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• RESEARCH PAPER •

Special Focus on Advanced Techniques for Event-Triggered Control and Estimation

Event-triggered attack-tolerant tracking control design for networked nonlinear control systems under DoS jamming attacks

Xiaoli CHEN & Youguo WANG*

School of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210023, China

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Abstract This paper addresses the problem of event-triggered attack-tolerant tracking control for a networked nonlinear system under spasmodic denial-of-service (DoS) attacks. Compared with some existing results, the exact duration of DoS attacks is not required while only assuming attainable bounds of attack frequency and duration. First, a new event-triggered attack-tolerant fuzzy tracking controller is proposed, to reduce the amount of sensor data transmissions over the sensor-to-controller (S-C) channel while counteracting unknown DoS attacks. Second, for the purpose of performance analysis and synthesis, a unified event-triggered Takagi-Sugeno (T-S) fuzzy switched model is established, which accounts for a suitable attack-resilient event-triggered communication scheme and unknown DoS jamming signals. Third, using piecewise Lyapunov-Krasovskii functional (PLKF) analysis technique, a new criterion is derived to ensure exponential stability of the resulting switched tracking error system while achieving a weighted H_∞ performance level. Additionally, the relationship among the parameters of a DoS attack signal, the triggering parameters, the fuzzy controller gains, the sampling period, and the decay rate can be quantitatively characterized. Moreover, the triggering matrix parameter and fuzzy controller gains are obtained by finding a feasible solution to a set of linear matrix inequalities (LMIs). Finally, numerical verification is performed to demonstrate the effectiveness of the proposed control design method.

Keywords jamming attacks, event-triggered control, piecewise Lyapunov-Krasovskii functional, T-S fuzzy system

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1 Introduction

The underlying assumption for analyzing and synthesizing some existing networked control systems (NCSs) is that sensor/controller data are transmitted securely and dependably over communication channels. Such an assumption has been commonly made in traditional wired/wireless networked systems and has resulted in several effective control design methods for various linear or nonlinear NCSs (see the survey papers [1–3]). In practical networked applications, however, secure communication channels among different system components comprising sensors, controllers, and actuators cannot always be guaranteed. For example, a malicious adversary can hijack a vehicle-to-vehicle communication network with the aim of sending fake vehicle distances among networked intelligent cars, thereby causing traffic congestion or

* Corresponding author (email: Wangyg@njupt.edu.cn)

accidents. As a result, cyber-security issues of NCSs have received intensive research attention from the control community in recent years (e.g., [4–8]).

Depending on different attack targets, the two main forms of cyber attacks in NCSs are deception attacks and denial-of-service (DoS) attacks [9]. The former aims to affect the integrality of measurement and control of data [7, 8, 10–12] for false injection attacks and replay attacks [13]. The latter aims to jam network channels to interrupt data availability [14, 15], thereby causing performance degradation or even instability of an NCS regardless of the structure of the attacked systems. This paper focuses on DoS attacks, which have been widely studied from different viewpoints in recent years. To name a few, the authors [16, 17] investigated a type of optimal DoS attack from the perspective of attack scheduling. In [18–20], some defensive control strategies were designed from the perspective of the defender. In [21–23], a game theory approach was studied between the DoS attackers and the defender. The aforementioned results are derived based on the assumption that communication between the sensor (controller) and controller (actuator) is time-triggered. In other words, data sampling and/or transmission frequency are regulated after a fixed period of time has lapsed. This may lead to a waste of precious computation and communication resources [24–30].

To alleviate unnecessary consumption of limited computation and communication resources, so-called event-triggered communication strategies have been proposed for NCSs or wireless NCSs. Recently, many results on event-triggered security control or estimation of linear or nonlinear NCSs subject to DoS attacks have been reported. To name a few, stability analysis of linear NCSs is investigated in [31–37]. Load frequency security controller synthesis of event-triggered networked multi-area power systems is addressed in [38]. Event-based state-feedback stabilizing controllers are designed for linear NCSs in [39] and then are extended to a class of linear NCSs with parameter uncertainties and signal quantizations in [40]. Quantized state-feedback stabilization and stability analysis of networked nonlinear systems are studied in [41]. Event-based resilient H_∞ filtering of linear NCSs is solved in [42].

In another research direction, event-triggered output-tracking control of linear or nonlinear NCSs has attracted considerable attention owing to its wide areas such as robot control, flight control and motor control. The goal of network-based tracking control is to ensure that the output of a controlled plant can accurately track the output of a given reference model using a remote controller via a communication network. As stated in [43], managing the tracking control problem is more difficult than the stabilization problem. To date, some important results on event-triggered output tracking control of linear or nonlinear NCSs have been reported (see [44–47] and the references therein). However, these results do not take into account cyber-security issues during control design, and so far, the attention to event-triggered tracking control for NCSs under cyber-attacks has not been much. Therefore, developing a new event-triggered H_∞ attack-tolerant tracking controller for nonlinear NCSs by taking into account the effects of DoS attacks is very important, and this is the goal of the study.

In this paper, we address the problem of event-triggered attack-tolerant output-tracking control for a nonlinear NCS subject to DoS attacks. We consider a more general case that DoS attacks occur nonperiodically, and it is different from [39, 40] that concerns periodic DoS attack. We consider an NCS where a nonlinear controlled plant is represented by the well-known continuous-time T-S fuzzy model. In our study, the plant output, the reference model output, and the control signal are transmitted through respective communication channels. Non-periodic DoS attacks may block the transmission of output data and the control signal across two channels. Using the delay system and switched system approaches, a new switched system with an artificial delay is established. Subsequently, based on the piecewise Lyapunov-Krasovskii functional (PLKF) analysis technique, a new approach to co-designing a resilient event-triggering scheme and fuzzy state-feedback controllers is proposed, so that the exponential stability of the resultant switched system with a weighted H_∞ disturbance attenuation level could be achieved. Using the designed fuzzy controller, the output of the closed-loop networked T-S fuzzy system can safely track the output of a given reference model in the H_∞ sense, despite the presence of DoS attacks and transmission delays. Finally, a numerical example is employed to illustrate the effectiveness of the theoretical results.

The results in Section 3 are partially presented in [48]; in this paper, we provide complete and rigorous

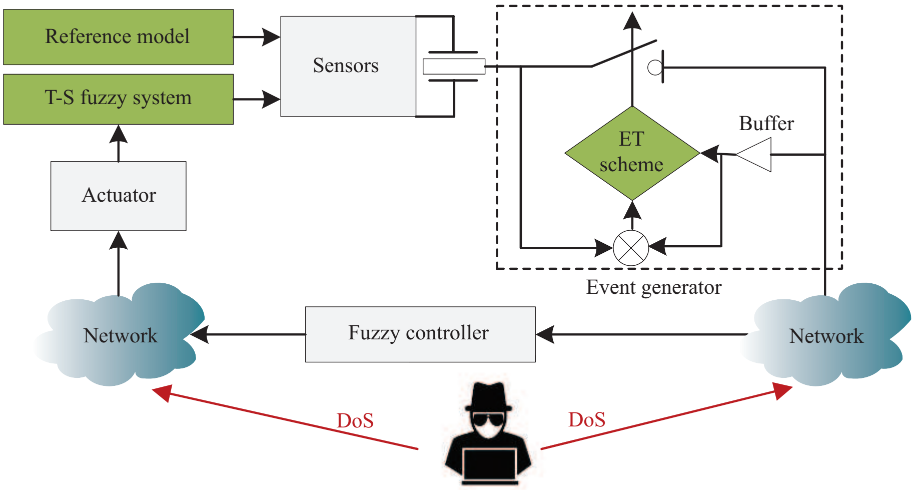

Figure 1 (Color online) Networked tracking control framework under non-periodic DoS attacks.

proof as well as detailed simulation results, and provide insightful discussions on several important issues during analysis and design. Moreover, this paper extends the results in [48] to the weighted H_∞ performance analysis and takes into account the effect of time varying transmission delays that are inevitable during data transmission.

Notations. The notations throughout this paper are provided in standard format. $\mathbb{R}$ and $\mathbb{N}$ represent the sets of real numbers and non-negative integers, respectively. The symbol I is used to represent the identical matrix with appropriate dimensions. For a symmetric and positive matrix, L, $\lambda_{\max}(L)$ and $\lambda_{\min}(L)$ represent the maximum and minimum eigenvalues of matrix L, respectively.

2 Problem formulation and modeling

In this paper, we consider the networked tracking control problem of a continuous-time nonlinear plant characterized by the T-S fuzzy model, with a fuzzy state-feedback controller as shown in Figure 1, where non-periodic DoS attacks attempt to block the communication between the sensor and the fuzzy controller, and between the fuzzy controller and the actuator. Subsequently, we introduce the T-S fuzzy system model, the reference model, an event generator, a fuzzy controller, and DoS attacks. We then establish a unified event-triggered T-S fuzzy tracking error system model under DoS attacks. Furthermore, the control objective of this paper is formulated.

2.1 T-S fuzzy model

The dynamic model of the nonlinear controlled plant (see Figure 1) can be approximated by the well-known T-S model [49], where the l-th rule can be stated as follows.

Plant rule l: IF $\eta_1(t)$ is θ_{l1} and $\cdots$ and $\eta_j(t)$ is θ_{lj}, THEN

$$\begin{cases} \dot{x}(t) = \mathcal{A}_l x(t) + \mathcal{B}_l u(t) + \mathcal{B}_{wl} w(t), \\ y(t) = \mathcal{C}_l x(t), \end{cases} \tag{1}$$

where θ_{lm} $(l = 1, 2, \ldots, r; m = 1, 2, \ldots, j)$ denote the fuzzy sets, r denotes the number of IF-THEN rules, $\eta(t) = [\eta_1(t), \eta_2(t), \ldots, \eta_j(t)]^{\mathrm{T}}$ denotes the premise variable vector; $x(t) \in \mathbb{R}^{n_x}$ is the state vector, $y(t) \in \mathbb{R}^p$ is the output vector, $u(t) \in \mathbb{R}^q$ is the control input, $w(t) \in \mathbb{R}^{n_w}$ is the external disturbance and $w(t) \in L_2[0, \infty)$, $\mathcal{A}_l \in \mathbb{R}^{n_x \times n_x}$, $\mathcal{B}_l \in \mathbb{R}^{n_x \times q}$, $\mathcal{B}_{wl} \in \mathbb{R}^{n_x \times n_w}$, $\mathcal{C}_l \in \mathbb{R}^{p \times n_x}$, and n_x, n_w, p, q, and $r \in \mathbb{N}$.

According to [49], the system (1) can be expressed as

$$\begin{cases} \dot{x}(t) = \sum_{l=1}^{r} \xi_l(\eta(t)) \left[\mathcal{A}_l x(t) + \mathcal{B}_l u(t) + \mathcal{B}_{wl} w(t) \right], \\ y(t) = \sum_{l=1}^{r} \xi_l(\eta(t)) \mathcal{C}_l x(t), \end{cases} \tag{2}$$

where

$$\xi_l(\eta(t)) = \frac{\phi_l(\eta(t))}{\sum_{l=1}^{r} \phi_l(\eta(t))}, \quad \phi_l(\eta(t)) = \prod_{m=1}^{j} \theta_{lm}(\eta_m(t)),$$

and $\theta_{lm}(\eta_m(t))$ represents the membership value of $\eta_m(t)$ in θ_{lm}. For all $t > 0$, $\phi_l(\eta(t)) \geqslant 0$ ($l = 1, 2, \ldots, r$) and $\sum_{l=1}^{r} \phi_l(\eta(t)) > 0$. Therefore, it is easy to derive that

$$\sum_{l=1}^{r} \xi_l(\eta(t)) = 1 \quad \text{and} \quad \xi_l(\eta(t)) \geqslant 0. \tag{3}$$

For the sake of simplicity, we use ξ_l to denote $\xi_l(\eta(t))$ in the subsequent research.

2.2 Reference model

Considering the following commonly used reference model:

$$\begin{cases} \dot{x}_r(t) = \mathcal{A}_r x_r(t) + \mathcal{B}_r r(t), \\ y_r(t) = \mathcal{C}_r x_r(t), \end{cases} \tag{4}$$

where $x_r(t) \in \mathbb{R}^{n_{r_x}}$ is the reference state, $r(t) \in \mathbb{R}^{n_{rr}}$ is the reference input, and $y_r(t) \in \mathbb{R}^{n_{y_r}}$ is the reference output, $\mathcal{A}_r \in \mathbb{R}^{n_{r_x} \times n_{r_x}}$, $\mathcal{B}_r \in \mathbb{R}^{n_{r_x} \times n_{rr}}$, and $\mathcal{C}_r \in \mathbb{R}^{n_{y_r} \times n_{r_x}}$ are the given constant matrices, and n_{r_x}, n_{r_r}, and $n_{y_r} \in \mathbb{N}$.

2.3 DoS attack model

In this study, to mathematically explore the influence of DoS attacks, we use the time interval $[g_{n-1}, g_{n-1} + s_{n-1}) \triangleq \mathcal{G}_{1,n-1}$ to denote that the attack signal is asleep in the n-th jamming period and therefore, the communication among the event generator, the controller, and the actuator is allowed. The time interval $[g_{n-1} + s_{n-1}, g_n) \triangleq \mathcal{G}_{2,n-1}$ is utilized to show the n-th attack interval where the attack signal is active, and therefore, data packets cannot be successfully sent to the controller and received by the actuator during the active period of the jammer. The parameters g_n, $g_n + s_n$, and g_{n+1} satisfy $0 = g_0 < g_0 + s_0 < g_1 < g_1 + s_1 < g_2 < \cdots < g_{n-1} + s_{n-1} < g_n < \cdots$.

Generally speaking, arbitrarily choosing the intervals $\mathcal{G}_{1,n}$ and $\mathcal{G}_{2,n}$ is not possible because they are often limited in terms of power and seriously affect the stability of the considered system. As a result, the following assumptions on both frequency and duration of DoS attacks are made.

Assumption 1. There exist two scalars $\varpi \geqslant 0$ and $d > 0$ such that

$$n(0, t) \leqslant \varpi + \frac{t}{d}, \tag{5}$$

where $n(0, t)$ denotes the switching times of DoS off/on from the initial instant 0 to the current time instant t.

Assumption 2. There exist three real numbers $s_{\min} > 0$, $s_{\max} > 0$, and $d_{\max} > 0$ satisfying

$$\begin{cases} \inf_{n \in \mathbb{N}} \{s_n\} \geqslant s_{\min}, \quad \sup_{n \in \mathbb{N}} \{s_n\} \leqslant s_{\max} < +\infty, \\ \sup_{n \in \mathbb{N}} \{g_n - g_{n-1} - s_{n-1}\} \leqslant d_{\max} < +\infty. \end{cases} \tag{6}$$

Remark 1. Note that condition (5) in Assumption 1 is fairly common in literature that considers DoS attack signals (e.g., [31,33,34,36,37]). In general, to achieve stability, the frequency at which DoS attacks can occur must be sufficiently small compared with the minimum sampling rate. As mentioned in [33], a natural approach to express this requirement is using the concept of average dwell-time. The DoS duration condition (6) in Assumption 2 requires that communication continues for some time after the DoS attack signal has been inactive. Moreover, because each jamming attack cannot last too long, a new condition (6) imposed on DoS jamming attack signals is developed to introduce the minimum time when DoS jammers must be "sleeping", and the maximum time when the jammers must be "active". In fact, these assumptions further justify the power-constraint nature of DoS jamming signals by the fact $\frac{g_n-g_{n-1}-s_{n-1}}{s_{n-1}} \leqslant \frac{g_n-g_{n-1}-s_{\min}}{s_{\min}} \leqslant \frac{d_{\max}}{s_{\min}} < +\infty$, $\forall n \in \mathbb{N}$.

2.4 Resilient event-triggered communication scheme

Inspired by [32], a new version of an event-based attack-resilient communication mechanism is designed. An important feature of this new triggering scheme is that it is resistant to spasmodic DoS attacks, thereby satisfying Assumptions 1 and 2.

Definition 1. Let $t_{k,n}$ denote the current triggering instant occurring in the n-th jammer action interval $[h_{n-1}, h_n]$. Subsequently, the next triggering instant in the n-th jamming action period is iteratively defined as

$$t_{k+1,n}h = t_{k,n}h + \inf_{j\geqslant 1}\{jh \mid t_{k_j}h \text{ satisfying (8) and } t_{k_j}h \in \mathcal{G}_{1,n-1}\}, \tag{7}$$

where $\{t_{k,n}h\} \subseteq \mathcal{G}_{1,n-1}, \{t_{k,n}h\} \neq \emptyset, t_{k_j}h = t_{k,n}h + jh$, and $t_{k_j}h$ satisfies the following relation:

$$\sigma X^{\mathrm{T}}\left(t_{k_j}h\right)\Omega X\left(t_{k_j}h\right) < \epsilon^{\mathrm{T}}\left(t_{k_j}h\right)\Omega\epsilon\left(t_{k_j}h\right), \tag{8}$$

where $X(t) = [x^{\mathrm{T}}(t), x_r^{\mathrm{T}}(t)]^{\mathrm{T}}$, $\epsilon\left(t_{k_j}h\right) = X\left(t_{k_j}h\right) - X(t_{k,n}h)$, $\sigma \in (0,1)$ is a predefined parameter, $\Omega > 0$ is a weighting matrix parameter, and the constant scalar $h > 0$ denotes the sampling period. If no event especially occurs in $\mathcal{G}_{1,n-1}$, i.e., $\{t_{k,n}h\} = \emptyset$, then the next triggering will be scheduled at exactly the right end point g_n of $\mathcal{G}_{2,n-1}$.

Remark 2. It is worth emphasizing here that if the DoS attack signal is sleeping, one can enforce the condition $\sigma X^{\mathrm{T}}(t_{k,n}h)\Omega X(t_{k,n}h) \geqslant \epsilon^{\mathrm{T}}\left(t_{k_j}h\right)\Omega\epsilon\left(t_{k_j}h\right)$ holds for all $t \in \cup_{n\in\mathbb{N}}\mathcal{G}_{1,n}$, while if the attack signal is active, that is, for all $t \in \cup_{n\in\mathbb{N}}\mathcal{G}_{2,n}$, one cannot enforce the above relation. Compared with the formulation proposed in [31,33–35], this treatment further reduces the update frequency of the controller.

2.5 Event-triggered attack-tolerant fuzzy tracking controller structure

In this paper, apart from considering the spasmodic DoS attacks mentioned above, we take into account the effect of the small time-varying transmission delay on the control system. For this purpose, we use $\delta_{k,n}$ as the time instant when the released sampled data $(t_{k,n}, X(t_{k,n}h))$ is successfully received by zero-order hold (ZOH), where $t_{k,n}h \leqslant \delta_{k,n} < g_{n-1} + s_{n-1}$ for $k \in \varphi(n) \triangleq \{0, 1, \ldots, k(n)\}$ with $k(n) = \sup\{k \in \mathbb{N} \mid \delta_{k,n} \leqslant g_{n-1} + s_{n-1}\}, n \in \mathbb{N}$. Based on Assumption 2, we obtain $0 < \delta_{1,n} < \delta_{2,n} < \cdots < \delta_{k,n} < \cdots$. Furthermore, the transmission delay of the successfully transmitted sampled data at instant $t_{k,n}h$ in the n-th jamming period can be expressed as $\tau_{k,n} = \delta_{k,n} - t_{k,n}h$. Here, for $k \in \varphi(n)$, $n \in \mathbb{N}$, we assume that $\tau_{k,n} \in [0, \bar{\tau})$ with $\bar{\tau} < h$.

According to the previous statements, the fuzzy rules of the controller for $t \in [\delta_{k,n}, \delta_{k+1,n})$ can be represented as the following.

Rule s: IF $\eta_1(t_{k,n}h)$ is θ_{s1}, $\eta_2(t_{k,n}h)$ is $\theta_{s2}, \ldots, \eta_j(t_{k,n}h)$ is θ_{sj}, THEN

$$u(t) = K_s X(t_{k,n}h), \quad k \in \varphi(n), n \in \mathbb{N},$$

where K_s $(s = 1, 2, \ldots, r)$ are fuzzy gains. Then, for $t \in [\delta_{k,n}, \delta_{k+1,n})$, the fuzzy controller can be described as

$$u(t) = \sum_{s=1}^{r}\xi_s\left(\eta\left(t - \tau_{t_{k,n}}\right)\right)K_s X(t_{k,n}h), \quad k \in \varphi(n), n \in \mathbb{N}. \tag{9}$$

Based on the above analysis together with the Remark 1 of [50], the real $u(t)$ of the controlled plant can be rewritten as

$$u(t)=\begin{cases}\sum\limits_{s=1}^{r}\xi_s\left(\eta\left(t-\tau_{t_{k,n}}\right)\right)K_sX\left(t_{k,n}h\right), & t\in\mathcal{G}_{1,n-1}\cap[\delta_{k,n},\delta_{k+1,n}),\\ 0, \quad t\in\mathcal{G}_{2,n-1},k\in\varphi(n),n\in\mathbb{N}.\end{cases}\tag{10}$$

For notational simplicity in what follows, $\xi_s(\eta(t-\tau_{t_{k,n}}))$ and $\xi_l(\eta(t))$ will be written as $\xi_s^{k,n}$ and ξ_l, respectively. Additionally, to facilitate the subsequent analysis of the fuzzy control system, we make an assumption on the premise variables ξ_s and $\xi_s^{k,n}$ as in [51–53].

Assumption 3. Some real numbers, γ_s $(s=1,2,\ldots,r)$, exist such that $\xi_s^{k,n}=\gamma_s\xi_s$, where $0<\gamma_{\min}\leqslant\gamma_s\leqslant\gamma_{\max}$, $\gamma_{\min}$ and $\gamma_{\max}$ are given positive scalars.

2.6 Fuzzy switched tracking error system under DoS attacks

First, simplifying the exposition, we define $I_{k,n}\triangleq[\delta_{k,n},\delta_{k+1,n})$ for $k\in\varphi(n)$, $n\in\mathbb{N}$, $e(t)=y(t)-y_r(t)$,

$$\bar{\mathcal{A}}_l=\begin{bmatrix}\mathcal{A}_l & 0\\ 0 & \mathcal{A}_r\end{bmatrix},\quad \bar{\mathcal{B}}_l=\begin{bmatrix}\mathcal{B}_l\\ \mathbf{0}\end{bmatrix},\quad \bar{H}_l=\begin{bmatrix}\mathcal{B}_{wl} & 0\\ 0 & \mathcal{B}_r\end{bmatrix},\quad \bar{\mathcal{C}}_l=\begin{bmatrix}\mathcal{C}_l & -\mathcal{C}_r\end{bmatrix},\quad \bar{w}(t)=\begin{bmatrix}w(t)\\ r(t)\end{bmatrix},$$

and then by combining (10) and (2), the switched tracking error control system can be expressed as

$$\begin{cases}\dot{X}(t)=\begin{cases}\sum\limits_{l=1}^{r}\sum\limits_{s=1}^{r}\xi_l\xi_s^{k,n}\left[\bar{\mathcal{A}}_lX(t)+\bar{\mathcal{B}}_lK_sX(t_{k,n}h)+\bar{H}_l\bar{w}(t)\right], & t\in I_{k,n}\cap\mathcal{G}_{1,n-1},\\ \sum\limits_{l=1}^{r}\xi_l\left[\bar{\mathcal{A}}_lX(t)+\bar{H}_l\bar{w}(t)\right], & t\in\mathcal{G}_{2,n-1},\end{cases}\\ e(t)=\sum\limits_{l=1}^{r}\xi_l\bar{\mathcal{C}}_lX(t),\ t\geqslant0.\end{cases}\tag{11}$$

Next, for ease of system analysis, similar to [40], we transform the switched tracking error control system (11) into a switched delay system. To this end, we decompose the intervals $I_{k,n}$ into the following subintervals:

$$I_{k,n}=\left\{\cup_{z=1}^{\lambda_{k,n}-1}\left[\delta_{k,n}+(z-1)h,\delta_{k,n}+zh\right)\right\}\cup\left[\delta_{k,n}+\lambda_{k,n}h-h,\delta_{k+1,n}\right),\tag{12}$$

where $k\in\varphi(n)$, $n\in\mathbb{N}$, and $\lambda_{k,n}=\inf\{m\in\mathbb{N}\mid\delta_{k+1,n}\leqslant\delta_{k,n}+zh\}$, which means that $\delta_{k,n}+(\lambda_{k,n}-1)h<\delta_{k+1,n}$.

Let

$$\begin{cases}T_{k,n}^{z}=[\delta_{k,n}+(z-1)h,\delta_{k,n}+zh), & z\in\{1,2,\ldots,\lambda_{k,n}-1\},\\ T_{k,n}^{\lambda_{k,n}}=[\delta_{k,n}+\lambda_{k,n}h-h,\delta_{k+1,n}).\end{cases}\tag{13}$$

Notice that

$$\mathcal{G}_{1,n-1}=\cup_{k=0}^{k(n)}\{I_{k,n}\cap\mathcal{G}_{1,n-1}\}\subseteq\cup_{k=0}^{k(n)}I_{k,n}.\tag{14}$$

Combining (12)–(14), the interval $\mathcal{G}_{1,n-1}$ can be described as

$$\mathcal{G}_{1,n-1}=\cup_{k=0}^{k(n)}\cup_{z=1}^{\lambda_{k,n}}\left\{T_{k,n}^{z}\cap\mathcal{G}_{1,n-1}\right\}.$$

Let $\varkappa_{k,n}^{z}=T_{k,n}^{z}\cap\mathcal{G}_{1,n-1}$. Then $\mathcal{G}_{1,n-1}=\cup_{k=0}^{k(n)}\cup_{z=1}^{\lambda_{k,n}}\varkappa_{k,n}^{z}$. For $k\in\varphi(n)$, $n\in\mathbb{N}$, define two piecewise functions:

$$\rho_{k,n}(t)=\begin{cases}t-t_{k,n}h,\ t\in\varkappa_{k,n}^{1},\\ t-t_{k,n}h-h,\ t\in\varkappa_{k,n}^{2},\\ \vdots\\ t-t_{k,n}h-\lambda_{k,n}h+h,\ t\in\varkappa_{k,n}^{\lambda_{k,n}},\end{cases}$$

and

$$\tau_{k,n}(t)=\begin{cases}X(t_{k,n}h)-X(t_{k,n}h),\ t\in\varkappa_{k,n}^{1},\\ X(t_{k,n}h)-X(t_{k,n}h+h),\ t\in\varkappa_{k,n}^{2},\\ \vdots\\ X(t_{k,n}h)-X(t_{k,n}h+\lambda_{k,n}h-h),\ t\in\varkappa_{k,n}^{\lambda_{k,n}}.\end{cases}$$

Based on the expressions of $\rho_{k,n}(t)$ and $\tau_{k,n}(t)$, for $t\in I_{k,n}\cap\mathcal{G}_{1,n-1}$, $k\in\varphi(n)$, $n\in\mathbb{N}$, we obtain

$$X(t_{k,n}h)=\tau_{k,n}(t)+X(t-\rho_{k,n}(t)),\quad \rho_{k,n}(t)\in[0,\tau_M)\ \text{with}\ \tau_M=h+\bar{\tau},\tag{15}$$

with which the system (11) can be described as

$$\begin{cases}\dot{X}(t)=\begin{cases}\sum\limits_{l=1}^{r}\sum\limits_{s=1}^{r}\xi_l\xi_s^{k,n}\big[\bar{\mathcal{A}}_lX(t)+\bar{\mathcal{B}}_lK_sX(t-\rho_{k,n}(t))\\ \quad+\bar{\mathcal{B}}_lK_s\tau_{k,n}(t)+\bar{H}_l\bar{w}(t)\big],\ t\in I_{k,n}\cap\mathcal{G}_{1,n-1},\\ \sum\limits_{l=1}^{r}\xi_l\big[\bar{\mathcal{A}}_lX(t)+\bar{H}_l\bar{w}(t)\big],\ t\in\mathcal{G}_{2,n-1},\end{cases}\\ e(t)=\sum\limits_{l=1}^{r}\xi_l\bar{\mathcal{C}}_lX(t),\ t\geqslant0,\\ X(t)=\chi(t)=\begin{bmatrix}x(t)\\ x_r(t)\end{bmatrix}=\chi(0),\ t\in[-\tau_M,0],\end{cases}\tag{16}$$

where $\chi(t)$ denotes the continuous initial condition, $\tau_{k,n}(t)$ and $\varepsilon_{k,n}(t)$ for $t\in I_{k,n}\cap\mathcal{G}_{1,n-1}$, $k\in\varphi(n)$, $n\in\mathbb{N}$, meet

$$\tau_{k,n}^{\mathrm{T}}(t)\Omega\tau_{k,n}(t)\leqslant\sigma X^{\mathrm{T}}(t-\rho_{k,n}(t))\Omega X(t-\rho_{k,n}(t)).\tag{17}$$

Note that there are two modes switching in two different time intervals in the fuzzy switched delay system model (16). According to this feature, choosing the PLKF to manage switching phenomenon shown in (16) is preferred. Therefore, we construct the following PLKF for controller synthesis of the fuzzy switched delay system (16):

$$V(t)=\begin{cases}V_1(t),\ t\in I_{k,n}\cap\mathcal{G}_{1,n-1},\\ V_2(t),\ t\in\mathcal{G}_{2,n-1},\end{cases}\tag{18}$$

where

$$\begin{aligned}V_i(t)=&X^{\mathrm{T}}(t)\mathcal{P}_iX(t)+\int_{t-\tau_M}^{\mathrm{T}}X^{\mathrm{T}}(s)\mathrm{e}^{2(-1)^i\alpha_i(t-s)}\mathcal{Q}_iX(s)\mathrm{d}s\\ &+\int_{-\tau_M}^{0}\int_{t+\theta}^{\mathrm{T}}\dot{X}^{\mathrm{T}}(s)\mathrm{e}^{2(-1)^i\alpha_i(t-s)}\mathcal{R}_i\dot{X}(s)\mathrm{d}s\mathrm{d}\theta\\ &+\int_{-\tau_M}^{0}\int_{t+\theta}^{\mathrm{T}}\dot{X}^{\mathrm{T}}(s)\mathrm{e}^{2(-1)^i\alpha_i(t-s)}\mathcal{Z}_i\dot{X}(s)\mathrm{d}s\mathrm{d}\theta,\end{aligned}$$

with $\mathcal{P}_i>0$, $\mathcal{Q}_i>0$, $\mathcal{R}_i>0$, $\mathcal{Z}_i>0$, $\alpha_i>0$, $i\in\{1,2\}$.

To facilitate the derivation of the main results at a later stage, some useful definitions are first introduced.

Definition 2. The fuzzy switched delay system (16) without disturbance is said to be globally exponentially stable (GES) under DoS attacks, satisfying Assumptions 1 and 2, if two real numbers $\beta>0$ and $\alpha>0$ exist that satisfy $\|X(t)\|\leqslant\beta\|\chi(0)\|_{\tau_M}\mathrm{e}^{-\alpha t}$, where $\|\chi(0)\|_{\tau_M}=\sup_{-\tau_M\leqslant\theta\leqslant0}\{\|\chi(\theta)\|,\|\dot{\chi}(\theta)\|\}$ and α is called the decay rate.

Definition 3. For a given scalar $\gamma>0$, the fuzzy switched delay system (16) is said to be GES with a prescribed H_∞ disturbance attenuation γ under DoS attacks satisfying Assumptions 1 and 2, if it is GES in the sense of Definition 2, under zero initial conditions satisfying $\|e(t)\|_2\leqslant\gamma\|\bar{w}(t)\|_2$ for non-zero $\bar{w}(t)\in L_2[0,+\infty)$.

Then, the event-triggered attack-tolerant tracking control design problem explored in this study is described as follows: consider the networked tracking control framework as in Figure 1, design the fuzzy tracking controller gain K_s $(s=1,2,\ldots,r)$ in (10) and the triggering parameter Ω in (7) simultaneously such that the fuzzy switched delay system (16) is GES and satisfies a weighted H_∞ disturbance attenuation level γ for all admissible DoS attacks satisfying Assumptions 1 and 2.

3 Main results

To prove the fuzzy switched delay system (16) is GES for all admissible DoS attacks satisfying Assumptions 1 and 2, the following technical lemma is required.

Lemma 1. Consider the fuzzy switched delay system (16) under DoS attacks satisfying Assumptions 1 and 2 with the given $\varpi \in \mathbb{R}_{\geqslant 0}$, $d \in \mathbb{R}_{>h}$, and K_s $(s=1,2,\ldots,r)$. For some predetermined positive real numbers α_i, $\gamma_{\min}$, $\gamma_{\max}$, $\sigma<1$, $\bar{\tau}$ and h, if there exist matrices $\mathcal{P}_i>0$, $\mathcal{R}_i>0$, $\mathcal{Q}_i>0$, $\mathcal{Z}_i>0$, $\Omega>0$, matrices S_{ils}, M_{ils}, and N_{ils} of appropriate dimensions, $i\in\{1,2\}$, such that

$$\Pi_{ill}<0,\quad l=1,2,\ldots,r, \tag{19}$$

$$\Pi_{ils}+\beta_{\min}\Pi_{isl}<0,\quad 1\leqslant l<s\leqslant r, \tag{20}$$

$$\Pi_{ils}+\beta_{\max}\Pi_{isl}<0,\quad 1\leqslant l<s\leqslant r, \tag{21}$$

where

$$\Pi_{ils}=\begin{bmatrix} \Pi^i_{11ls} & * & * & * & * & * \\ \sqrt{\tau_M}S^{\mathrm{T}}_{ils} & \Pi^i_{22} & * & * & * & * \\ \sqrt{\tau_M}N^{\mathrm{T}}_{ils} & 0 & \Pi^i_{33} & * & * & * \\ \sqrt{\tau_M}M^{\mathrm{T}}_{ils} & 0 & 0 & \Pi^i_{44} & * & * \\ \sqrt{\tau_M}\mathcal{Z}_i\Gamma_{ils} & 0 & 0 & 0 & \Pi^i_{55} & * \\ \sqrt{\tau_M}\mathcal{R}_i\Gamma_{ils} & 0 & 0 & 0 & 0 & \Pi^i_{66} \end{bmatrix},$$

$$\Pi^1_{1ls}=\begin{bmatrix} \mathcal{P}_1\bar{\mathcal{A}}_l+\bar{\mathcal{A}}_l^{\mathrm{T}}\mathcal{P}_1+\mathcal{Q}_1+2\alpha_1\mathcal{P}_1 & * & * & * \\ K_s^{\mathrm{T}}\bar{\mathcal{B}}_l^{\mathrm{T}}\mathcal{P}_1 & \sigma\Omega & * & * \\ 0 & 0 & -\mathrm{e}^{-2\alpha_1\tau_M}\mathcal{Q}_1 & * \\ K_s^{\mathrm{T}}\bar{\mathcal{B}}_l^{\mathrm{T}}\mathcal{P}_1 & 0 & 0 & -\Omega \end{bmatrix},$$

$$\Pi^2_{1ls}=\begin{bmatrix} \mathcal{P}_2\bar{\mathcal{A}}_l+\bar{\mathcal{A}}_l^{\mathrm{T}}\mathcal{P}_2+\mathcal{Q}_2-2\alpha_2\mathcal{P}_2 & * & * \\ 0 & 0 & * \\ 0 & 0 & -\mathrm{e}^{2\alpha_2\tau_M}\mathcal{Q}_2 \end{bmatrix},\quad \Pi^i_{11ls}=\Pi^i_{1ls}+\varpi_{ils}+\varpi^{\mathrm{T}}_{ils},$$

$$\Pi^i_{22}=-\mathrm{e}^{2(-1)^i\alpha_i\kappa_i\tau_M}R_i,\quad \Pi^i_{33}=-\mathrm{e}^{2(-1)^i\alpha_i\kappa_i\tau_M}\mathcal{R}_i,\ \kappa_1=1,\ \kappa_2=0,$$

$$\Pi^i_{44}=-\mathrm{e}^{2(-1)^i\alpha_i\kappa_i\tau_M}\mathcal{Z}_i,\ \kappa_1=1,\ \kappa_2=0,\ \ \Pi^i_{55}=-\mathcal{Z}_i,\ \ \Pi^i_{66}=-\mathcal{R}_i,\ \beta_{\min}=\frac{\gamma_{\min}}{\gamma_{\max}},\ \beta_{\max}=\frac{1}{\beta_{\min}},$$

$$\Gamma_{1ls}=\begin{bmatrix}\bar{\mathcal{A}}_l & \bar{\mathcal{B}}_lK_s & 0 & \bar{\mathcal{B}}_lK_s\end{bmatrix},\quad \Gamma_{2ls}=\begin{bmatrix}\bar{\mathcal{A}}_l & 0 & 0\end{bmatrix},$$

$$\varpi_{1ls}=\begin{bmatrix}M_{1ls}+N_{1ls} & -N_{1ls}+S_{1ls} & -M_{1ls}-S_{1ls} & 0\end{bmatrix},$$

$$\varpi_{2ls}=\begin{bmatrix}M_{2ls}+N_{2ls} & -N_{2ls}+S_{2ls} & -M_{2ls}-S_{2ls}\end{bmatrix},$$

then, along the trajectory of the fuzzy switched delay system (16) with $\bar{w}(t)=0$, we have

$$V_i(t)\leqslant \mathrm{e}^{2(-1)^i\alpha_i(t-t_{i,n-1})}V_i(t_{i,n-1}),\quad t\in[t_{i,n-1},t_{3-i,n+i-2}), \tag{22}$$

where $i \in \{1,2\}, n \in \mathbb{N}$, $V_i(t)$ is defined in (18) and

$$t_{i,n} = \begin{cases} g_n, \ i=1, \\ g_n + s_n, \ i=2. \end{cases}$$

Proof. See Appendix A.

Remark 3. In Lemma 1, we adopt the commonly used method to estimate the function V_i, which may bring some conservatism. In fact, by using the affine canonical Bessel-Legendre inequality [54], the estimations that we can get are better than those in (50)–(52). This will be addressed in our future work.

Based on the above lemma, we can readily obtain the stability analysis result summarized below.

3.1 Stability analysis

Theorem 1. Consider the fuzzy switched delay system (16) under DoS attacks satisfying Assumptions 1 and 2 with the given $\varpi \in \mathbb{R}_{\geqslant 0}$, $d \in \mathbb{R}_{>h}$, and K_s $(s = 1, 2, \ldots, r)$. For some given real numbers $0 < \sigma < 1$, $\gamma_{\min} > 0$, $\gamma_{\max} > 0$, $\alpha_i > 0$, $\mu_i > 0$, $s_{\min} > 0$, $d_{\max} > 0$, $\bar{\tau} > 0$ and h satisfying

$$0 < 2\alpha_1 (s_{\min} - h - \bar{\tau}) - 2\alpha_2 (d_{\max} + h + \bar{\tau}) - \ln(\mu_1\mu_2), \tag{23}$$

if there exist matrices $\mathcal{P}_i > 0$, $\mathcal{R}_i > 0$, $\mathcal{Q}_i > 0$, $\mathcal{Z}_i > 0$, $\Omega > 0$, matrices M_{ils}, N_{ils}, and S_{ils} of appropriate dimensions, $i \in \{1, 2\}$ such that (19)–(21) and the following linear matrix inequalities (LMIs) hold:

$$\mathcal{P}_1 \leqslant \mu_2 \mathcal{P}_2, \tag{24}$$

$$\mathcal{P}_2 \leqslant \mu_1 \mathrm{e}^{2(\alpha_1+\alpha_2)(h+\bar{\tau})} \mathcal{P}_1, \tag{25}$$

$$\mathcal{Q}_i \leqslant \mu_{3-i} \mathcal{Q}_{3-i}, \tag{26}$$

$$\mathcal{R}_i \leqslant \mu_{3-i} \mathcal{R}_{3-i}, \tag{27}$$

$$\mathcal{Z}_i \leqslant \mu_{3-i} \mathcal{Z}_{3-i}, \tag{28}$$

then, the system (16) is GES with decay rate β, where

$$\beta = \frac{2\alpha_1 (s_{\min} - h - \bar{\tau}) - 2\alpha_2 (d_{\max} + h + \bar{\tau}) - \ln(\mu_1\mu_2)}{2\tau_D}. \tag{29}$$

Proof. Following [40], it is easy to prove the result.

Remark 4. If the fuzzy switched delay system (16) is GES, as proposed by Theorem 1, then the following three relations (i)–(iii) can be drawn.

(i) The value of $\bar{\tau}$ is bounded by $\bar{\tau}^* \triangleq \frac{2\alpha_1 s_{\min} - 2\alpha_2 d_{\max} - \ln(\mu_1\mu_2)}{2(\alpha_1+\alpha_2)} - h$. In fact, from (23), we have

$$\begin{aligned} 0 &< 2\alpha_1 s_{\min} - 2(\alpha_1+\alpha_2)\tau_M - 2\alpha_2 d_{\max} - \ln(\mu_1\mu_2) \\ &\Leftrightarrow 2(\alpha_1+\alpha_2)\tau_M < 2\alpha_1 s_{\min} - 2\alpha_2 d_{\max} - \ln(\mu_1\mu_2) \\ &\Leftrightarrow \tau_M < \frac{2\alpha_1 s_{\min} - 2\alpha_2 d_{\max} - \ln(\mu_1\mu_2)}{2(\alpha_1+\alpha_2)} \\ &\Leftrightarrow \bar{\tau} < \bar{\tau}^*. \end{aligned} \tag{30}$$

Similarly, from (23) it follows that

$$\text{(ii)} \quad d_{\max} < d^*_{\max} \triangleq \frac{2\alpha_1 (s_{\min} - \tau_M) - 2\alpha_2 \tau_M - \ln(\mu_1\mu_2)}{2\alpha_2}, \tag{31}$$

and

$$\text{(iii)} \quad s_{\min} > s^*_{\min} \triangleq \frac{2\alpha_2 (d_{\max} + \tau_M) + 2\alpha_1 \tau_M + \ln(\mu_1\mu_2)}{2\alpha_1}, \tag{32}$$

which means that the active/sleeping time of DoS attack signal cannot be very large/small, respectively. This is reasonable and conforms to the actual situation.

3.2 Weighted H_∞ tracking control performance analysis

Theorem 2. Consider the fuzzy switched delay system (16) under DoS attacks satisfying Assumptions 1 and 2 with the given $\varpi \in \mathbb{R}_{\geqslant 0}$, $d \in \mathbb{R}_{>h}$, and K_s $(s = 1, 2, \ldots, r)$. For some predetermined positive scalars γ, σ, $\gamma_{\min}$, $\gamma_{\max}$, $s_{\min}$, $s_{\max}$, α_i, μ_i, $d_{\max}$, $\bar{\tau}$ and h satisfying (23), the fuzzy switched system (16) is GES with a weighted H_∞ performance level

$$\tilde{\gamma}^* = \sqrt{\frac{\rho_{\max}}{\rho_{\min}}}\gamma,$$

where $\rho_{\min} = \min\{1, \frac{1}{\mu_2}\}$, $\rho_{\max} = \max\{\mathrm{e}^{2\alpha_2 d_{\max}}, \frac{\mathrm{e}^{2\alpha_1 s_{\max}}}{\mu_2}\}$, if there exist symmetric positive definite matrices $\mathcal{P}_i$, $\mathcal{R}_i$, $\mathcal{Q}_i$, $\mathcal{Z}_i$, Ω, matrices $\tilde{M}_{ils}$, $\tilde{N}_{ils}$, and $\tilde{S}_{ils}$, $i \in \{1, 2\}$, such that (24)–(28) and (33)–(35) hold:

$$\Xi_{ill} < 0, \quad l = 1, 2, \ldots, r, \tag{33}$$

$$\Xi_{ils} + \beta_{\min}\Xi_{isl} < 0, \quad 1 \leqslant l < s \leqslant r, \tag{34}$$

$$\Xi_{ils} + \beta_{\max}\Xi_{isl} < 0, \quad 1 \leqslant l < s \leqslant r, \tag{35}$$

where

$$\Xi_{ils} = \begin{bmatrix} \Xi^i_{11ls} & * & * & * & * & * & * \\ \sqrt{\tau_M}\tilde{N}^{\mathrm{T}}_{ils} & \Xi^i_{22} & * & * & * & * & * \\ \sqrt{\tau_M}\tilde{S}^{\mathrm{T}}_{ils} & 0 & \Xi^i_{33} & * & * & * & * \\ \sqrt{\tau_M}\tilde{M}^{\mathrm{T}}_{ils} & 0 & 0 & \Xi^i_{44} & * & * & * \\ \sqrt{\tau_M}\mathcal{Z}_i\Gamma_{ils} & 0 & 0 & 0 & \Xi^i_{55} & * & * \\ \sqrt{\tau_M}\mathcal{R}_i\Gamma_{ils} & 0 & 0 & 0 & 0 & \Xi^i_{66} & * \\ \Phi_{ils} & 0 & 0 & 0 & 0 & 0 & \Xi^i_{77} \end{bmatrix},$$

$$\Xi^i_{11ls} = \Xi^i_{1ls} + \tilde{\varpi}_{ils} + \tilde{\varpi}^{\mathrm{T}}_{ils}, \quad \Xi^i_{22} = -\mathrm{e}^{2(-1)^i\alpha_i\kappa_i\tau_M}\mathcal{R}_i, \quad \Xi^i_{33} = -\mathrm{e}^{2(-1)^i\alpha_i\kappa_i\tau_M}\mathcal{R}_i, \ \kappa_1 = 1, \ \kappa_2 = 0,$$

$$\Xi^i_{44} = -\mathrm{e}^{2(-1)^i\alpha_i\kappa_i\tau_M}\mathcal{Z}_i, \ \kappa_1 = 1, \ \kappa_2 = 0, \quad \Xi^i_{55} = -\mathcal{Z}_i, \quad \Xi^i_{66} = -\mathcal{R}_i, \quad \Xi^i_{77} = -I,$$

$$\Gamma_{1ls} = \begin{bmatrix} \bar{\mathcal{A}}_l & \bar{\mathcal{B}}_l K_s & 0 & \bar{\mathcal{B}}_l K_s & \bar{H}_l \end{bmatrix}, \quad \Gamma_{2ls} = \begin{bmatrix} \bar{\mathcal{A}}_l & 0 & 0 & \bar{H}_l \end{bmatrix}, \quad \Xi^1_{1ls} = \begin{bmatrix} \Pi^1_{1ls} & * \\ \bar{H}^{\mathrm{T}}_l\mathcal{P}_1 & -\gamma^2 I \end{bmatrix},$$

$$\Xi^2_{1ls} = \begin{bmatrix} \Pi^2_{1ls} & * \\ \bar{H}^{\mathrm{T}}_l\mathcal{P}_2 & -\gamma^2 I \end{bmatrix}, \quad \tilde{\varpi}_{1ls} = \begin{bmatrix} \tilde{M}_{1ls} + \tilde{N}_{1ls} & \tilde{S}_{1ls} - \tilde{N}_{1ls} & -\tilde{S}_{1ls} - \tilde{M}_{1ls} & 0 & 0 \end{bmatrix},$$

$$\tilde{\varpi}_{2ls} = \begin{bmatrix} \tilde{N}_{2ls} + \tilde{M}_{2ls} & \tilde{S}_{2ls} - \tilde{N}_{2ls} & -\tilde{S}_{2ls} - \tilde{M}_{2ls} & 0 \end{bmatrix}, \quad \Phi_{1ls} = \begin{bmatrix} \bar{\mathcal{C}}_l & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \Phi_{2ls} = \begin{bmatrix} \bar{\mathcal{C}}_l & 0 & 0 & 0 \end{bmatrix}.$$

Proof. See Appendix B.

Remark 5. Compared with the input-state stable (ISS) analysis results under DoS attacks obtained in [31, 50], the achieved H_∞ performance level in Theorem 2 is weighted, based on the techniques used in (B3)–(B10).

3.3 Event-triggered attack-tolerant H_∞ tracking controller synthesis

In this subsection, based on Theorem 2, synthesis of the event-triggered attack-tolerant H_∞ tracking controller is conducted.

Theorem 3. Consider the fuzzy switched delay system (16) under DoS attacks satisfying Assumptions 1 and 2 with the given $\varpi \in \mathbb{R}_{\geqslant 0}$, $d \in \mathbb{R}_{>h}$. For some predetermined positive real numbers γ, σ, $\gamma_{\min}$, $\gamma_{\max}$, $l_{\max}$, ρ_j $(j = 1, 2, 3, 4)$, ε_i, ϕ_i, η_i, α_i, μ_i, $s_{\min}$, $d_{\max}$, $\bar{\tau}$ and h satisfying (23), the fuzzy switched delay system (16) with $K_s = Y_s\mathcal{X}_1^{-1}$, $s = 1, 2, \ldots, r$, is GES and achieves the desired H_∞ performance $\tilde{\gamma}^*$, where $\tilde{\gamma}^*$ is defined in Theorem 2, if there exist symmetry positive definite matrices $\mathcal{X}_i$, $\hat{\mathcal{P}}_i$, $\hat{\mathcal{Q}}_i$, $\hat{\mathcal{R}}_i$, $\hat{\mathcal{Z}}_i$, $\hat{\Omega}$, and matrices $\hat{S}_{ils}$, $\hat{M}_{ils}$, $\hat{N}_{ils}$, Y_s, $i \in \{1, 2\}$ of appropriate dimensions satisfying the following LMIs:

$$\hat{\Xi}_{ill} < 0, \quad l = 1, 2, \ldots, r, \tag{36}$$

$$\hat{\Xi}_{ils} + \beta_{\min}\hat{\Xi}_{isl} < 0, \quad 1 \leqslant l < s \leqslant r, \tag{37}$$

$$\hat{\Xi}_{ils} + \beta_{\max}\hat{\Xi}_{ils} < 0, \quad 1 \leqslant l < s \leqslant r, \tag{38}$$

$$\begin{bmatrix} -\mu_2\mathcal{X}_2 & * \\ \mathcal{X}_2 & -\mathcal{X}_1 \end{bmatrix} \leqslant 0, \tag{39}$$

$$\begin{bmatrix} -\mu_1 \mathrm{e}^{2(\alpha_1+\alpha_2)\tau_M}\mathcal{X}_1 & * \\ \mathcal{X}_1 & -\mathcal{X}_2 \end{bmatrix} \leqslant 0, \tag{40}$$

$$\begin{bmatrix} -\mu_{3-i}\hat{\mathcal{Q}}_{3-i} & * \\ \mathcal{X}_{3-i} & \phi_i^2\hat{\mathcal{Q}}_i - 2\phi_i\mathcal{X}_i \end{bmatrix} \leqslant 0, \tag{41}$$

$$\begin{bmatrix} -\mu_{3-i}\hat{\mathcal{R}}_{3-i} & * \\ \mathcal{X}_{3-i} & \varepsilon_i^2\hat{\mathcal{R}}_i - 2\varepsilon_i\mathcal{X}_i \end{bmatrix} \leqslant 0, \tag{42}$$

$$\begin{bmatrix} -\mu_{3-i}\hat{\mathcal{Z}}_{3-i} & * \\ \mathcal{X}_{3-i} & \eta_i^2\hat{\mathcal{Z}}_i - 2\eta_i\mathcal{X}_i \end{bmatrix} \leqslant 0, \tag{43}$$

where

$$\hat{\Xi}_{ils} = \begin{bmatrix} \hat{\Xi}^i_{11ls} & * & * & * & * & * & * \\ \sqrt{\tau_M}\hat{N}^{\mathrm{T}}_{ils} & \hat{\Xi}^i_{22} & * & * & * & * & * \\ \sqrt{\tau_M}\hat{S}^{\mathrm{T}}_{ils} & 0 & \hat{\Xi}^i_{33} & * & * & * & * \\ \sqrt{\tau_M}\hat{M}^{\mathrm{T}}_{ils} & 0 & 0 & \hat{\Xi}^i_{44} & * & * & * \\ \sqrt{\tau_M}\hat{\Gamma}^{\mathrm{T}}_{ils} & 0 & 0 & 0 & \hat{\Xi}^i_{55} & * & * \\ \sqrt{\tau_M}\hat{\Gamma}^{\mathrm{T}}_{ils} & 0 & 0 & 0 & 0 & \hat{\Xi}^i_{66} & * \\ \hat{\Phi}_{ils} & 0 & 0 & 0 & 0 & 0 & \hat{\Xi}^i_{77} \end{bmatrix},$$

$$\hat{\Xi}^i_{11ls} = \hat{\Xi}^i_{1ls} + \hat{\varpi}_{ils} + \hat{\varpi}^{\mathrm{T}}_{ils}, \quad \hat{\Xi}^1_{22} = \hat{\Xi}^1_{33} = -\mathrm{e}^{-2\alpha_1\tau_M}\hat{\mathcal{R}}_1,$$
$$\hat{\Xi}^2_{22} = \hat{\Xi}^2_{33} = -\hat{\mathcal{R}}_2, \quad \hat{\Xi}^1_{44} = -\mathrm{e}^{-2\alpha_1\tau_M}\hat{\mathcal{Z}}_1, \quad \hat{\Xi}^2_{44} = -\hat{\mathcal{Z}}_2,$$
$$\hat{\Xi}^1_{55} = \rho_1^2\hat{\mathcal{Z}}_1 - 2\rho_1\mathcal{X}_1, \quad \hat{\Xi}^2_{55} = \rho_3^2\hat{\mathcal{Z}}_2 - 2\rho_3\mathcal{X}_2,$$
$$\hat{\Xi}^1_{66} = \rho_2^2\hat{\mathcal{R}}_1 - 2\rho_2\mathcal{X}_1, \quad \hat{\Xi}^2_{66} = \rho_4^2\hat{\mathcal{R}}_2 - 2\rho_4\mathcal{X}_2, \quad \hat{\Xi}^i_{77} = -I,$$
$$\hat{\Gamma}_{1ls} = \begin{bmatrix} \bar{\mathcal{A}}_l\mathcal{X}_1 & \bar{\mathcal{B}}_l Y_s & 0 & \bar{\mathcal{B}}_l Y_s & \bar{H}_l \end{bmatrix}, \quad \hat{\Gamma}_{2ls} = \begin{bmatrix} \bar{\mathcal{A}}_l\mathcal{X}_2 & 0 & 0 & \bar{H}_l \end{bmatrix},$$

$$\hat{\Xi}^1_{1ls} = \begin{bmatrix} \bar{\mathcal{A}}_l\mathcal{X}_1 + \mathcal{X}_1\bar{\mathcal{A}}_l^{\mathrm{T}} + \hat{\mathcal{Q}}_1 + 2\alpha_1\mathcal{X}_1 & * & * & * & * \\ Y_s^{\mathrm{T}}\bar{\mathcal{B}}_l^{\mathrm{T}} & \sigma\hat{\Omega} & * & * & * \\ 0 & 0 & -\mathrm{e}^{-2\alpha_1\tau_M}\hat{\mathcal{Q}}_1 & * & * \\ Y_s^{\mathrm{T}}\bar{\mathcal{B}}_l^{\mathrm{T}} & 0 & 0 & -\hat{\Omega} & * \\ \bar{H}_l^{\mathrm{T}} & 0 & 0 & 0 & -\gamma^2 I \end{bmatrix},$$

$$\hat{\Xi}^2_{1ls} = \begin{bmatrix} \bar{\mathcal{A}}_l\mathcal{X}_2 + \mathcal{X}_2\bar{\mathcal{A}}_l^{\mathrm{T}} + \hat{\mathcal{Q}}_2 - 2\alpha_2\mathcal{X}_2 & * & * & * \\ 0 & 0 & * & * \\ 0 & 0 & -\mathrm{e}^{2\alpha_2\tau_M}\hat{\mathcal{Q}}_2 & * \\ \bar{H}_l^{\mathrm{T}} & 0 & 0 & -\gamma^2 I \end{bmatrix},$$

$$\hat{\varpi}_{1ls} = \begin{bmatrix} \hat{M}_{1ls} + \hat{N}_{1ls} & -\hat{N}_{1ls} + \hat{S}_{1ls} & -\hat{M}_{1ls} - \hat{S}_{1ls} & 0 & 0 \end{bmatrix},$$
$$\hat{\varpi}_{2ls} = \begin{bmatrix} \hat{M}_{2ls} + \hat{N}_{2ls} & -\hat{N}_{2ls} + \hat{S}_{2ls} & -\hat{M}_{2ls} - \hat{S}_{2ls} & 0 \end{bmatrix},$$
$$\hat{\Phi}_{1ls} = \begin{bmatrix} \bar{\mathcal{C}}_l\mathcal{X}_1 & 0 & 0 & 0 & 0 \end{bmatrix}, \quad \hat{\Phi}_{2ls} = \begin{bmatrix} \bar{\mathcal{C}}_l\mathcal{X}_2 & 0 & 0 & 0 \end{bmatrix}.$$

Moreover, once a feasible solution is found in the above LMIs, the fuzzy gains of the attack-tolerant fuzzy controller (9) can be obtained as $K_s = Y_s X_1^{-1}$, $s = 1, 2, \ldots, r$.

Proof. Because of a space constraint, we have omitted the proof. The result can be derived following the proof of Theorem 2 in [40].

Remark 6. If the resilient event-triggering scheme (7) and event-triggered tracking controller (10) under non-periodic DoS jamming attacks are co-designed as proposed in Theorem 3, a degree of freedom in the design is the choice of the parameters α_i, μ_i, $s_{\min}$, and $d_{\max}$. The restriction on parameters $s_{\min}$ and $d_{\max}$ is that the inequality (23) holds, and this possibility provides a lower bound and upper bound for the values $s_{\min}$ and $d_{\max}$ can take for some prescribed scalars α_i, μ_i, h, and $\bar{\tau}$. When $d_{\max}$ is chosen as large as possible, we can expect that the controller will be able to tolerate longer DoS jamming attacks. However, according to (32), this leads to a larger value of $s^*_{\min}$, which is undesirable. Therefore, a tradeoff for a good choice of α_i, μ_i, $s_{\min}$, and $d_{\max}$ has to be found in practical applications.

Remark 7. Based on the statement of Remark 6, when some parameters mentioned in the above synthesis result are predetermined, the corresponding synthesis conditions become strict LMIs. Therefore, we can formulate the following optimization problem, which facilitates us to design the event-triggered attack-tolerant fuzzy tracking controller gains in (10) and the matrix parameter in (9) minimizing the H_∞ performance level for some given parameters $s_{\min}$, $s_{\max}$, α_1, α_2, μ_1, μ_2, and $d_{\max}$:

$$\min\ \hat{\gamma} \quad \text{s.t. (23) and (36)–(43) with } \hat{\gamma} = \gamma^2. \tag{44}$$

If there exists an optimal solution $\hat{\gamma}^*$ for the above optimization problem, then the fuzzy tracking error system (16) with the obtained event-triggered fuzzy tracking controller (9) can achieve the optimal weighted H_∞ performance index $\bar{\gamma}^* = \sqrt{\hat{\gamma}^* \frac{\rho_{\max}}{\rho_{\min}}}$, where the meanings of $\rho_{\min}$ and $\rho_{\max}$ are the same as those in Theorem 2.

Remark 8. Interestingly, the stability analysis technique proposed in Theorem 1 suggests that when Assumption 2 is replaced with Assumption 2 in [31], the stability conditions given in Theorem 1 do not need to be considerably adjusted except that the inequality (23) needs to be replaced by

$$\frac{\frac{\ln(\mu_1\mu_2)}{\alpha_1+\alpha_2} + h}{\tau_D} + \frac{1}{T} < \frac{\alpha_1}{\alpha_1+\alpha_2}, \tag{45}$$

where $\frac{1}{T}$ denotes the average DoS duration [31]. Correspondingly, the exponential convergence decay β is changed to

$$\bar{\beta} = \frac{\bar{\lambda}}{2}, \tag{46}$$

where $\bar{\lambda} = \alpha_1 - \frac{\ln(\mu_1\mu_2)+(\alpha_1+\alpha_2)h}{\tau_D} - \frac{\alpha_1+\alpha_2}{T}$. Furthermore, the relation $\|e(t)\|_2 \leqslant \tilde{\gamma}^* \|\bar{w}(t)\|_2$ shown in Theorem 2 is accordingly modified as

$$\int_0^\infty \mathrm{e}^{-\rho t} \|e(t)\|^2 \mathrm{d}t \leqslant \varrho\gamma^2 \int_0^\infty \|\bar{w}(t)\|^2 \mathrm{d}t, \tag{47}$$

where $\rho = \frac{\ln(\mu_1\mu_2)+(\alpha_1+\alpha_2)h}{\tau_D}$,

$$\varrho = \chi\left[-\left(\frac{1+\frac{\alpha_2}{\alpha_1}}{T} - 1\right)^{-1}\right], \quad \chi = \mathrm{e}^{\upsilon\ln(\mu_1\mu_2)+(\alpha_1+\alpha_2)(\upsilon h+\kappa)}.$$

Proof of the above conclusion (45)–(47) has been omitted here for simplicity. Generally, the main results based on Assumptions 1 and 2 proposed in this paper may be less conservative than the results based on Assumptions 1 and 2 [31], because more refined information on DoS attacks are used here.

Remark 9. Notice that the major differences between the present paper and [38] are as follows: (1) Multi-area power systems are considered in [38], while a sampled-data networked T-S fuzzy system is discussed in this paper. (2) The description of the constraints on DoS attack behavior in [38] is based on the maximum allowable number of successive packet losses, while in this paper, the DoS attack mode is constrained by minimal "sleeping" period, maximal "active" period of DoS attacks, and the DoS frequency. (3) The common quadratic Lyapunov function is used in [38], while in this paper, by introducing conceptions of minimal "sleeping" period and maximal "active" period of DoS attacks, the PLKF approach is employed to analyze the exponential stability and weighted H_∞ performance.

4 An illustrative example

Consider the nonlinear systems taken from [45]

$$\begin{cases} \dot{x}_1(t) = x_2(t), \\ \dot{x}_2(t) = -x_1^3(t) - 0.2x_2(t) + 12\cos(t) + u(t). \end{cases} \tag{48}$$

Define a compact set $\mathbb{D}$ (the universe of discourse); choose the premise variable $z(t) = x_1(t)$; the nonlinear system (48) can be written as the T-S fuzzy model (2) with

$$\begin{aligned} &\mathcal{A}_1 = \begin{bmatrix} 0 & 1 \\ 0 & -0.1 \end{bmatrix}, \quad \mathcal{B}_1 = \mathcal{B}_{w1} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \\ &\mathcal{A}_2 = \begin{bmatrix} 0 & 1 \\ -25 & -0.1 \end{bmatrix}, \quad \mathcal{B}_2 = \mathcal{B}_{w2} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \\ &\mathcal{C}_1 = \mathcal{C}_2 = \begin{bmatrix} 1 & 0 \end{bmatrix}, \\ &\mathbb{D} = \{x(t) : \| x_1(t) \| \leqslant 5, \| x_2(t) \| \leqslant 4\}, \end{aligned}$$

while membership functions are chosen as $h_1(x_1(t)) = 1 - \frac{x_1^2}{25}$, $h_2(x_1(t)) = 1 - h_1(x_1(t))$. The reference model is chosen as

$$\begin{cases} \dot{x}_r(t) = \begin{bmatrix} 0 & 1 \\ -3 & -2 \end{bmatrix} x_r(t) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} r(t), \\ y_r(t) = [\,-1 \ \ -1\,] x_r(t), \end{cases}$$

where $x_r(t) = [\,x_{r1}^{\mathrm{T}}(t) \ x_{r2}^{\mathrm{T}}(t)\,]^{\mathrm{T}}$.

First, we validate the effectiveness of the proposed collaborative design method of the attack-tolerant weighted H_∞ tracking controller and event generator. For this purpose, choose $h = 0.01$ s, $\alpha_1 = 0.15$, $\alpha_2 = 2$, $\mu_1 = 1.02$, $\mu_2 = 1.02$ satisfying (23), $\rho_j = 5$ $(j = 1,2,3,4)$, $\varepsilon_i = 10$, $\phi_i = 10$, $\eta_i = 10$ $(i = 1,2)$, $\sigma = 0.1$, $\gamma_{\min} = 0.5$, $\gamma_{\max} = 1$, $\gamma_1 = \gamma_2 = 0.7$, $\tau_M = 0.015$, $s_{\min} = 6$, $s_{\max} = 8$, $d_{\max} = 0.4$. Using Remark 6, the obtained optimal solution $\bar{\gamma}^* = 0.5190$, and the corresponding fuzzy gains K_1, K_2, and the triggering parameter Ω are given by

$$\begin{aligned} K_1 &= \begin{bmatrix} -14.3371 & -10.9877 & -3.0642 & -4.1990 \end{bmatrix}, \\ K_2 &= \begin{bmatrix} 0.2558 & -10.9780 & -3.0040 & -4.1949 \end{bmatrix}, \\ \Omega &= \begin{bmatrix} 11.9716 & * & * & * \\ 13.1001 & 20.6284 & * & * \\ 3.8408 & 6.8915 & 3.7795 & * \\ 5.0105 & 7.9222 & 2.6984 & 3.0492 \end{bmatrix}. \end{aligned}$$

Thus, the value of $\hat{\gamma}^* = \sqrt{\bar{\gamma}^* \frac{\rho_{\max}}{\rho_{\min}}} = 2.3918$.

Next, we show the effectiveness of the attack-tolerant H_∞ tracking controller for the fuzzy switched delay systems under DoS attacks. To this end, the simulation time is set to 50 s, and the external disturbance input and the reference input of the system (48) are chosen as

$$w(t) = \begin{cases} 1, & \text{if } 5 \leqslant t \leqslant 10, \\ 0, & \text{otherwise}, \end{cases}$$

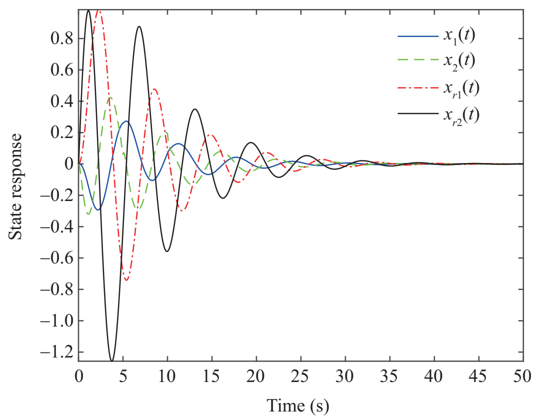

Figure 2 (Color online) State response of the controlled plant and the reference model without DoS jamming attacks.

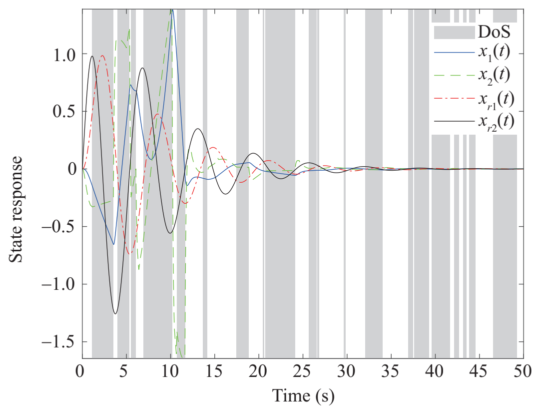

Figure 3 (Color online) State response of the controlled plant and the reference model under DoS jamming attacks.

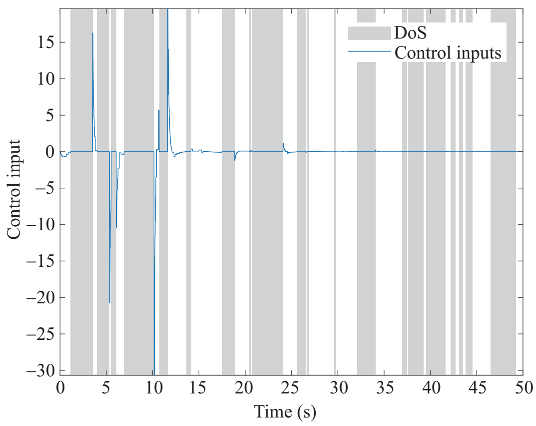

Figure 4 (Color online) Control input under DoS jamming attacks.

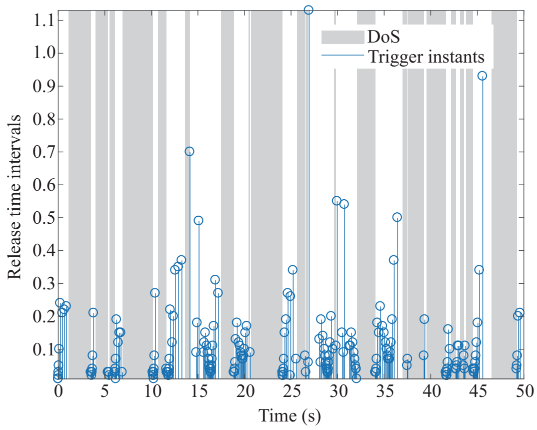

Figure 5 (Color online) Release time intervals and release instants under DoS jamming attacks.

and $r(t) = 4\sin(t+0.5)\mathrm{e}^{-0.15t}$, respectively. By performing simple calculations, one obtains $\frac{\|e(t)\|_2}{\|w(t)\|_2+\|r(t)\|_2} = 0.4062 < \hat{\gamma}^* = 2.3918$, which implies the effectiveness of the proposed attack-tolerant H_∞ tracking controller.

For simulation, the initial condition is zero. The external disturbance and the reference signal are the same as those previously used. The other related parameters are also unchanged. The state response of the controlled plant and the reference model with/without considering DoS attacks are shown in Figures 2 and 3, respectively. By comparison, we discover that the overshoot of the controlled plant and the reference model clearly increase when the DoS attacks are active. However, the closed-loop system remains stable despite the presence of intermittent DoS attacks. Figure 4 describes the control input curve and clearly indicates that the zero input strategy may consume less energy than the ZOH strategy used in [31] because updating the control input is not needed as long as the system is under DoS attacks. Figure 5 shows the release instants and release time intervals, and clearly indicates that the developed event-triggered mechanism is capable of reducing data transmission while compensating for data losses caused by DoS attacks. The output-tracking error response is shown in Figure 6, which illustrates that the tracking error control system can be stabilized despite the presence of DoS attacks. To summarize, these figures show that when the DoS attacks intermittently occur, the controlled plant with the designed tracking controller can effectively follow the reference model, and the proposed event-triggered attack-tolerant H_∞ tracking control method can still effectively work.

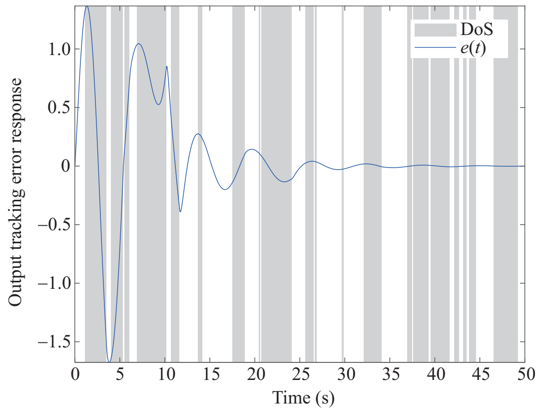

Figure 6 (Color online) Output tracking error response under DoS jamming attacks.

5 Conclusion

The event-triggered attack-tolerant tracking controller synthesis of nonlinear system over a network subject to DoS attacks was studied. To resist DoS attacks and reduce the transmission of sensor data via a network, a new attack-resilient event-triggered strategy was developed. A fuzzy switched delay system model with an asynchronous premise was established to combine the impacts of the triggering scheme and spasmodic DoS attacks. By adopting the piecewise LKF method, a collaborative design solution of attack-tolerant H_∞ fuzzy controller and event generator was provided. A numerical example as provided to validate the efficiency of the developed design method. Our future work will be to further develop the proposed method by reducing its conservativeness with some new techniques, such as the discontinuous LKF approach. Furthermore, extending the proposed approach to discussing the security tracking control design for a nonlinear two-link robot system shown in [55] will be interesting.

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Appendix A Proof of Lemma 1

Because system (16) is a hybrid fuzzy switched system, we will estimate the upper bound of $V_i(t)$ from the two cases mentioned below.

Case 1. When DoS jamming attack signals are sleeping, i.e., $t \in I_{k,n} \cap \mathcal{G}_{1,n-1}$, for any given $k \in \varphi(n)$, taking the time derivation of $V_1(t)$ along the trajectory of the fuzzy switched delay system (16), one has

$$\begin{aligned}\dot{V}_1(t) \leqslant\ & -2\alpha_1 V_1(t) + 2\alpha_1 X^{\mathrm{T}}(t)\mathcal{P}_1 X(t) + 2X^{\mathrm{T}}(t)\mathcal{P}_1\dot{X}(t) + X^{\mathrm{T}}(t)\mathcal{Q}_1 X(t)\\ & - X^{\mathrm{T}}(t-\tau_M)\mathrm{e}^{-2\alpha_1\tau_M}\mathcal{Q}_1 X(t-\tau_M) + \tau_M\dot{X}^{\mathrm{T}}(t)(\mathcal{R}_1+\mathcal{Z}_1)\dot{X}(t)\\ & - \mathrm{e}^{-2\alpha_1\tau_M}\sum_{r=1}^{3} I_r + 2\sum_{r=4}^{6} I_r,\end{aligned} \tag{A1}$$

where $\nu_1 = X(t) - X(t-\tau_M) - \int_{t-\tau_M}^{\mathrm{T}} \dot{X}(s)\,\mathrm{d}s$, $\nu_2 = X(t) - X\left(t-\rho_{k,n}(t)\right) - \int_{t-\rho_{k,n}(t)}^{\mathrm{T}} \dot{X}(s)\,\mathrm{d}s$, $\nu_3 = X\left(t-\rho_{k,n}(t)\right) - X(t-\tau_M) - \int_{t-\tau_M}^{t-\rho_{k,n}(t)} \dot{X}(s)\,\mathrm{d}s$, and

$$\begin{aligned} I_1 &= \int_{t-\tau_M}^{\mathrm{T}} \dot{X}^{\mathrm{T}}(s)\mathcal{Z}_1\dot{X}(s)\,\mathrm{d}s, \quad I_2 = \int_{t-\rho_{k,n}(t)}^{\mathrm{T}} \dot{X}^{\mathrm{T}}(s)\mathcal{R}_1\dot{X}(s)\,\mathrm{d}s,\\ I_3 &= \int_{t-\tau_M}^{t-\rho_{k,n}(t)} \dot{X}^{\mathrm{T}}(s)\mathcal{R}_1\dot{X}(s)\,\mathrm{d}s, \quad I_4 = \sum_{l=1}^{r}\sum_{s=1}^{r}\xi_l\xi_s^{k,n}\zeta^{\mathrm{T}}(t)M_{1ls}\nu_1,\\ I_5 &= \sum_{l=1}^{r}\sum_{s=1}^{r}\xi_l\xi_s^{k,n}\zeta^{\mathrm{T}}(t)N_{1ls}\nu_2, \quad I_6 = \sum_{l=1}^{r}\sum_{s=1}^{r}\xi_l\xi_s^{k,n}\zeta^{\mathrm{T}}(t)S_{1ls}\nu_3. \end{aligned}$$

Using the element inequality to deal with the integral terms in (A1), we obtain

$$\begin{aligned}\dot{V}_1(t) \leqslant\ & -2\alpha_1 V_1(t) + \sum_{l=1}^{r}\sum_{s=1}^{r}\xi_l\xi_s^{k,n}\zeta^{\mathrm{T}}(t)[\Pi_{11ls}^1 + \tau_M N_{1ls}\mathrm{e}^{2\alpha_1\tau_M}\mathcal{R}_1^{-1}N_{1ls}^{\mathrm{T}}\\ & + \tau_M M_{1ls}\mathrm{e}^{2\alpha_1\tau_M}\mathcal{Z}_1^{-1}M_{1ls}^{\mathrm{T}} + \tau_M S_{1ls}\mathrm{e}^{2\alpha_1\tau_M}\mathcal{R}_1^{-1}S_{1ls}^{\mathrm{T}} + \tau_M\Gamma_{1ls}^{\mathrm{T}}(\mathcal{R}_1+\mathcal{Z}_1)\Gamma_{1ls}]\zeta(t).\end{aligned} \tag{A2}$$

Based on Assumption 3, it follows that

$$\dot{V}_1(t) + 2\alpha_1 V_1(t) \leqslant \sum_{l=1}^{r}\gamma_l\xi_l^2\zeta^{\mathrm{T}}(t)\Pi_{1ll}\zeta(t) + \sum_{l=1}^{r-1}\sum_{s>l}^{r}\xi_l\xi_s^{k,n}\zeta^{\mathrm{T}}(t)\left[\gamma_s\Pi_{1ls} + \gamma_l\Pi_{1sl}\right]\zeta(t), \tag{A3}$$

where $\Pi_{1ls} = \Pi_{11ls}^1 + \tau_M N_{1ls}\mathrm{e}^{2\alpha_1\tau_M}\mathcal{R}_1^{-1}N_{1ls}^{\mathrm{T}} + \tau_M M_{1ls}\mathrm{e}^{2\alpha_1\tau_M}\mathcal{Z}_1^{-1}M_{1ls}^{\mathrm{T}} + \tau_M S_{1ls}\mathrm{e}^{2\alpha_1\tau_M}\mathcal{R}_1^{-1}S_{1ls}^{\mathrm{T}} + \tau_M\Gamma_{1ls}^{\mathrm{T}}(\mathcal{R}_1+\mathcal{Z}_1)\Gamma_{1ls}$, Π_{11ls}^1, N_{1ls}, M_{1ls}, S_{1ls} and Γ_{1ls} are defined in (19)–(21).

Define $\beta_{ls} = \frac{\gamma_l}{\gamma_s}$ $(l, s = 1, 2, \ldots, r)$. Notice that γ_l and $\gamma_s \in [\gamma_{\min}, \gamma_{\max}]$, and then $\beta_{ls} \in [\beta_{\min}, \beta_{\max}]$. Therefore, from (A3), it yields that

$$\gamma_s\Pi_{1ls} + \gamma_l\Pi_{1sl} < 0 \Leftrightarrow \Pi_{1ls} + \beta_{ls}\Pi_{1sl} < 0. \tag{A4}$$

Applying the matrix convex property, it follows from (A4) that

$$\Pi_{1ls} + \beta_{ls}\Pi_{1sl} < 0 \Leftrightarrow \begin{cases}\Pi_{1ls} + \beta_{\min}\Pi_{1sl} < 0,\\ \Pi_{1ls} + \beta_{\max}\Pi_{1sl} < 0.\end{cases} \tag{A5}$$

Thus, by combining (19)–(21), for $t \in I_{k,n} \cap \mathcal{G}_{1,n-1}$, we have

$$\dot{V}_1(t) + 2\alpha_1 V_1(t) \leqslant 0.$$

In view of the arbitrariness of k, for any $t \in \mathcal{G}_{1,n-1}$, one has

$$V_1(t) \leqslant \mathrm{e}^{-2\alpha_1(t-t_{1,n-1})} V_1(t_{1,n-1}). \tag{A6}$$

Case 2. When DoS jamming attack signals are active, i.e., $t \in \mathcal{G}_{2,n-1}$, following Case 1, we obtain

$$\dot{V}_2(t) - 2\alpha_1 V_2(t) \leqslant \sum_{l=1}^{r} \gamma_l \xi_l^2 \zeta^{\mathrm{T}}(t) \Pi_{2ll} \zeta(t) + \sum_{l=1}^{r-1} \sum_{s>l}^{r} \xi_l \xi_s \zeta^{\mathrm{T}}(t) [\gamma_s \Pi_{2ls} + \gamma_l \Pi_{2sl}] \zeta(t), \tag{A7}$$

where $\Pi_{2ls} = \Pi_{11ls}^2 + \tau_M N_{2ls} \mathcal{R}_2^{-1} N_{2ls}^{\mathrm{T}} + \tau_M M_{2ls} \mathcal{Z}_2^{-1} M_{2ls}^{\mathrm{T}} + \tau_M S_{2ls} \mathcal{R}_2^{-1} S_{2ls}^{\mathrm{T}} + \tau_M \Gamma_{2ls}^{\mathrm{T}} (\mathcal{R}_2 + \mathcal{Z}_2) \Gamma_{2ls}$. The remaining proof is similar to Case 1, and we can obtain that for $t \in \mathcal{G}_{2,n-1}$, $\dot{V}_2(t) \leqslant 2\alpha_2 V_2(t)$, which implies

$$V_2(t) \leqslant \mathrm{e}^{2\alpha_2(t-t_{2,n-1})} V_2(t_{2,n-1}). \tag{A8}$$

According to (A6)–(A8), the estimation of $V_i(t)$ in (22) is obtained.

Appendix B Proof of Theorem 2

Let $-\gamma^2 \bar{w}^{\mathrm{T}}(t) \bar{w}(t) + \mathrm{e}^{\mathrm{T}}(t) e(t) \triangleq J(t)$. Similar to Lemma 1, for $\bar{w}(t) \neq 0$, from (33)–(35), we have

$$\frac{\mathrm{d}V_1(t)}{\mathrm{d}t} + 2\alpha_1 V_1(t) + J(t) \leqslant 0, \quad t \in \mathcal{G}_{1,n}, \tag{B1}$$

and

$$\frac{\mathrm{d}V_2(t)}{\mathrm{d}t} - 2\alpha_2 V_2(t) + J(t) \leqslant 0, \quad t \in \mathcal{G}_{2,n}. \tag{B2}$$

Now, for $t \in [g_k, g_k + s_k)$, multiplying $\frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}$ on both sides of (B1) yields

$$\frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}\left[\frac{\mathrm{d}V_1(t)}{\mathrm{d}t} + 2\alpha_1 V_1(t)\right] \leqslant \frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}[-J(t)]. \tag{B3}$$

Integrating both sides of (B3) from $t = g_k$ to $g_k + s_k$ yields

$$\int_{g_k}^{g_k+s_k} \frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}\left[\frac{\mathrm{d}V_1(t)}{\mathrm{d}t} + 2\alpha_1 V_1(t)\right]\mathrm{d}t \leqslant \int_{g_k}^{g_k+s_k} \frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}[-J(t)]\,\mathrm{d}t. \tag{B4}$$

Summing both sides of (B4), one has

$$\sum_{k=0}^{n}\int_{g_k}^{g_k+s_k} \frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}\left[\frac{\mathrm{d}V_1(t)}{\mathrm{d}t} + 2\alpha_1 V_1(t)\right]\mathrm{d}t \leqslant \sum_{k=0}^{n}\int_{g_k}^{g_k+s_k} \frac{1}{\mu_2}\mathrm{e}^{-2\alpha_1(g_k-t)}[-J(t)]\,\mathrm{d}t. \tag{B5}$$

Similarly, for $t \in [g_k + s_k, g_{k+1})$, it follows from (B2) that

$$\sum_{k=0}^{n}\int_{g_k+s_k}^{g_{k+1}} \mathrm{e}^{2\alpha_2(g_k+s_k-t)}\left[\frac{\mathrm{d}V_2(t)}{\mathrm{d}t} - 2\alpha_2 V_2(t)\right]\mathrm{d}t \leqslant \sum_{k=0}^{n}\int_{g_k+s_k}^{g_{k+1}} \mathrm{e}^{2\alpha_2(g_k+s_k-t)}[-J(t)]\,\mathrm{d}t. \tag{B6}$$

Now, $\forall t \in [0, g_{n+1})$, adding both sides of (B5) and (B6), and using Theorem 1, we have

$$\begin{aligned}
&\sum_{k=0}^{n}\int_{g_k}^{g_k+s_k} \frac{\mathrm{e}^{-2\alpha_1(g_k-t)}}{\mu_2}[-J(t)]\,\mathrm{d}t + \sum_{k=0}^{n}\int_{g_k+s_k}^{g_{k+1}} \mathrm{e}^{2\alpha_2(g_{k+1}-t)}[-J(t)]\,\mathrm{d}t \\
&\geqslant \sum_{k=0}^{n}\int_{g_k}^{g_k+s_k} \frac{\mathrm{e}^{-2\alpha_1(g_k-t)}}{\mu_2}\left[\frac{\mathrm{d}V_1(t)}{\mathrm{d}t} + 2\alpha_1 V_1(t)\right]\mathrm{d}t + \sum_{k=0}^{n}\int_{g_k+s_k}^{g_{k+1}} \mathrm{e}^{2\alpha_2(g_k+s_k-t)}\left[\frac{\mathrm{d}V_2(t)}{\mathrm{d}t} - 2\alpha_2 V_2(t)\right]\mathrm{d}t \\
&\geqslant \frac{V_1(g_{n+1}) - V_1(0)}{\mu_2} + \sum_{k=0}^{n} V_1(g_k+s_k)\left(\frac{\mathrm{e}^{2\alpha_1 s_{\min}}}{\mu_2} - \mu_1 \mathrm{e}^{2\alpha_2 d_{\max} + 2(\alpha_1+\alpha_2)\tau_M}\right).
\end{aligned} \tag{B7}$$

Noting $V_1(g_{n+1}) \geqslant 0$, $V_1(g_k + s_k) \geqslant 0$, $V_1(0) = 0$, and (23), it follows from (B7) that

$$\sum_{k=0}^{n}\left(\int_{g_k}^{g_k+s_k} \frac{\mathrm{e}^{-2\alpha_1(g_k-t)}}{\mu_2}[-J(t)]\,\mathrm{d}t + \int_{g_k+s_k}^{g_{k+1}} \mathrm{e}^{2\alpha_2(g_{k+1}-t)}[-J(t)]\,\mathrm{d}t\right) \geqslant 0. \tag{B8}$$

Using Assumption 2, if $t \in [g_k, g_k + s_k)$, $k \in \{0, 1, 2, \ldots, n\}$, $n \in \mathbb{N}$, then

$$1 \leqslant \mathrm{e}^{-2\alpha_1(g_k-t)} \leqslant \mathrm{e}^{2\alpha_1 s_k} \leqslant \mathrm{e}^{2\alpha_1 s_{\max}}. \tag{B9}$$

On the other hand, if $t \in [g_k + s_k, g_{k+1})$, then

$$1 \leqslant \mathrm{e}^{2\alpha_2(g_{k+1}-t)} \leqslant \mathrm{e}^{2\alpha_2(g_{k+1}-g_k-s_k)} \leqslant \mathrm{e}^{2\alpha_2 d_{\max}}. \tag{B10}$$

Combining (B8)–(B10), for $\bar{w}(t) \in L_2[0, +\infty)$, we obtain $\|e(t)\|_2 \leqslant \tilde{\gamma}^* \|\bar{w}(t)\|_2$, where $\tilde{\gamma}^* = \sqrt{\frac{\rho_{\max}}{\rho_{\min}}}\gamma$, $\rho_{\min}$ and $\rho_{\max}$ have been defined in Theorem 2.

When $\bar{w}(t) = 0$, according to (B1) and (B2), we get $\frac{\mathrm{d}V_1(t)}{\mathrm{d}t} + 2\alpha_1 V_1(t) \leqslant 0$ for $t \in \mathcal{G}_{1,n}$ and $\frac{\mathrm{d}V_2(t)}{\mathrm{d}t} - 2\alpha_2 V_2(t) \leqslant 0$ for $t \in \mathcal{G}_{2,n}$. Then, by applying Theorem 1, it follows that the fuzzy switched system (16) is GES. Therefore, based on Definition 3, the proof is complete.