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Event-Driven Control for Switched Systems With Quantization and Packet Loss

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ABSTRACT In this paper, the problem of designing the quantized feedback controller for a class of continuous-time switched systems with packet loss and event-driven scheme is considered. Two novel event-driven schemes are proposed to reduce the amount of data transmission on the network while ensuring the system stability. Under the assumption of dwell time and maximum consecutive packet loss, we obtain the upper bound of Lyapunov function for both mode-match and mode-mismatch situations. By combining with the mode mismatch interval and the upper bound of Lyapunov function, the practical stability of the closed-loop system is guaranteed. Two numerical examples are given to show the potential of the proposed techniques.

INDEX TERMS Switched systems, quantization, packet loss, event-driven scheme, practical stability.

I. INTRODUCTION

During the past few decades, switched systems, one special class of hybrid systems, have been widely investigated and many useful results have been obtained (see, for example [1]–[7]). If the data of a switched system is transmitted through the network, then the controller design will subject to the effect of quantization (caused by limited communication rate), delay and packet loss (caused by network congestion). In addition, reducing the amount of network data transmission through an appropriate transmission mechanism also has important research value. Therefore, this paper will discuss the issues of quantization, packet loss and event-driven scheme of the continuous-time switched systems. Obviously, quantization will affect the accuracy of the transmitted data because of quantization errors. The packet loss affects the reliability of the transmitted data. Meanwhile, the data sampling and the switching signals loss can influence the mismatch interval of the system mode and the controller mode, which brings difficulties to the system analysis. The research goal of this paper is how to use the inaccurate and unreliable quantized sampling data to design a controller ensuring the system stability while reducing the amount of network data transmission.

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The switched systems with quantization have been discussed in many documents. Existing literature can be divided into two categories depending on the type of quantizer. The first category is the switched systems with dynamic quantization, which is represented by zoom strategy [8], [9]. The design idea is to update the quantization rules to ensure higher quantization accuracy near the origin, thus make the system asymptotically stable [10]–[13]. The second category is the switched systems with static quantization, which is represented by logarithmic quantizer and uniform quantizer. If the quantization level is infinite, such as the standard logarithmic quantizer [14], [15], the system can still achieve asymptotical stability. Then the research focus is how to design a feedback matrix to ensure the system stability [16]–[21]. However, if the quantization level is finite, then the practical stability of the system can only be guaranteed [22]–[26]. This paper adopts a quantizer proposed in [26], which belongs to the category of static quantizers with finite quantization level. It is worth mentioning that [21] also discusses the event-driven issue, and an event-driven mechanism by comparing the states at sampling times is designed. By analyzing of Lyapunov-Krasovskii functional candidates, the stochastic finite-time bounded of the system is guaranteed. Different from [21], the event-driven mechanism designed in this paper is according to the quantized sampling states, and the quadratic piece-wise Lyapunov functional is analyzed to ensure the practical stability of the system.

The switched systems with packet loss have also obtained many results, such as [28]–[30]. Given the packet loss rate of the random packet loss process, the mean square stability of the system can be obtained if the packet loss rate meets certain conditions. If it is assumed that the random packet loss process has the largest number of consecutive packet losses, then we can obtain the asymptotic stability or practical stability of the system from the worst case. The packet loss discussed in this article belongs to the second category.

If the switched systems are affected by event-driven scheme, the recent results can be found in [31]–[35]. Literature [31] introduces an event-triggered algorithm to stabilizing a switched linear system by using a pseudo-Lyapunov function. By unifying the switched system, event-triggered scheme, transmission delays and cyber attacks into a new closed-loop control system, sufficient conditions are given to guarantee the finite-time bounded of the networked switched system in [32]. In [33], the authors co-design a novel switching event-triggered scheme and a mode-dependent adaptive control law to guarantee the tracking error belonging to an adjustable neighborhood of the origin. An event-triggered scheme is constructed by using the difference between the states at the current sampling time and the last transmission time in [34], and the exponentially stability is guaranteed by analyzing the quadratic piece-wise Lyapunov functional. Some event-triggered conditions by comparing of the state at different sampling times are given in [35]. Furthermore, the switching synchronization problems for two continuous-time switched non-linear systems are studied there. However, the issue of quantization does not involve in [31]–[35].

To the best of our knowledge, this work is the first result that combines switching, quantization, packet loss and event-driven scheme exception of [36]. In [36], the authors study the fault detection of the switched systems with dynamic quantizer and packet loss. By modeling a novel switched system according to packet dropout, a switching strategy which combines average dwell time and event-driven switching is proposed. Sufficient conditions for the existence of fault detection filters are given by analyzing the relationship between the switching signal and the packet dropout rate. Different from [36], this paper focuses on the controller design of the switched system under the influence of quantization, packet loss and event-driven scheme. The detailed comparison between document [36] and this paper is shown in table 1.

In this work, our contributions are third aspects with respect to earlier literature. First, this paper discusses the quantized stabilization of the switched systems with packet loss and event-driven scheme, which has not been discussed before. Second, two novel event-driven schemes are proposed

TABLE 1. Document [36] vs. this paper.

	Document [36]	This paper
Research focus	fault detection filter	controller
Quantizer	dynamic quantizer	static quantizer
Packet loss	packet loss rate	maximum consecutive packet loss
Event-driven scheme	switching	transmission

to reduce the amount of data transmission while ensuring the system stability. Third, the upper bound of the interval where the system mode and the controller mode are not matched is given under the influence of packet loss and switch. On this basis, sufficient conditions ensuring the practical stability of the system are obtained by analyzing the Lyapunov function.

The remainder of the paper is organized as follows. Problem formulation and preliminaries are illustrated in Section II. Section III obtains the stability of the closed-loop system on the basis of analyzing the upper bound of Lyapunov function and total mismatch time. Two numerical examples are included in Section IV to show the effectiveness of the main results. Section V draws conclusion.

Notations. Throughout the paper, we use $\mathbb{R}^n$ to denote the n-dimensional Euclidean space. $\mathbb{N}$ represents the positive integers set. "$\top$" stands for matrix transposition. The Euclidean norm is adopted as $\|\cdot\|$. For a vector x, $\|x\| := (x^\top x)^{1/2}$. For a matrix M, the induced norm is defined by $\|M\| := \sup\{\|Mx\| : x \in \mathbb{R}^n, \|x\| = 1\}$. The signal $\lfloor a \rfloor$ denotes the largest integer which is smaller than or equal to a. $\lambda_{\max}(P)$ and $\lambda_{\min}(P)$ represent, respectively, as the smallest and biggest eigenvalues of the positive-definite matrix P. For a set $\mathcal{Q} \subset \mathbb{R}^n$, $\mathrm{Cl}(\mathcal{Q})$, $\mathrm{Int}(\mathcal{Q})$, and $\partial(\mathcal{Q})$ are its closure, interior, and boundary, respectively.

II. PROBLEM FORMULATION AND PRELIMINARIES

System configuration studied in this paper is shown in Fig.1, in which, $x_k = x(kT_s)$ and $\sigma_k = \sigma(kT_s)$ with the sampling period T_s. The symbol (a, b, c) denotes that a and b are obtained at time c. The plant formulation, the network-induced effect and the controller design are described detailedly in this section.

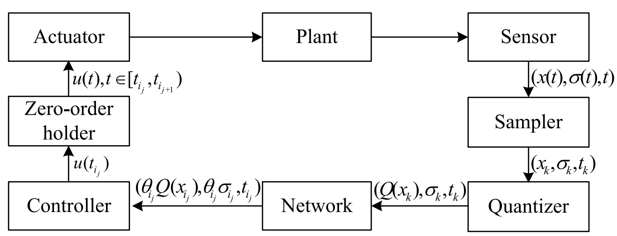

FIGURE 1. System configuration.

A. PLANT FORMULATION

The continuous-time switched system is formulated as follows:

$$\dot{x}(t) = A_{\sigma(t)} x(t) + B_{\sigma(t)} u(t) \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the system state, $u(t) \in \mathbb{R}^m$ is the control input. The switching signal $\sigma(t) : [0, \infty) \rightarrow \Psi$ denotes the active mode at time t with a finite index set Ψ. We call the discontinuities of σ as "switching time" or "switch". $N_\sigma(t, s)$ denotes the number of switches in $[s, t)$.

Assumption 1: The individual system $(A_p, B_p) : p \in \Psi$ of the switched system (1) is stabilizable by state feedback, that is there exists a feedback matrix $K_p, p \in \Psi$ such that $A_p + B_pK_p$ is Hurwitz.

Assumption 2: There is a dwell time $\varphi T_s, \varphi \geq 2(\gamma + 1)$ such that $N_\sigma(t + \varphi T_s, t) \leq 1$ for all $t \geq 0$, where γ is the maximum consecutive packet loss defined in section II-B.

B. NETWORK-INDUCED EFFECT

Here, we discuss the issues of quantization, packet loss and event-driven scheme deduced by the network. Data quantization is inevitable due to that the network bandwidth is always limited, and the packet loss is caused by the congestion and unreliable transmissions.

1) QUANTIZATION

This paper adopts a memoryless quantizer defined in [26]. For any bounded set Ξ, there is a finite subset ω_δ of an index set ω such that $\Xi \subset \cup_{\upsilon \in \omega_\delta} \mathcal{M}_\upsilon$, where $\{\mathcal{M}_\upsilon\}_{\upsilon \in \omega}$ is the finite partition of $\mathbb{R}^n$. The quantizer is represented as

$$\begin{aligned} Q : \mathbb{R}^n &\rightarrow \{q_\upsilon\}_{\upsilon \in \omega} \subset \mathbb{R}^n \\ x &\mapsto q_\upsilon \text{ if } x \in \mathcal{M}_\upsilon (\upsilon \in \omega). \end{aligned} \tag{2}$$

Furthermore, we assume that if $\mathrm{Cl}(\mathcal{M}_\upsilon)$ includes the origin, then $q_\upsilon = 0$.

Lemma 3 [26]: For the above quantizer, there are positive numbers β_0 and $\phi_0(p, q)$ such that

$$\|B_pK_qQ(x)\| \leq \beta_0\|x\| \tag{3a}$$
$$\|PB_pK_q(Q(x) - x)\| \leq \phi_0(p, q)\|x\| \tag{3b}$$

for all $p, q \in \Psi$ and $x \in \bar{\varepsilon}_P(\chi R) \subset \bigcup_{\upsilon \in \omega_\delta} \mathcal{M}_\upsilon$, in which

$$\beta_0 = \max_{p,q \in \Psi} \max_{\upsilon \in \omega_\delta} \frac{\|B_pK_qq_\upsilon\|}{\min_{x \in \mathcal{M}_\upsilon} \|x\|}$$

and $\phi_0(p, q) = \max\{\|PB_pK_q\|, \hat{\phi}_0(p, q)\}$ with

$$\hat{\phi}_0(p, q) = \max_{\upsilon \in \omega_\delta \setminus \omega_0} \frac{\|PB_pK_q\| \max_{x \in \mathcal{M}_\upsilon} \|q_\upsilon - x\|}{\min_{x \in \mathcal{M}_\upsilon} \|x\|}$$

and $\omega_0 = \{\upsilon \in \omega : 0 \in \mathrm{Cl}(\mathcal{M}_\upsilon)\}$. Moreover, $\bar{\varepsilon}_P(\chi R)$ is defined by (13a) with χ given by (46).

Specially, it is obvious that

$$\|B_pK_pQ(x)\| \leq \tilde{\beta}_0\|x\| \tag{4}$$

for all $p \in \Psi$ and $x \in \bar{\varepsilon}_P(\chi R) \subset \bigcup_{\upsilon \in \omega_\delta} \mathcal{M}_\upsilon$ with

$$\tilde{\beta}_0 = \max_{p \in \Psi} \max_{\upsilon \in \omega_\delta} \frac{\|B_pK_pq_\upsilon\|}{\min_{x \in \mathcal{M}_\upsilon} \|x\|} < \beta_0. \tag{5}$$

2) PACKET LOSS

The variable θ_k in the system configuration indicates the packet loss that may occur when the data is transmitted over the network. If $\theta_k = 1$, then it means that the data packet is transmitted successfully, and the controller can use the received data $Q(x_k)$ and σ_k to design the control algorithm at time $t_k = kT_s$. Otherwise, if $\theta_k = 0$, then packet loss occurs. We assume that the controller knows whether the system sends data, and sets the control signal to 0 when the data is lost. This article assumes that the maximum consecutive packet loss for θ_k is γ, which means that if the data packets at the previous γ sampling times are lost, then the data packets of the current time must be successfully transmitted to the controller.

3) EVENT-DRIVEN SCHEME

To reduce the network burden, we set the *quantized sampling data* to be transmitted just at some specific times. Denote the transmission times as $t_{i_j}, j \in \mathbb{N}$ and $i_j \in \mathbb{N} \cup \{0\}$ satisfying $i_1 = 0$ and $i_j < i_{j+1}$. Two event-driven schemes are designed in this paper, in which i_{j+1} is selected, respectively, as

$$\begin{aligned} i_{j+1} = \min\Big\{k > i_j \Big| &\max_{p,q \in \Psi} \|B_pK_q(Q(x(t_{i_j})) - Q(x(t_k)))\| \\ &> \gamma_0\|x(t_k)\|\Big\}, \quad k \in \mathbb{N} \cup \{0\} \end{aligned} \tag{6a}$$

$$\begin{aligned} i_{j+1} = \min\Big\{k > i_j \Big| &\max_{p,q \in \Psi} \|B_pK_q(Q(x(t_{i_j})) - x(t_k))\| \\ &> \gamma_0\|x(t_k)\|\Big\}, \quad k \in \mathbb{N} \cup \{0\} \end{aligned} \tag{6b}$$

with any given constant γ_0.

Since the switching signal σ_k is very important to the controller design, we assume that it is transmitted from the system to the controller at each sampling time. Therefore, the transmission of the switching signal is affected by packet loss but not by the event-driven scheme.

Remark 4: Different from the existing literature, such as [21], this article designs an event-driven strategy based on the quantized data. Since the controller received the quantized data $Q(x(t_{i_j}))$ at the last transmission time, it is more practical to determine whether to transmit data based on the difference between $Q(x(t_{i_j}))$ and the sampling state $x(t_k)$ (or between $Q(x(t_{i_j}))$ and the quantized sampling state $Q(x(t_k))$).

Remark 5: In this paper, we assume that the data transmission from the controller to the plant (i.e. forward chancel) is not affected by the network-induced influence but only by data sampling. Thus, the system can receive the control signal $u(t_{i_j})$ in $[t_{i_j}, t_{i_{j+1}})$. In fact, if the forward chancel is affected by the limited bandwidth of the network, the control signal available on the system is $Q(u(t_{i_j}))$. In addition, if the forward chancel is affected by the event-driven scheme at the same time, an appropriate event-driven scheme for the control signals should be designed by comprehensive analyzing quantization strategy and (6) to ensure the stability of the closed-loop system. This is an issue we will consider in the future.

C. CONTROLLER DESIGN

For easy analysis, we denote $\sigma([t]^-) = \theta_k\sigma(t_k) + (1-\theta_k)\theta_{k-1}\sigma(t_{k-1}) + \ldots + (1-\theta_k)(1-\theta_{k-1})\ldots(1-\theta_{k-\gamma+1})\theta_{k-\gamma}\sigma(t_{k-\gamma})$ and $x([t]^-) = x(t_k)$ for any $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$. Obviously, $\sigma([t]^-) \in \Psi$ holds under the assumption that the maximum consecutive packet loss for θ_k is γ. Under the influence of quantization, packet loss and event-driven scheme, the control input $u(t)$, $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$ is designed as

$$u(t) = K_{\sigma([t]^-)}\theta_{i_j}Q(x(t_{i_j})) \tag{7}$$

with the feedback matrix $K_p, p \in \Psi$ determined by Assumption 1.

For the system (1) with the controller (7), that is

$$\dot{x}(t) = A_{\sigma(t)}x(t) + B_{\sigma(t)}K_{\sigma([t]^-)}\theta_{i_j}Q(x(t_{i_j})) \tag{8}$$

for all $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$, we select Lyapunov function as $V(x(t)) = x^\top(t)Px(t)$ for any given positive-definite matrix P. It holds that

$$\begin{aligned}
&\dot{V}_p(x(t), Q(x(t_{i_j})), \theta_{i_j}) \\
&\quad = (A_px(t) + \theta_{i_j}B_pK_pQ(x(t_{i_j})))^\top Px(t) \\
&\qquad + x^\top(t)P(A_px(t) + \theta_{i_j}B_pK_pQ(x(t_{i_j}))), \\
&\qquad \text{if } \sigma(t) = \sigma([t]^-) = p
\end{aligned} \tag{9a}$$

$$\begin{aligned}
&\dot{V}_{p,q}(x(t), Q(x(t_{i_j})), \theta_{i_j}) \\
&\quad = (A_px(t) + \theta_{i_j}B_pK_qQ(x(t_{i_j})))^\top Px(t) \\
&\qquad + x^\top(t)P(A_px(t) + \theta_{i_j}B_pK_qQ(x(t_{i_j}))), \\
&\qquad \text{if } \sigma(t) = p, \sigma([t]^-) = q.
\end{aligned} \tag{9b}$$

for any $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$.

Remark 6: It is worth mentioning that, under the influence of event-driven mechanism and packet loss, the closed-loop system (8) has a piecewise continuous solution:

$$x(t) = \Phi(t, t_k)x(t_k) + \theta_{i_j}\int_{t_k}^{t}\Phi(t,\tau)B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau \tag{10}$$

for all $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$, where $\Phi(t, t_k)$ denotes the state-transition matrix of the system (1). It guarantees the forward completeness of the system (8) (i.e. the solutions of (8) exist globally, for positive time).

Remark 7: Due to that the solutions of the system (8) are piecewise continuous, the Lyapunov function $V(x(t))$ defined above is just piecewise differentiable rather than full-interval differentiable. Hence, the standard Lyapunov theorem (i.e. $\dot{V}(x(t)) < 0$) can not be used to testify the asymptotic stability of the closed-loop system (8). The proof process of system stability is briefly described as follows:

Step 1: Seeking positive numbers $\tilde{C}$ and $\tilde{D}$ satisfying $\dot{V}_p \leq -\tilde{C}\|x(t)\|^2$ and $\dot{V}_{p,q} \leq \tilde{D}\|x(t)\|^2$, respectively.

Step 2: Looking for the total mismatch time under the influence of packet loss and switch.

Step 3: Analyzing the properties of Lyapunov function by combining Steps 1 and 2, thus obtaining the practical stability of the system (8).

It is worth mentioning that the proof idea of this article is similar to literature [26] (switched systems with quantization) and [27] (switched systems with quantization and delay). As can be seen from the following analysis, the main difficulty and innovation of this article lies in the calculation of mismatch interval, i.e. Step 2.

Assumption 8: For the system

$$\dot{x}(t) = A_px(t) + B_pK_pQ(x([t]^-)), p \in \Psi \tag{11}$$

without switch, packet loss and event-driven scheme, we suppose that $x(t)$ with $x_0 \in \bar{\varepsilon}_P(R)$ satisfies

$$\dot{V}_p(x(t), Q(x([t]^-)), 1) \leq -C\|x(t)\|^2 \tag{12}$$

or $x(t) \in \underline{\varepsilon}_P(r)$, where C is a positive number, $\bar{\varepsilon}_P(R)$ and $\underline{\varepsilon}_P(r)$ are, respectively, defined as

$$\bar{\varepsilon}_P(R) := \{x(t) \in \mathbb{R}^n : V(x(t)) \leq R^2\lambda_{\max}(P)\} \tag{13a}$$
$$\underline{\varepsilon}_P(r) := \{x(t) \in \mathbb{R}^n : V(x(t)) \leq r^2\lambda_{\min}(P)\} \tag{13b}$$

with $R > r > 0$.

Moreover, in order to anti-packet loss, anti-switch and anti-event-driven scheme, we assume that the system (11) is stable enough such that

$$C > 2\|P\|e^{\Lambda T_s}\max\{\tilde{\beta}_0, \gamma_0/(1-\tilde{\eta}_1), \max_{p\in\Psi}\|B_pK_p\|, \gamma_0/(1-\tilde{\eta}_2)\} \tag{14}$$

with $\Lambda = \max_{p\in\Psi}\|A_p\|$ and $\tilde{\eta}_1$, $\tilde{\eta}_2$ defined by (21).

III. MAIN RESULT

Definition 9: The system (8) is *practical stable* if, for any $x(0) \in \mathrm{Int}(\bar{\varepsilon}_P(R))$, $\sigma_0 \in \Psi$ and the given positive numbers χ and κ, there exists a time instant $T_r \geq 0$ such that $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r)), \forall t \geq T_r$, and such that $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R)), \forall t \geq 0$.

The purpose of this section is obtaining the practical stability of the system (8) by analyzing the upper bound of $\dot{V}_p(x(t), q_x(t))$, $\dot{V}_{p,q}(x(t), q_x(t))$ and the mode mismatch interval.

A. UPPER BOUND OF $\dot{V}_p$

The following lemma is useful to obtain the upper bound of $\dot{V}_p(x(t), Q(x(t_{i_j})), \theta_{i_j})$.

Lemma 10: For the system (8), suppose that T_s is small enough such that

$$\eta_1 = \frac{\gamma_0 + \beta_0}{\Lambda}(e^{\Lambda T_s} - 1) < 1 \tag{15a}$$
$$\eta_2 = \frac{\gamma_0 + \max_{p,q\in\Psi}\|B_pK_q\|}{\Lambda}(e^{\Lambda T_s} - 1) < 1. \tag{15b}$$

Define $\beta_1 = e^{\Lambda T_s}/(1-\theta_{i_j}\eta_1)$ and $\beta_2 = e^{\Lambda T_s}/(1-\theta_{i_j}\eta_2)$. If $x([t]^-) \in \bar{\varepsilon}_P(\chi R)$, for all $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$, we have

$$\|x([t]^-)\| < \beta_1\|x(t)\| \tag{16}$$

and

$$\|x([t]^-)\| < \beta_2\|x(t)\| \tag{17}$$

under event-driven scheme (6a) and (6b), respectively. Specially, if the modes of the plant and the controller are matched, that is, $\sigma([t]^-) = \sigma(t)$, then β_0 can be replaced by $\tilde{\beta}_0$ in (15a).

Proof: It follows from (10) and $\Phi(t, t_k)^{-1}\Phi(t, \tau) = \Phi(\tau, t_k)^{-1}$ that

$$x(t_k) = \Phi(t, t_k)^{-1}x(t) - \theta_{i_j}\int_{t_k}^{t}\Phi(\tau, t_k)^{-1}B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau.$$

By considering

$$\|\Phi(t, t_k)^{-1}\| \le e^{(t-t_k)\|A_{\sigma([t]^-)}\|} \le e^{\Lambda(t-t_k)} < e^{\Lambda T_s}, \quad (18)$$

it yields

$$\|x(t_k)\| \le e^{\Lambda T_s}\|x(t)\| + \theta_{i_j}\left\|\int_{t_k}^{t}\Phi(\tau, t_k)^{-1}B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau\right\|. \quad (19)$$

Under the event-driven scheme (6a), we get

$$\begin{aligned}
&\left\|\int_{t_k}^{t}\Phi(\tau, t_k)^{-1}B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau\right\| \\
&= \left\|\int_{t_k}^{t}\Phi(\tau, t_k)^{-1}B_{\sigma(\tau)}K_{\sigma([t]^-)}(Q(x(t_{i_j})) - Q(x([t]^-)) + Q(x([t]^-)))d\tau\right\| \\
&\le \int_{t_k}^{t}\|\Phi(\tau, t_k)^{-1}\|d\tau(\gamma_0\|x(t_k)\| + \beta_0\|x(t_k)\|) \\
&\le \frac{\gamma_0 + \beta_0}{\Lambda}(e^{\Lambda T_s} - 1)\|x(t_k)\| = \eta_1\|x(t_k)\|. \quad (20)
\end{aligned}$$

Combined (15a), (19) with (20) indicates that (16) holds under the event-driven scheme (6a).

Moreover, if the event-driven scheme (6b) is adopted, one has

$$\begin{aligned}
&\left\|\int_{t_k}^{t}\Phi(\tau, t_k)^{-1}B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau\right\| \\
&= \left\|\int_{t_k}^{t}\Phi(\tau, t_k)^{-1}B_{\sigma(\tau)}K_{\sigma([t]^-)}(Q(x(t_{i_j})) - x(t_k) + x(t_k))d\tau\right\| \\
&\le \int_{t_k}^{t}\|\Phi(\tau, t_k)^{-1}\|d\tau(\gamma_0\|x(t_k)\| + \max_{p,q\in\Psi}\|B_pK_q\|\|x(t_k)\|) \\
&\le \frac{\gamma_0 + \max_{p,q\in\Psi}\|B_pK_q\|}{\Lambda}(e^{\Lambda T_s} - 1)\|x(t_k)\| \\
&= \eta_2\|x(t_k)\|,
\end{aligned}$$

which guarantees (17) by using (15b) and (19). □

Define

$$\begin{aligned}
\tilde{\eta}_1 &= \frac{\gamma_0 + \tilde{\beta}_0}{\Lambda}(e^{\Lambda T_s} - 1) < \eta_1 < 1 \\
\tilde{\eta}_2 &= \frac{\gamma_0 + \max_{p\in\Psi}\|B_pK_p\|}{\Lambda}(e^{\Lambda T_s} - 1) < \eta_2 < 1 \quad (21)
\end{aligned}$$

and $\tilde{\beta}_1 = e^{\Lambda T_s}/(1 - \theta_{i_j}\tilde{\eta}_1)$, $\tilde{\beta}_2 = e^{\Lambda T_s}/(1 - \theta_{i_j}\tilde{\eta}_2)$.

For all $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$ and $x([t]^-) \in \bar{\varepsilon}_P(\chi R)$, it holds that

$$\begin{aligned}
&\dot{V}_p(x(t), Q(x(t_{i_j})), \theta_{i_j}) \\
&= (A_px(t) + B_pK_pQ(x([t]^-)))^\top Px(t) \\
&\quad + x^\top(t)P(A_px(t) + B_pK_pQ(x([t]^-))) \\
&\quad + 2\theta_{i_j}x^\top(t)PB_pK_p(Q(x(t_{i_j})) - Q(x([t]^-))) \\
&\quad - 2(1 - \theta_{i_j})x^\top(t)PB_pK_pQ(x([t]^-)) \\
&\le -C\|x(t)\|^2 + 2\theta_{i_j}\|P\|\gamma_0\|x([t]^-)\|\|x(t)\| \\
&\quad + 2(1 - \theta_{i_j})\|P\|\tilde{\beta}_0\|x([t]^-)\|\|x(t)\| \\
&\le (-C + 2\theta_{i_j}\|P\|\gamma_0\tilde{\beta}_1 + 2(1 - \theta_{i_j})\|P\|\tilde{\beta}_0\tilde{\beta}_1)\|x(t)\|^2 \\
&\le (-C + 2\|P\|e^{\Lambda T_s}\max\{\tilde{\beta}_0, \gamma_0/(1 - \tilde{\eta}_1)\})\|x(t)\|^2 \\
&:= -\tilde{C}_1\|x(t)\|^2 \quad (22)
\end{aligned}$$

under event-driven scheme (6a) by using (4), (9a), (12) and (16); and

$$\begin{aligned}
&\dot{V}_p(x(t), Q(x(t_{i_j})), \theta_{i_j}) \\
&= (A_px(t) + B_pK_pQ(x([t]^-)))^\top Px(t) \\
&\quad + x^\top(t)P(A_px(t) + B_pK_pQ(x([t]^-))) \\
&\quad + 2\theta_{i_j}x^\top(t)PB_pK_p(Q(x(t_{i_j})) - x(t_k)) \\
&\quad - 2(1 - \theta_{i_j})x^\top(t)PB_pK_px(t_k) \\
&\le -C\|x(t)\|^2 + 2\theta_{i_j}\|P\|\gamma_0\|x([t]^-)\|\|x(t)\| \\
&\quad + 2(1 - \theta_{i_j})\|P\|\max_{p\in\Psi}\|B_pK_p\|\|x([t]^-)\|\|x(t)\| \\
&\le (-C + 2\theta_{i_j}\|P\|\gamma_0\tilde{\beta}_2 + 2(1 - \theta_{i_j})\|P\| \\
&\quad \times \max_{p\in\Psi}\|B_pK_p\|\tilde{\beta}_2)\|x(t)\|^2 \\
&\le (-C + 2\|P\|e^{\Lambda T_s}\max\{\max_{p\in\Psi}\|B_pK_p\|, \gamma_0/(1 - \tilde{\eta}_2)\}) \\
&\quad \times \|x(t)\|^2 \\
&:= -\tilde{C}_2\|x(t)\|^2 \quad (23)
\end{aligned}$$

under event-driven scheme (6b). By (14), we get $\tilde{C}_1 > 0$ and $\tilde{C}_2 > 0$.

B. UPPER BOUND OF $\dot{V}_{p,q}$

The following lemma is useful to establish the upper of $\dot{V}_{p,q}(x(t), Q(x(t_{i_j})), \theta_{i_j})$.

Lemma 11: For the system (8), define

$$\begin{aligned}
\varepsilon_1 &= (e^{\Lambda T_s} - 1)\left(1 + \theta_{i_j}\frac{\gamma_0 + \beta_0}{\Lambda}\right), \\
\varepsilon_2 &= (e^{\Lambda T_s} - 1)\left(1 + \theta_{i_j}\frac{\gamma_0 + \max_{p,q\in\Psi}\|B_pK_q\|}{\Lambda}\right). \quad (24)
\end{aligned}$$

Then we have

$$\|x(t) - x(t_k)\| < \varepsilon_1\|x(t_k)\| \quad (25)$$

and

$$\|x(t) - x(t_k)\| < \varepsilon_2\|x(t_k)\| \quad (26)$$

for all $t \in [t_k, t_{k+1}) \subset [t_{i_j}, t_{i_{j+1}})$ with $x(t_k) \in \bar{\varepsilon}_P(\chi R)$ under event-driven scheme (6a) and (6b), respectively.

Proof: By (10), we get

$$x(t)-x(t_k)=(\Phi(t,t_k)-I)x(t_k)+\theta_{i_j}\int_{t_k}^{t}\Phi(t,\tau)B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau. \tag{27}$$

for all $t\in[t_k,t_{k+1})\subset[t_{i_j},t_{i_{j+1}})$. Moreover, it holds that

$$\begin{aligned}&\left\|\int_{t_k}^{t}\Phi(t,\tau)B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau\right\|\\&\le\int_{t_k}^{t}\|\Phi(t,\tau)\|d\tau\|B_{\sigma(\tau)}K_{\sigma([t]^-)}(Q(x(t_{i_j}))-Q(x([t]^-))\\&\quad+Q(x([t]^-)))\|\\&\le(e^{\Lambda T_s}-1)\frac{\gamma_0+\beta_0}{\Lambda}\|x(t_k)\|\end{aligned}\tag{28}$$

and

$$\begin{aligned}&\left\|\int_{t_k}^{t}\Phi(t,\tau)B_{\sigma(\tau)}K_{\sigma([t]^-)}Q(x(t_{i_j}))d\tau\right\|\\&\le\int_{t_k}^{t}\|\Phi(t,\tau)\|d\tau\|B_{\sigma(\tau)}K_{\sigma([t]^-)}(Q(x(t_{i_j}))-x(t_k)\\&\quad+x(t_k))\|\\&\le(e^{\Lambda T_s}-1)\frac{\gamma_0+\max_{p,q\in\Psi}\|B_pK_q\|}{\Lambda}\|x(t_k)\|\end{aligned}\tag{29}$$

under event-driven scheme (6a) and (6b), respectively. Summarized above, (25) and (26) can be obtained by using $\|\Phi(t,t_k)-I\|<e^{\Lambda T_s}-1$ which is obtained from Proposition 7 in [26]. □

If the event-driven scheme (6a) is adopted, we know that

$$\begin{aligned}&\dot V_{p,q}(x(t),Q(x(t_{i_j})),\theta_{i_j})\\&=2x^\top(t)P(A_p+B_pK_q)x(t)+2\theta_{i_j}x^\top(t)PB_pK_q\\&\quad\times(Q(x(t_{i_j}))-Q(x([t]^-)))+2x^\top(t)PB_pK_q\\&\quad\times(Q(x([t]^-))-x(t))-2(1-\theta_{i_j})x^\top(t)\\&\quad\times PB_pK_qQ(x([t]^-))\\&<2\max_{p\neq q\in\Psi}(\|P(A_p+B_pK_q)\|+\theta_{i_j}\gamma_0\beta_1\|P\|+(\phi_0(p,q)\\&\quad+\|PB_pK_q\|\varepsilon_1)\beta_1+(1-\theta_{i_j})\beta_0\beta_1\|P\|)\|x(t)\|^2\\&:=2\max_{p\neq q\in\Psi}\Pi_1(p,q,\theta_{i_j})\|x(t)\|^2\le\tilde D_1\|x(t)\|^2\end{aligned}\tag{30}$$

holds for all $t\in[t_k,t_{k+1})\subset[t_{i_j},t_{i_{j+1}})$ and $x([t]^-)\in\bar\varepsilon_P(\chi R)$, where $\tilde D_1:=2\max_{\theta_{i_j}=0,1}\max_{p\neq q\in\Psi}\Pi_1(p,q,\theta_{i_j})$.

Similarly, if the event-driven scheme (6b) is adopted, we obtain that

$$\begin{aligned}&\dot V_{p,q}(x(t),Q(x(t_{i_j})),\theta_{i_j})\\&=2x^\top(t)P(A_p+B_pK_q)x(t)+2\theta_{i_j}x^\top(t)PB_pK_q\\&\quad\times(Q(x(t_{i_j}))-x(t_k))+2x^\top(t)PB_pK_q\\&\quad\times(x(t_k)-x(t))-2(1-\theta_{i_j})x^\top(t)PB_pK_qx(t_k)\\&<2\max_{p\neq q\in\Psi}(\|P(A_p+B_pK_q)\|+\theta_{i_j}\gamma_0\beta_2\|P\|\\&\quad+\|PB_pK_q\|\varepsilon_2\beta_2+(1-\theta_{i_j})\beta_2\|PB_pK_q\|)\|x(t)\|^2\\&:=2\max_{p\neq q\in\Psi}\Pi_2(p,q,\theta_{i_j})\|x(t)\|^2\le\tilde D_2\|x(t)\|^2\end{aligned}\tag{31}$$

holds for all $t\in[t_k,t_{k+1})\subset[t_{i_j},t_{i_{j+1}})$ and $x([t]^-)\in\bar\varepsilon_P(\chi R)$, where $\tilde D_2:=2\max_{\theta_{i_j}=0,1}\max_{p\neq q\in\Psi}\Pi_2(p,q,\theta_{i_j})$.

C. UPPER BOUND OF MODE MISMATCH INTERVAL

Definition 12: For any $\tau_2>\tau_1\ge0$, we define the mode mismatch interval $\mu(\tau_2,\tau_1)$ as follows:

$$\mu(\tau_2,\tau_1):=\text{the length of the set }\{\tau\in[\tau_1,\tau_2):\sigma(\tau)\neq\sigma([\tau]^-)\}.$$

Lemma 13: Fix $\varphi\in\mathbb{N}$ satisfying $\varphi\ge2(\gamma+1)$. For any switching signal σ with dwell time φT_s, the mode mismatch interval μ satisfies

$$\mu(t,0)<\left(\frac{\gamma}{\gamma+1}+\frac{1}{\varphi}\right)t+\left(\frac{1}{\gamma+1}+1\right)T_s \tag{32}$$

for any $t>0$. Moreover, if $\sigma(T_0)\neq\sigma([T_0]^-)$, then, for any $t>T_0$, it holds that

$$\mu(t,T_0)<\left(\frac{\gamma}{\gamma+1}+\frac{1}{\varphi}\right)(t-T_0)+\left(\frac{\gamma}{\gamma+1}+2\right)T_s. \tag{33}$$

Proof: Consider that the mode mismatch interval is only affected by packet loss and switch, we first establish the upper bound of $\mu(t,0)$. Assume that there are m switches in $[0,t)$, and we denote them as $\tilde t_1,\tilde t_2,\ldots,\tilde t_m$. We have

$$\mu([t]^-,0)=\sum_{k=0}^{[t]^-/T_s-1}\mu(t_{k+1},t_k) \tag{34}$$

with $t_0=0$ and $t_k=kT_s$. By considering

$$\mu(t_{k+1},t_k)=\begin{cases}[\tilde t_l]^-+T_s-\tilde t_l & \text{if there is a switch } \tilde t_l \text{ in } [t_k,t_{k+1}) \text{ and } \theta_k=1\\ 0 & \text{if there are no switch in } [t_k,t_{k+1}) \text{ and } \theta_k=1\\ T_s & \text{if } \theta_k=0\end{cases}$$

for any $k=0,1,\ldots,[t]^-/T_s-1$, we obtain that

$$\begin{aligned}\mu(t_{k+1},t_k)&=(1-\theta_k)T_s+\theta_k\psi_k([\tilde t_l]^-+T_s-\tilde t_l)\\&<T_s-\theta_kT_s(1-\psi_k),\end{aligned}\tag{35}$$

where

$$\psi_k=\begin{cases}1 & \text{if there is a switch in } [t_k,t_{k+1})\\ 0 & \text{if there are no switch in} [t_k,t_{k+1}).\end{cases}$$

Combined with (34) and (35) gives us that

$$\begin{aligned}\mu([t]^-,0)&<\sum_{k=0}^{[t]^-/T_s-1}(T_s-\theta_kT_s(1-\psi_k))\\&=[t]^--\sum_{k=0}^{[t]^-/T_s-1}\theta_kT_s(1-\psi_k).\end{aligned}\tag{36}$$

For $\sum_{k=0}^{[t]^-/T_s-1}\theta_kT_s(1-\psi_k)$, there are $[t]^-/T_s$ transmissions, and the number of successful transmissions is at least

$\lfloor [t]^-/((\gamma+1)T_s)\rfloor$. Then the number of intervals without packet loss and switch is at least $\lfloor [t]^-/((\gamma+1)T_s)\rfloor - \tilde{m}$, where

$$\tilde{m} = \begin{cases} m-1 & \text{if there is a switch in } [[t]^-, t) \\ m & \text{if there are no switch in} [[t]^-, t). \end{cases}$$

We can claim that $\lfloor [t]^-/((\gamma+1)T_s)\rfloor - \tilde{m} \geq 0$. In fact, if $\tilde{m} = 0$, then $\lfloor [t]^-/((\gamma+1)T_s)\rfloor \geq 0$ obviously holds. Otherwise, if $\tilde{m} \geq 1$, then we have

$$\left\lfloor \frac{[t]^-}{(\gamma+1)T_s} \right\rfloor \geq \frac{\tilde{m}\varphi}{\gamma+1} - 1 \geq 2\tilde{m} - 1 \geq \tilde{m}$$

by using $\varphi \geq 2(\gamma+1)$. Thus we get

$$\sum_{k=0}^{[t]^-/T_s - 1} \theta_k T_s(1-\psi_k) \geq \left(\left\lfloor \frac{[t]^-}{(\gamma+1)T_s} \right\rfloor - \tilde{m}\right)T_s > \frac{[t]^-}{\gamma+1} - (\tilde{m}+1)T_s. \quad (37)$$

Applying (37) to (36), we have

$$\mu([t]^-, 0) < \frac{\gamma}{\gamma+1}[t]^- + (\tilde{m}+1)T_s,$$

and thus

$$\begin{aligned} \mu(t,0) &< \frac{\gamma}{\gamma+1}[t]^- + (\tilde{m}+1)T_s + t - [t]^- \\ &\leq t - \frac{[t]^-}{\gamma+1} + (m+1)T_s \\ &< t - \frac{t-T_s}{\gamma+1} + T_s + \frac{t}{\varphi} \\ &= \left(\frac{\gamma}{\gamma+1} + \frac{1}{\varphi}\right)t + \left(\frac{1}{\gamma+1} + 1\right)T_s, \end{aligned}$$

where the last inequality is based on $t \geq \tilde{t}_m \geq m\varphi T_s$. Hence (32) holds.

Next, we show (33). Similarly, we assume that m switches occur in (T_0, t), and let them as $\tilde{t}_1, \tilde{t}_2, \ldots, \tilde{t}_m$.

Obviously, it holds that

$$\mu([T_0]^- + T_s, T_0) \leq [T_0]^- + T_s - T_0. \quad (38)$$

Consider that $\sigma(T_0) \neq \sigma([T_0]^-)$ may be caused by switch or packet loss, we define $\tilde{t}_0$ as follows:

1) there is a switch in $[[T_0]^-, T_0)$, then we define $\tilde{t}_0$ as such switch;

2) there are no switch in $[[T_0]^-, T_0)$ but packet loss occurs at $[T_0]^-$:

2.1) if there exist switches before $[T_0]^-$, then we define $\tilde{t}_0$ as the last switch before $[T_0]^-$;

2.2) if there are no switch before $[T_0]^-$, then $\tilde{t}_0$ is defined as $[T_0]^- - \varphi T_s$.

Let $\xi_l = (\tilde{t}_{l+1} - \tilde{t}_l) - \varphi T_s, \forall \in \{0, 1, \ldots, m-1\}$, then $\xi_l \geq 0$. Hence $t - T_0 = m\varphi T_s + (t-\tilde{t}_m) + \sum_{l=0}^{m-1}\xi_l - (T_0 - \tilde{t}_0)$.

1) If

$$(t - \tilde{t}_m) + \sum_{l=0}^{m-1}\xi_l \geq T_0 - \tilde{t}_0, \quad (39)$$

then $t - T_0 \geq m\varphi T_s$, and thus $mT_s \leq \frac{t-T_0}{\varphi}$. Using (35) and (38) gives that

$$\begin{aligned} &\mu(t, T_0) \\ &\leq [T_0]^- + T_s - T_0 + \sum_{k=([T_0]^-+T_s)/T_s}^{[t]^-/T_s} (T_s - \theta_k T_s(1-\psi_k)) \\ &\leq T_s + ([t]^- - [T_0]^-) - \sum_{k=([T_0]^-+T_s)/T_s}^{[t]^-/T_s} \theta_k T_s(1-\psi_k). \end{aligned} \quad (40)$$

Similar to the analysis of (37), we have

$$\sum_{k=([T_0]^-+T_s)/T_s}^{[t]^-/T_s} \theta_k T_s(1-\psi_k) > \frac{[t]^- - [T_0]^-}{\gamma+1} - (\tilde{m}+1)T_s, \quad (41)$$

in which

$$\tilde{m} = \begin{cases} m-2 & \text{if } [[t]^-, t) \text{ and } [T_0, [T_0]^- + T_s) \text{ both have a switch} \\ m-1 & \text{if } [[t]^-, t) \text{ or } [T_0, [T_0]^- + T_s) \text{ has a switch} \\ m & \text{if there are no switch in } [[t]^-, t) \text{ and } [T_0, [T_0]^- + T_s). \end{cases}$$

Applying (41) to (40) results in that

$$\begin{aligned} \mu(t, T_0) &\leq (m+2)T_s + \frac{\gamma}{\gamma+1}([t]^- - [T_0]^-) \\ &\leq \frac{t-T_0}{\varphi} + 2T_s + \frac{\gamma}{\gamma+1}(t - T_0 + T_s) \\ &= \left(\frac{\gamma}{\gamma+1} + \frac{1}{\varphi}\right)(t-T_0) + \left(\frac{\gamma}{\gamma+1} + 2\right)T_s. \end{aligned}$$

2) If $(t-\tilde{t}_m) + \sum_{l=0}^{m-1}\xi_l < T_0 - \tilde{t}_0$, then $mT_s \leq (t-T_0)/\varphi$ does not hold. Combined with (38), $\mu(t, [t]^-) \leq t - [t]^-$ and

$$\begin{aligned} &\mu([t]^-, [T_0]^- + T_s) \\ &= \sum_{k=([T_0]^-+T_s)/T_s}^{([t]^- - T_s)/T_s} (T_s - \theta_k T_s(1-\psi_k)) \\ &\leq ([t]^- - [T_0]^- - T_s) - \frac{[t]^- - [T_0]^- - T_s}{\gamma+1} + (\tilde{m}+1)T_s \end{aligned}$$

results in that

$$\begin{aligned} \mu(t, T_0) &\leq t - T_0 - \frac{[t]^- - [T_0]^- - T_s}{\gamma+1} + T_s + mT_s \\ &< t - T_0 - \frac{t - T_0 - 2T_s}{\gamma+1} + T_s + \frac{t - \tilde{t}_0}{\varphi} \\ &= \frac{\gamma}{\gamma+1}(t - T_0) + \frac{t-\tilde{t}_0}{\varphi} + T_s + \frac{2}{\gamma+1}T_s \end{aligned}$$

by using $mT_s \leq (t-\tilde{t}_0)/\varphi$. Thus (33) holds if

$$\begin{aligned} &\frac{\gamma}{\gamma+1}(t-T_0) + \frac{t-\tilde{t}_0}{\varphi} + T_s + \frac{2}{\gamma+1}T_s \\ &\quad\leq \left(\frac{\gamma}{\gamma+1} + \frac{1}{\varphi}\right)(t-T_0) + \left(\frac{\gamma}{\gamma+1} + 2\right)T_s, \end{aligned} \quad (42)$$

which is equal to $(T_0 - \tilde{t}_0)/\varphi + 2/(\gamma+1)T_s \leq T_s + \gamma/(\gamma+1)T_s$.

Consider $\varphi \geq 2(\gamma+1)$ and $T_0 - \tilde{t}_0 < [T_0]^- + T_s - \tilde{t}_0 \leq (\tilde{l}+1)T_s \leq (\gamma+1)T_s$, where $\tilde{l} \geq 0$ is the consecutive packet loss before T_0, we get

$$\frac{T_0 - \tilde{t}_0}{\varphi} + \frac{2}{\gamma+1}T_s - T_s v \leq \frac{T_s}{2} + \frac{2}{\gamma+1}T_s - T_s = \frac{3-\gamma}{2(\gamma+1)}T_s,$$

which is smaller than $\gamma/(\gamma+1)T_s$ if $\gamma \geq 1$. Hence, (42), and thus (33) can be obtained. Otherwise, if $\gamma = 0$, that is, the system without packet loss, then (33) obviously holds according to Proposition 18 in [26]. □

D. PRACTICAL STABILITY ANALYSIS

The practical stability of the system (8) under event-driven scheme (6a) is discussed in this section. For the case of event-driven scheme (6b), the stability analysis can be obtained just replacing $\tilde{C}_1$ and $\tilde{D}_1$ by $\tilde{C}_2$ and $\tilde{D}_2$, respectively. The following lemmas are first established, which are useful to obtain the practical stability of the system (8).

Lemma 14: Let Assumptions 1-8 hold. Let $\bar{C} := \tilde{C}_1/\lambda_{\max}(P)$ and $\bar{D} := \tilde{D}_1/\lambda_{\min}(P)$. If

$$\bar{C} > (\bar{D}+\bar{C})\left(\frac{\gamma}{\gamma+1} + \frac{1}{\varphi}\right), \tag{43}$$

then there is a time $T_r \geq 0$ such that $x(T_r) \in \underline{\varepsilon}_P(r)$ for any $x(0) \in \mathrm{Int}(\bar{\varepsilon}_P(R))$ and $\sigma(0) \in \Psi$, and moreover $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R))$ for any $t \in [0, T_r]$.

Proof: We first prove that $x(t)$ does not leave $\mathrm{Int}(\bar{\varepsilon}_P(\chi R))$ without belonging to $\underline{\varepsilon}_P(r)$. Assume that there is a time $0 < T_R < T_r$ such that

$$\begin{aligned} &x(T_R) \in \partial\bar{\varepsilon}_P(\chi R), \text{ and} \\ &x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R)) \setminus \underline{\varepsilon}_P(r)\ (0 \leq t < T_R). \end{aligned} \tag{44}$$

Based on (22) and (30), we know that $\dot{V}_p(x(t), q_x(t)) \leq -\bar{C}V(x(t))$ and $\dot{V}_{p,q}(x(t), q_x(t)) < \bar{D}V(x(t))$. Hence, in accordance with (43) and $x(0) \in \mathrm{Int}(\bar{\varepsilon}_P(R))$, we get

$$\begin{aligned} V(x(T_R)) &\leq \exp(\bar{D}\mu(T_R,0) - \bar{C}(T_R - \mu(T_R,0)))V(x(0)) \\ &= \exp\left(\left((\bar{D}+\bar{C})\left(\frac{\gamma}{\gamma+1}+\frac{1}{\varphi}\right) - \bar{C}\right)T_R\right) \\ &\quad \times \exp\left((\bar{D}+\bar{C})\left(\frac{1}{\gamma+1}+1\right)T_s\right)V(x(0)) \\ &< \exp\left((\bar{D}+\bar{C})\left(\frac{1}{\gamma+1}+1\right)T_s\right)R^2\lambda_{\max}(P) \\ &= (\chi R)^2\lambda_{\max}(P) \end{aligned} \tag{45}$$

with

$$\chi \doteq \exp\left(\frac{\bar{D}+\bar{C}}{2}\left(\frac{1}{\gamma+1}+1\right)T_s\right). \tag{46}$$

However, $x(T_R) \in \partial\bar{\varepsilon}_P(\chi R)$ means that $V(x(T_R)) = (\chi R)^2\lambda_{\max}(P)$, and we have a contradiction. Thus T_R satisfying (44) does not exist. Hence $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R))$ for any $t \in [0, T_r]$.

Next, we will show that there exists $T_r \geq 0$ such that $x(T_r) \in \underline{\varepsilon}_P(r)$. Assume $x(t) \notin \underline{\varepsilon}_P(r)$ for any $t > 0$, it means that $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R))\backslash\underline{\varepsilon}_P(r)$. Based on (45), we get

$$V(x(t)) < \exp\left((\bar{D}+\bar{C})\left(\frac{1}{\gamma+1}+1\right)t\right)V(x(0)). \tag{47}$$

Hence $\lim_{t\to\infty} V(x(t)) = \infty$, which is contradict with $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R))\backslash\underline{\varepsilon}_P(r), \forall t > 0$. Thus it must be a time $T_r \geq 0$ such that $x(T_r) \in \underline{\varepsilon}_P(r)$. □

The same as Lemma 16 in [26], we can also define a small interval I_δ such that $V(x(t))$ is differentiable in I_δ under the influence of packet loss and event-driven scheme. By using the mean value theorem, the following lemma holds.

Lemma 15: Let Assumptions 1-8 hold. If $x(t)$ leaves $\underline{\varepsilon}_P(r)$ at T_0, then $\sigma(T_0) \neq \sigma([T_0]^-)$.

Lemma 16: Let Assumptions 1-8 hold. Assume that T_0 is a time at which $x(t)$ leaves $\underline{\varepsilon}_P(r)$. Define

$$\kappa := \exp\left(\frac{\bar{D}+\bar{C}}{2}\left(\frac{\gamma}{\gamma+1}+2\right)T_s\right).$$

If κ satisfies

$$\kappa^2 r^2 \lambda_{\min}(P) < R^2\lambda_{\max}(P), \tag{48}$$

then there exists $T_1 \geq T_0$ such that $x(T_1) \in \underline{\varepsilon}_P(r)$ and $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r)), \forall t \in [T_0, T_1]$ for any $\sigma(T_0) \in \Psi$.

Proof: If $t > T_0$ satisfying $x(t') \in \bar{\varepsilon}_P(\chi R)\backslash\underline{\varepsilon}_P(r)$ for all $t' \in [T_0, t)$, then $V(x(t))$ satisfies

$$\begin{aligned} V(x(t)) &\leq \exp\left(\left((\bar{D}+\bar{C})\left(\frac{\gamma}{\gamma+1}+\frac{1}{\varphi}\right) - \bar{C}\right)(t-T_0)\right) \\ &\quad \times \exp\left((\bar{D}+\bar{C})\left(\frac{\gamma}{\gamma+1}+2\right)T_s\right)V(x(T_0)) \\ &< \kappa^2 r^2\lambda_{\min}(P) < R^2\lambda_{\max}(P) \end{aligned} \tag{49}$$

based on (45). It means that $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(R)) \subset \mathrm{Int}(\bar{\varepsilon}_P(\chi R))$. By using the proof by contradiction similar to Lemma 14, there is a time $T_1 > T_0$ such that $x(T_1) \in \underline{\varepsilon}_P(r)$. Moreover, $V(x(t)) < \kappa^2\ r^2\lambda_{\min}(P)$ guarantees $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r))$, $\forall t \in [T_0, T_1]$. □

Theorem 17: Let Assumptions 1-8 hold. If (43) and (48) hold, then the system (8) is practical stability, that is, there is a time $T_r \geq 0$ such that $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r)), \forall t \geq T_r$ and $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R)), \forall t \geq 0$ for any $x(0) \in \mathrm{Int}(\bar{\varepsilon}_P(R))$ and $\sigma(0) \in \Psi$.

Proof: Lemma 14 tells us that $x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R))$, $\forall t \geq 0$. Next, we will show $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r)), \forall t \geq T_r$. Based on Lemma 14, we know that there exists T_r such that $x(T_r) \in \underline{\varepsilon}_P(r)$. Let $\tau_1, \tau_2, \ldots$ as the times at which $x(t)$ leaves $\underline{\varepsilon}_P(r)$. According to Lemmas 15 and 16, $\sigma(\tau_k) \neq \sigma([\tau_k]^-)$ and (49) holds. Then there exists $\hat{\tau}_k \in (\tau_k, \tau_{k+1}]$ such that $x(\hat{\tau}_k) \in \underline{\varepsilon}_P(r)$ and $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r)), \forall t \in (\tau_k, \tau_{k+1}]$. If there are finite $\{\tau_k\}$, then the practical stability can be obtained. Otherwise, if there are infinite $\{\tau_k\}$, then $\lim_{k\to\infty}\tau_k = \infty$ by using $\tau_{k+1} - \tau_k \geq \varphi T_s$. Hence $x(t) \in \mathrm{Int}(\underline{\varepsilon}_P(\kappa r))$, $\forall t \geq T_r$. □

IV. SIMULATION

In this section, we present two illustrative examples to demonstrate the validity and effectiveness of the main results.

A. TWO-TANK SYSTEM

For comparison with literature [26], let us first consider the following two-tank system denoted by the system (1) with $\sigma(t) \in \{1, 2\}$ and

$$A_1 = \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix}, \quad A_2 = A_1,$$
$$B_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ -1 \end{bmatrix}. \tag{50}$$

Choose $K_1 = -[0.6163\ 0.7979]$ and $K_2 = [0.7979\ 0.6163]$, then $A_1+B_1K_1$ and $A_2+B_2K_2$ are Hurwitz. The quantizer $Q(\cdot)$ is defined by $Q(x) = [Q_1(x_1)\ Q_2(x_2)]^\top$ with

$$Q_i(x_i) = \begin{cases} \dfrac{-\tilde{\xi}_0(\tilde{\eta}^{\xi} + \tilde{\eta}^{\xi+1})}{2} & \text{if } x_i \in [-\tilde{\xi}_0\tilde{\eta}^{\xi+1}, -\tilde{\xi}_0\tilde{\eta}^{\xi}) \\ 0 & \text{if } x_i \in [-\tilde{\xi}_0, \tilde{\xi}_0] \\ \dfrac{\tilde{\xi}_0(\tilde{\eta}^{\xi} + \tilde{\eta}^{\xi+1})}{2} & \text{if } x_i \in (\tilde{\xi}_0\tilde{\eta}^{\xi}, \tilde{\xi}_0\tilde{\eta}^{\xi+1}], \end{cases}$$

where $\tilde{\xi}_0 = 0.5$ and $\tilde{\eta} = 1.45$.

Let $T_s = 0.01$, $P = [1.2467\ 0.2230;\ 0.2230\ 1.2096]$. Assume $C = 90, R = 30, r = 0.71, \gamma = 3$ and $\varphi = 11$. If $\gamma_0 = 0.2$, then $\Lambda = 2, \beta_0 = \tilde{\beta}_0 = 1.2350, \eta_1 = 0.0145$ and $\eta_2 = 0.0122$. Then we have $\bar{C} = 59.4669, \bar{D} = 10.4187, \kappa = 2.6141, \chi = 1.5477$, which means that the conditions (14), (43) and (48) hold. Hence Theorem 17 is guaranteed.

In order to discuss the impact of γ_0 on the system performance, Table 2 lists the key parameters of the system under different values of γ_0 when $x_0 = [-17; 31.28] \in \text{Int}(\bar{\varepsilon}_P(R))$. In Table 2, κ_1 and χ_1 correspond to κ and χ in Theorem 17, respectively, under event-driven scheme (6a). The parameter ν_1 represents the number of transmissions in the first 200 sampling moments under event-driven scheme (6a). The variables κ_2, χ_2 and ν_2 are similarly defined under event-driven scheme (6b).

TABLE 2. The impact of γ_0 on system performance.

γ_0	0.01	0.1	0.5	1.4
κ_1	2.6141	2.6141	2.6141	2.6259
χ_1	1.5477	1.5477	1.5477	1.5509
ν_1	24	14	2	1
κ_2	2.6067	2.6067	2.6067	2.6254
χ_2	1.5457	1.5457	1.5457	1.5507
ν_2	28	19	2	1

From Table 1, we can see that the increment of γ_0 can reduce the number of data transmissions. However, too large γ_0 will increase the value of κ and χ, and thus reduce the system stability. Moreover, the event-driven scheme (6b) has a higher number of transmissions but better system stability than the event-driven scheme (6a) under the same γ_0.

Comparison: Compared to the case without packet loss and event-driven scheme in [26] (in which $\chi = 1$ and $\kappa = 1.0384$), it is obvious that the system stability obtained here is weaker than the one in [26] in the sense of bigger χ and κ. However, the data transmission rate in this paper is only 12%-14% of that in [26] when $\gamma_0 = 0.01$.

For the initial state $x_0 = [-17; 31.28]$ and $\gamma_0 = 0.2$, the switching modes of the system and the controller are given in Fig. 2. It can be seen from Fig. 2 that the controller mode does not always match the system mode. However, Fig. 3-4 show that the practical stability of the closed-loop can be guaranteed.

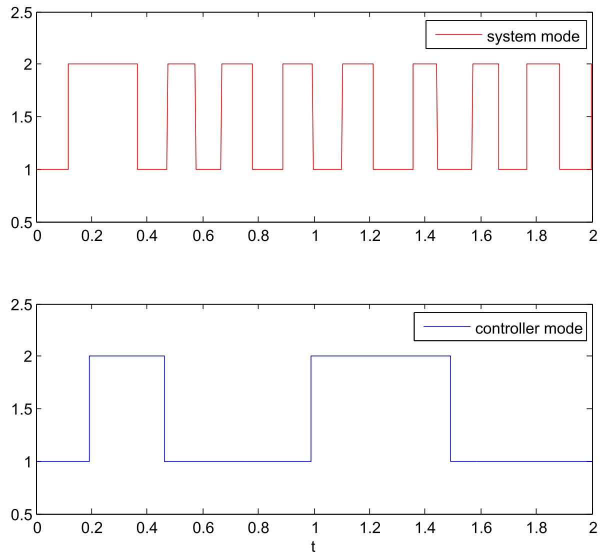

FIGURE 2. System mode and controller mode.

In Fig. 3-4, colored lines denote the state trajectories of the system under different initial states. The blue ellipse, red ellipse and black ellipse represent $\bar{\varepsilon}_P(R)$, $\text{Int}(\bar{\varepsilon}_P(\chi R))$ and $\text{Int}(\bar{\varepsilon}_P(\kappa R))$, respectively. Fig. 3 shows that $x(t) \in \text{Int}(\bar{\varepsilon}_P(\chi R)), \forall t \geq 0$. Fig. 4 guarantees that there is a time instant T_r such that $x(t) \in \text{Int}(\underline{\varepsilon}_P(\kappa r)), \forall t \geq T_r$. Since the theoretical analysis corresponding to the packet loss from the worst case, the upper bounds of the Lyapunov function, i.e. $(\chi R)^2\lambda_{\max}(P)$ and $(\kappa R)^2\lambda_{\max}(P)$, obtained here are conservative.

B. A NUMERICAL EXAMPLE

To show that there exist some times $\tilde{t} \geq 0$ such that $x(\tilde{t}) \in \text{Int}(\bar{\varepsilon}_P(\chi R)) \backslash \text{Int}(\bar{\varepsilon}_P(R))$, we consider the system (1) with

$$A_1 = \begin{bmatrix} -0.5 & 1.5 \\ 1 & -1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} -1 & 1 \\ 1 & -1 \end{bmatrix},$$
$$B_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ -1 \end{bmatrix}. \tag{51}$$

Select $K_1 = -[1.1163,\ 1.2979]$ and $K_2 = [0.9342,\ 0.5827]$. The other parameters are the same as Section IV-A. The closed-loop dynamic responses are given in Fig. 5 with different initial conditions. From such figure, it is obvious that

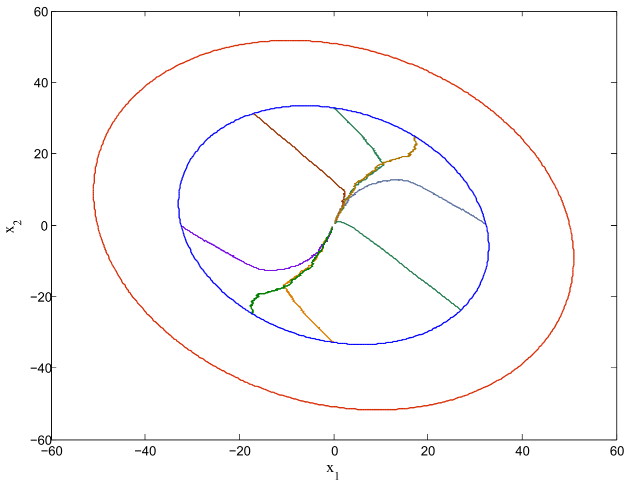

FIGURE 3. State trajectories in region $(-60, 60) \times (-60, 60)$.

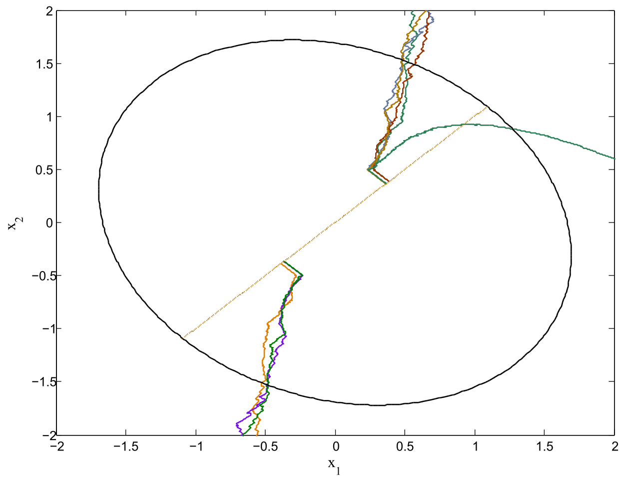

FIGURE 4. State trajectories in region $(-2, 2) \times (-2, 2)$.

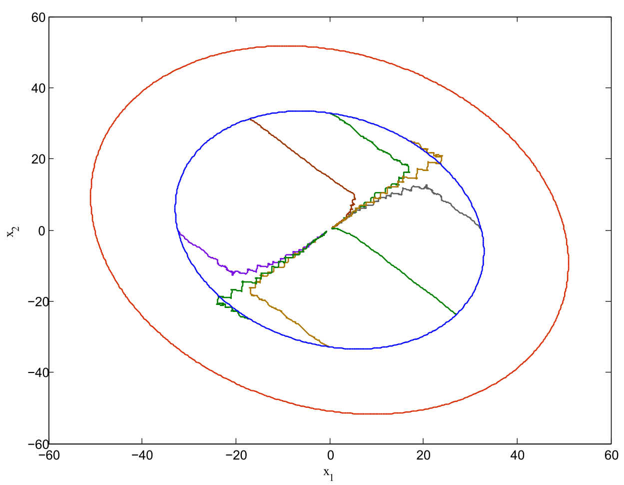

FIGURE 5. State trajectories in region $(-60, 60) \times (-60, 60)$.

$x(t) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R)), \forall t \geq 0$. Furthermore, we know that there are some $\tilde{t}$ such that $x(\tilde{t}) \in \mathrm{Int}(\bar{\varepsilon}_P(\chi R)) \backslash \mathrm{Int}(\bar{\varepsilon}_P(R))$.

V. CONCLUSION

For a class of continuous-time switched systems with packet loss, quantization and event-driven scheme, a controller is designed here to guarantee the practical stability of the closed-loop system by combining the upper bound of Lyapunov function and mode mismatch interval. The future work can involve the observer-based output feedback and the network-induced time-delay or disturbance.

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