmission probability.

Let

$$c = \sup_{y \neq 0} \frac{y^T(\mathbf{\Omega}_{e_0}^T \mathbf{U} \mathbf{\Omega}_{e_0} - \rho \mathbf{U})y}{y^T(\mathbf{\Omega}_{e_0}^T \mathbf{U} \mathbf{\Omega}_{e_0} - \mathbf{\Omega}_{e_1}^T \mathbf{U} \mathbf{\Omega}_{e_1})y} \tag{13}$$

represent the supremum of the left-hand term in (12). The supremum c^* in (13) can be easily obtained by the method in [14].

Based on the above discussion, we can obtain the following theorems about the relationship between control and communication.

Theorem 1. *Communication reliability and control performance: The communication reliability is directly determined by the control performance, where the reliability is constrained by the control performance c^*. Meanwhile, the control performance c^* decreases monotonously with ρ. Thus, high communication QoS leads to smooth plant state update, and low communication QoS leads to rough plant state update.*

Communication latency and control performance: The optimal c_m^* is related with $\mathbf{\Omega}_d$, $\mathbf{\Phi}_d$, which are effected by the communication latency. In addition, since $\Pr\{\alpha_n = 1\} < 1$, we have

$$(\mathbf{\Omega}_d + \mathbf{\Phi}_d)^T \mathbf{W} (\mathbf{\Omega}_d + \mathbf{\Phi}_d) \prec \rho \mathbf{W}, \tag{14}$$

which states that the control system should satisfy the required rate ρ. Thus, large transmission time delay leads to large $(\mathbf{\Omega}_d + \mathbf{\Phi}_d)$. This can further leads to large rate ρ. On the contrary, small transmission time delay leads to small rate ρ.

Based on the above discussion and considering the stable theorem in [8], we conclude that compered with high QoS service, low QoS service leads to larger Ω, which means that the state changes more rapidly and sharply as the time index k increases in the control process. This straightforwardly proofs the phenomenon in the above example.

IV. NUMERICAL SIMULATIONS

In this section, we provide simulation results to demonstrate the performance of our analysis in this paper. The maximum time delay of URLLC is 1 ms and the maximum packet loss ε is 10^{-5}. In contrast, the maximum time delay of the low QoS is 100 ms and the maximum packet loss of the low QoS is 10^{-3}. The control parameters are as follows: $\mathbf{A} = \begin{pmatrix} 2 & 14 \\ 0 & 1 \end{pmatrix}$, $\mathbf{B} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, $\mathbf{C} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$, $\mathbf{P}_0 = 0.01\mathbf{I}$, $\mathbf{W} = \mathbf{I}$, $U = \mathbf{I}$, $\mathbf{R}_n = \mathbf{I}$, and $\mathbf{R}_{n'} = 0.01\mathbf{I}$. For simplification, we assume that the initial state is $(100, 100)$. Each curve is obtained by 10000 Monte Carlo trails if there is no extra declaration. In addition, we adopt the average control cost to evaluate the control performance, which can be expressed as

$$J_{ave} = \frac{1}{N}\Sigma_{n=1}^{N} x_n^2. \tag{15}$$

Fig. 3 demonstrates the average control cost of our analysis, where the cases that only using high QoS and low QoS are

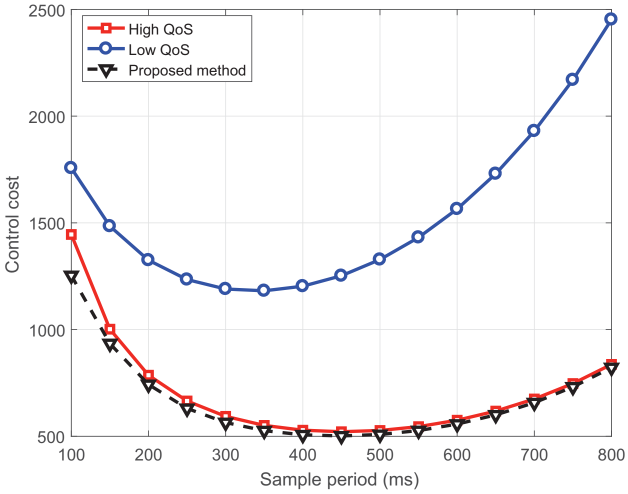

Fig. 3. Control cost versus control sample period.

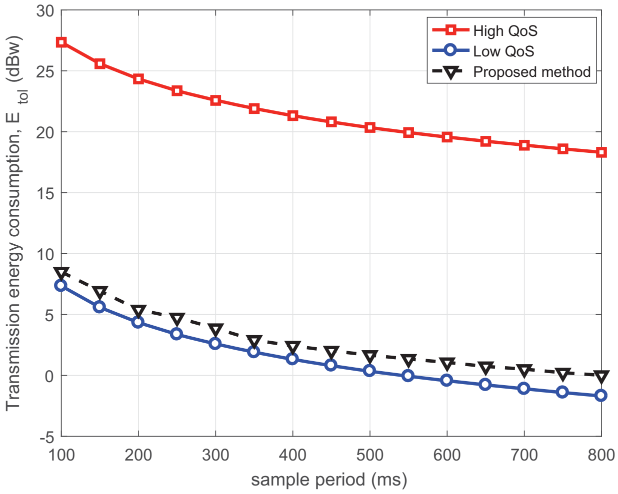

Fig. 4. Control cost versus control sample period.

considered. Here, the proposed method is obtained by the ideal case that we use the low QoS to replace the high QoS from where it has advantage over the high Qos, e.g., from $n \geq 5$ as shown in Fig. 2. From the figure, all the curves have an “U” shape. This is resulted by both the communication and control aspects. Specifically, large sample period leads to large control cost and large d_n/h_n leads to large control cost [9]. These two reasons lead to the “U” shape. Furthermore, the control cost of the proposed method is lower than that of the control process served by only high QoS and low QoS. However, since we adopt low QoS from where it has advantage over high QoS, the communication resource consumption can be significantly reduced.

Fig. 4 shows the wireless energy consumption of the proposed method. Compared with high QoS, the proposed method reduces the energy consumption by about 80%. Thus, the energy consumption of the proposed method is significantly reduced compared with the conventional method only using high QoS.

V. CONCLUSIONS

In this paper, we investigated the effect of dynamic wireless QoS for real-time wireless control in URLLC. We first illustrated the instantaneous control cost with different communication QoSs based on the communication and control co-design model, where we obtained that the low QoS has advantage over the high QoS at certain time indices. Then, we proposed a converting method to analyze the performance by converting the control performance requirement into communication QoS requirement. Simulation results showed that the proposed method achieves the better performance than that only using high URLLC QoS or low QoS.

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