

# Security Control for T–S Fuzzy Systems With Adaptive Event-Triggered Mechanism and Multiple Cyber-Attacks

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**Abstract**—This article focuses on the security control for Takagi–Sugeno (T–S) fuzzy systems with adaptive event-triggered mechanism (AETM) and multiple cyber-attacks, which include deception attacks and denial-of-service (DoS) attacks. A multiple cyber-attacks model is first established for T–S fuzzy systems by considering deception attacks and DoS attacks at the same time. An AETM is introduced to relieve the network load, where the threshold of event-triggering condition can be adaptively adjusted while preserving the system performance. Then a novel mathematical model for T–S fuzzy systems with multiple cyber-attacks and AETM is proposed first. Based on the built model, sufficient conditions to guarantee the exponentially mean square stability of the system are achieved by utilizing the Lyapunov stability theory. Moreover, the controller gains are derived with the help of a linear matrix inequality technique. Finally, simulated examples are presented for illustrating the effectiveness of the proposed method.

**Index Terms**—Adaptive event-triggered mechanism (AETM), multiple cyber-attacks, security control, Takagi–Sugeno (T–S) fuzzy systems.

## I. INTRODUCTION

**T**AKAGI–SUGENO (T–S) fuzzy systems can approximate nonlinear systems by using lots of fuzzy linear models, which can describe the local dynamics in different state-space regions [1]–[11]. In the recent decades, T–S fuzzy systems play a significant role in modeling and analyzing

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various systems, which results in a great number of achievements [12]–[18]. For instance, the T–S fuzzy systems were applied in [3] where the problem of quantized stabilization for networked control systems was addressed. Chadli *et al.* [7] studied the local stability issue for a kind of T–S fuzzy systems. In [15], the relaxed real-time scheduling stabilization was discussed for discrete-time T–S fuzzy systems. A class of cyber-physical systems was discussed which was approximated by the T–S fuzzy systems [16], [19]. In addition, the control problem of T–S fuzzy systems has also attracted great interests of scholars [20]–[22]. Liu *et al.* [20] concentrated on the problem of the networked fuzzy static output feedback control for discrete-time T–S fuzzy systems. The fuzzy predictive controller design was proposed for T–S fuzzy systems in [21].

In the networked systems, some issues brought by constrained network resources pose a grave threat to the system performance. Considerable efforts are made to solve these issues and many results are procurable. Time-triggered scheme is the most extensively used in the networked systems due to its simple task model, where all data are sampled and delivered in a fixed period. When the changes between the latest transmitted data and current sampling data are fairly small, a great quantity of similar data are delivered in the network, thus leading to network congestion and waste of communication resources. For the sake of relieving the unnecessary waste of network resources, scholars devote themselves into developing more effective data transmission strategies and put forward various event-triggered schemes [23]–[28]. Among these event-triggered mechanisms, an event-triggered scheme proposed in [25] has received wide applications since it supervises system states at discrete intervals and only allows the data violating the predefined condition to be sent out. Inspired by the event-triggered mechanism in [25], an adaptive event-triggered mechanism (AETM) is proposed in [29] to further economize the limited bandwidth and improve the utilization of communication resources. The event-triggered condition of AETM has a varying-threshold, thus it can adjust the sampling interval dynamically when maintaining the system performance. Zhang *et al.* [30] adopted the AETM to design an adaptive event-triggered controller for nonlinear networked systems. Through utilizing AETM, the controller design of networked interconnected control systems was proposed with the help of T–S fuzzy model in [31]. Additionally, the event-triggered mechanism in [25] are further developed, then hybrid-triggered mechanism and distributed event-triggered

mechanism are proposed [32]–[35]. Under the hybrid-triggered mechanism, time-triggered scheme, and event-triggered mechanism are stochastically switching according to the amount of transmitted data and network environment in the current network [3]. The hybrid-triggered mechanism was applied in [32] where the authors investigated the state estimation of T–S fuzzy systems. Through using the distributed event-triggered mechanism, Liu *et al.* [33] presented an algorithm of state estimator design for networked sensor systems.

The introduction of the network contributes to higher efficiency for data transmission, nevertheless, it also results in lots of problems, such as packet dropouts [36], time delay [37], [38], and stochastic uncertainties [39]. One of these important issues is the network security problem, which can drastically deteriorate the system performance. Therefore, a lot of efforts have been put into the researches on this problem [40]–[49]. In reality, the network is highly possible to be attacked by malicious signal, which results from the openness and sharability of network. Generally, the frequently studied network attacks contain deception attacks, replay attacks, denial-of-service (DoS) attacks, etc. The deception attacks degrade systems performance with the method of injecting the malicious data. By considering the impacts of deception attacks, the problem of event-based filter design for cyber-physical systems was addressed in [42]. The state estimator design for networked control systems subject to deception attacks was proposed in [33]. The replay attacks replay previous transmitted data, which leads to system performance deterioration. Liang *et al.* [45] focused on the distributed Kalman filtering for target tracking with the consideration of replay attacks. A stochastic coding detection scheme was proposed in [46] to improve the performance of cyber-physical systems against replay attacks. Besides, the DoS attacks are aimed at blocking the data transmission by taking up the network resources. By taking DoS attacks into account, the state estimation for T–S fuzzy systems with sensor saturation was investigated in [16]. Zhang *et al.* [47] focused on the robust output consensus for multiagent systems under DoS attacks. The controller design for networked control system with DoS attacks was proposed [48], [49]. To the best of our knowledge, there exists a considerable part of literatures where single cyber-attack is taken into account while few study is concerned with multiple cyber-attacks. As a consequence, the multiple cyber-attacks, containing deception attacks, and DoS attacks, are first considered when investigating the issue of security control for T–S fuzzy systems with AETM in this article.

The remainder of this article is organized as follows. The mathematical model of T–S fuzzy systems with AETM and multiple cyber-attacks is presented in Section II. The sufficient conditions ensuring system exponentially mean-square stable (EMSS) are acquired and the desired controller gains are accurately obtained in Section III. In Section IV, the usefulness of designed algorithm is confirmed through simulated examples.

*Notation:*  $R^m$ ,  $R^{m \times n}$ , and  $R_{\geq 0}$  stand for the  $m$ -dimensional Euclidean space, the set of  $m \times n$  real matrices, and non-negative real scalars, respectively; the identity matrix  $I$  is with appropriate dimension; for  $Z \in R^{m \times m}$ ,  $Z > 0$  represents that  $Z$  is a real symmetric positive definite matrix;  $X^T$  represents the

transposition of matrix  $X$ .  $\vartheta_{\max}(A)$  ( $\vartheta_{\min}(A)$ ) denotes the maximum (minimum) eigenvalue of matrix  $A$ .  $*$  in a symmetric matrix represents the entries implied by symmetry.  $\mathcal{N}$  stands for the set of positive integers.  $H_{l_2, n}^-$  presents that  $H_{l_2, n}$  is in time interval  $[H_{l_1, n}, H_{l_2, n})$ .

## II. PROBLEM FORMULATION AND MODELING

The framework of security control for T–S fuzzy systems with AETM and multiple cyber-attacks, which consist of DoS attacks and deception attacks, is shown in Fig. 1. In this framework, the sensor, the AETM, the controller, and a zero-order-hold (ZOH), a network channel are included. The sampled data are transmitted via the network from sensor to controller, controller to actuator. Besides, the influences of multiple cyber-attacks are taken into consideration.

Consider the following T–S fuzzy system with  $i$ th rule:

IF  $\phi_1(x(t))$  is  $G_1^i, \dots$ , and  $\phi_p(x(t))$  is  $G_p^i$ , THEN

$$\dot{x}(t) = A_i x(t) + B_i u(t) \quad (1)$$

where  $x(t) \in R^{m_1}$  is the state vector;  $u(t) \in R^{m_2}$  is the control output vector;  $A_i$  and  $B_i$  are constant matrices, which are with appropriate dimensions;  $G_v^i$  ( $i \in \{1, 2, \dots, r\} \triangleq \mathcal{D}$ ,  $v = 1, 2, \dots, p$ ) are the fuzzy sets;  $r$  is the number of IF-THEN rules; and the fuzzy premise variables are represented as  $\phi_v(x(t))$ ; for the sake of convenience,  $\phi_v(x(t))$  is abbreviated as  $\phi_v(x)$  and  $\phi(x) = [\phi_1(x), \phi_2(x), \dots, \phi_p(x)]$ .

Through the utilization of center-average defuzzifier, product interference, and singleton fuzzifier, the system (1) can be described as follows:

$$\dot{x}(t) = \sum_{i=1}^r \xi_i(\phi(x)) [A_i x(t) + B_i u(t)] \quad (2)$$

where  $\xi_i(\phi(x))$  is the normalized membership function satisfying  $\xi_i(\phi(x)) \geq 0$ ,  $\sum_{i=1}^r \xi_i(\phi(x)) = 1$  for  $i \in \mathcal{D}$ .  $\xi_i(\phi(x)) = (\chi_i(\phi(x)) / \sum_{i=1}^r \chi_i(\phi(x)))$ ,  $\chi_i(\phi(x)) = \prod_{v=1}^p \chi_v^i(\phi_v(x))$ ,  $\chi_v^i(\phi_v(x))$  represents the grade membership value of  $\phi_v(x)$ .

*Remark 1:* It is known to all that T–S fuzzy systems can serve as universal approximators of nonlinear systems, such as inverted pendulum systems and chaotic systems. Therefore, T–S fuzzy systems have been widely investigated in the past decades [12]–[15], [17]. In this article, the problem of security control for T–S fuzzy systems with AETM and multiple cyber-attacks is first studied.

The purpose of this article is to propose an algorithm of adaptive event-triggered controller design for T–S fuzzy systems under multiple cyber-attacks. Owing to the existence of network-induced delay, it is of rationality that the latest lagged premise variable  $\xi_j(\phi(\tilde{x}))$  is adopted in the controller design with  $j$ th rule as follows:

IF  $\phi_1(\tilde{x}(t))$  is  $J_1^j, \dots$ , and  $\phi_\kappa(\tilde{x}(t))$  is  $J_\kappa^j$ , THEN

$$u(t) = K_j \tilde{x}(t) \quad (3)$$

where  $\tilde{x}(t) \in R^{m_1}$  is the actual input of controller.  $J_q^j$  ( $j \in \mathcal{D}$ ,  $q = 1, 2, \dots, \kappa$ ) stand for the fuzzy sets;  $\phi_q(\tilde{x}(t))$  are fuzzy premise variables; for convenience,  $\phi_q(\tilde{x}(t))$  is represented by  $\phi_q(\tilde{x})$  and  $\phi(\tilde{x}) = [\phi_1(\tilde{x}), \phi_2(\tilde{x}), \dots, \phi_\kappa(\tilde{x})]$ .  $K_j \in R^{m_1 \times m_2}$  are controller gains to be determined.

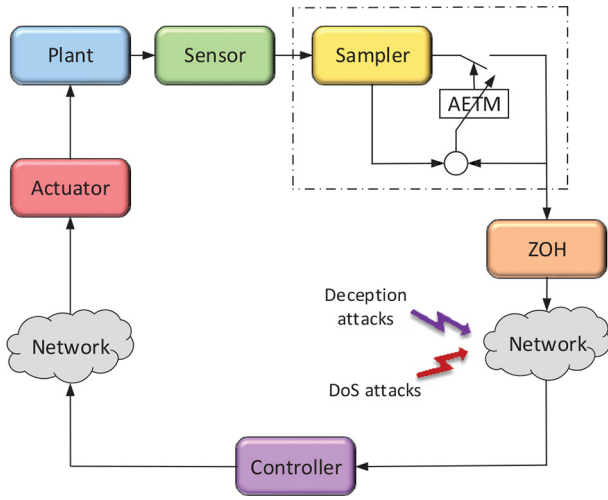


Fig. 1. Structure of T-S fuzzy systems with AETM and multiple cyber-attacks.

Then the following fuzzy controller is inferred:

$$u(t) = \sum_{j=1}^r \xi_j(\phi(\tilde{x})) K_j \tilde{x}(t) \quad (4)$$

where  $\xi_j(\phi(\tilde{x}))$  is the normalized membership function which satisfies  $\xi_j(\phi(\tilde{x})) \geq 0$ ,  $\sum_{j=1}^r \xi_j(\phi(\tilde{x})) = 1$  for  $j \in \mathcal{D}$ .  $\xi_j(\phi(\tilde{x})) = ([o_j(\phi(\tilde{x}))] / [\sum_{j=1}^r o_j(\phi(\tilde{x}))])$ ,  $o_j(\phi(\tilde{x})) = \prod_{q=1}^k d_q^j(\phi_q(\tilde{x}))$ ,  $d_q^j(\phi_q(\tilde{x}))$  denotes the grade membership value of  $\phi_q(\tilde{x})$ .

In order to save bandwidth resources, the AETM exhibited in Fig. 1 is adopted in this article. Denote  $h$  and  $t_k h$  as the sampling period and the latest transmitting instant, respectively, then the next triggering instant  $t_{k+1} h$  is given as follows:

$$t_{k+1} h = t_k h + \min_{b \in \mathcal{N}} \{ b h | \delta_k^T(t_k h) W \delta_k(t_k h) - \varepsilon(t) x^T(t_k h + b h) W x(t_k h + b h) > 0 \} \quad (5)$$

where weighting matrix  $W > 0$ ;  $b = 1, 2, \dots, \bar{b}$ , in which  $\bar{b}$  represents the maximum allowable number of successive packet losses;  $\varepsilon(t)$  is a variable of threshold and satisfies  $\varepsilon(t) \in (0, 1]$ ; and  $\delta_k(t_k h) = x(t_k h) - x(t_k h + b h)$ ,  $x(t_k h)$  represents the latest transmitted data,  $x(t_k h + b h)$  denotes the current sampling data.

Similar to [31], the interval  $[t_k h + v_k, t_{k+1} h)$  can be divided into  $\bar{b}$  subintervals, namely,  $[t_k h + v_k, t_{k+1} h) = \cup_{b=1}^{\bar{b}} [t_k h + b h - h + v_{k,b-1}, t_k h + b h + v_{k,b})$ , where  $v_{k,b}$  is a positive constant. It is worthy of being mentioned that  $\bar{b} = \sup_{b \geq 1} \{ \delta_k^T(t_k h) W \delta_k(t_k h) - \varepsilon(t) x^T(t_k h + b h) W x(t_k h + b h) \leq 0 \}$ .

It should be pointed out that the threshold  $\varepsilon(t)$  in (5) is a variable satisfying the following equality:

$$\dot{\varepsilon}(t) = \frac{1}{\varepsilon(t)} \left( \frac{1}{\varepsilon(t)} - \sigma \right) \delta_k^T(t_k h) W \delta_k(t_k h) \quad (6)$$

where  $\sigma > 0$  is utilized to adjust the convergence rate of  $\varepsilon(t)$ . Therefore, the triggering condition  $\delta_k^T(t_k h) W \delta_k(t_k h) - \varepsilon(t) x^T(t_k h + b h) W x(t_k h + b h) > 0$  can be dynamically adjusted according to the system states.

*Remark 2:* Compared with the existing event-triggered scheme [25] with a constant threshold parameter, the AETM has an advantage of saving limited network resources while keeping the desired system performance due to the varying-threshold  $\varepsilon(t)$ . When the system reaches stable,  $\delta_k^T(t_k h) W \delta_k(t_k h) \rightarrow 0$ , then  $\varepsilon(t)$  will maintain a constant. In particular, when setting  $\varepsilon(t) \equiv 0$ , the AETM turns to be a conventional time-triggered scheme.

*Remark 3:* In this article, the AETM (5) is introduced to mitigate communication burden and improve network resources utilization. The event-triggering threshold of AETM can be adaptively adjusted according to the parameters of system states. It needs to be pointed out that AETM has been widely applied in the analysis and design of networked systems [29]–[31]. Inspired by the mentioned literatures, the AETM (5) is adopted to investigate the security control problem of T-S fuzzy systems with multiple cyber-attacks in this article.

In the networked T-S fuzzy systems, due to the openness of communication channel, the network is more susceptible to malicious signals such as multiple cyber-attacks. In this article, the influences of multiple cyber-attacks, including deception attacks and DoS attacks are considered, which is shown in Fig. 1.

When the network is subjected to deception attacks, the deception attack signal  $h(x(t))$  may substitute for normal data. A Bernoulli variable  $\eta(t) \in \{0, 1\}$  is used to describe whether deception attacks occur or not, which is of the following statistical properties:

$$\mathbf{E}\{\eta(t)\} = \bar{\eta}, \quad \mathbf{E}\{(\eta(t) - \bar{\eta})^2\} = \bar{\eta}(1 - \bar{\eta}) = \rho^2$$

where  $\bar{\eta}$  and  $\rho^2$  denote the expectation of  $\eta(t)$  and the mathematical variance of  $\eta(t)$ , respectively.

*Assumption 1* [3]: For given constant matrix  $L$ , the deception attack function  $h(x(t))$  satisfies the following condition:

$$\|h(x(t))\|_2 \leq \|Lx(t)\|_2. \quad (7)$$

At the same time, we consider the effects of DoS attacks, then the actual signal transmitted to controller via the network with multiple cyber-attacks is presented as follows:

$$\tilde{x}(t) = \alpha(t)[(1 - \eta(t))h(x(t)) + \eta(t)x_e(t)] \quad (8)$$

where  $\alpha(t) = 0$  or  $\alpha(t) = 1$  represent the DoS attacks take place or not, respectively.  $\alpha(t) = 1$  denotes DoS jamming signal is sleeping when  $t \in [H_n, H_n + \mu_n)$ ;  $\alpha(t) = 0$  indicates the DoS jamming signal is active when  $t \in [H_n + \mu_n, H_{n+1})$ .  $n \in \mathcal{N}$  stands for the period number.  $H_{n+1}$  denotes the end instant of the  $n$ th active period and the starting instant of the  $(n+1)$ th sleeping period;  $\mu_n$  represents the length of the  $n$ th sleeping period. Obviously, one can get that the starting instants and end instants of DoS sleeping period satisfy  $0 \leq H_0 < H_0 + \mu_0 < H_1 < H_1 + \mu_1 < H_2 < \dots < H_n < H_n + \mu_n < H_{n+1} < \dots$ .  $x_e(t)$  is the normal signal which will be delivered over the network. For technical convenience,  $\forall n \in \mathcal{N}$ , let  $\mathcal{W}_{1,n} \triangleq [H_n, H_n + \mu_n)$ ,  $\mathcal{W}_{2,n} \triangleq [H_n + \mu_n, H_{n+1})$ .

*Remark 4:* It needs to be pointed out that the DoS attacks discussed in this article are assumed to be of unknown attack

period. In an attack period  $[H_n, H_{n+1})$ , namely,  $\mathcal{W}_{1,n} \cup \mathcal{W}_{2,n}$ , the DoS jamming signal is sleeping in  $\mathcal{W}_{1,n}$  while it is active in  $\mathcal{W}_{2,n}$ . Besides, DoS attacks block the transmitted signals from sensor to controller when active in the interval  $\mathcal{W}_{2,n}$ . In other words, the signals are transmitted successfully in  $\cup_{n \in \mathcal{N}} \mathcal{W}_{1,n}$  while the data transmission is failed in  $\cup_{n \in \mathcal{N}} \mathcal{W}_{2,n}$ .

*Remark 5:* In (8), when  $\eta(t) = 1$  and  $\alpha(t) = 1$ , the signal  $\tilde{x}(t)$  transmitted from the sensor to the controller is  $x_e(t)$ , which means that there is no cyber-attack occurring in the network; when  $\eta(t) = 0$  and  $\alpha(t) = 1$ , the actual signal  $\tilde{x}(t)$  transmitted to controller is  $h(x(t))$ , which means that the network is only subjected to deception attacks; when  $\alpha(t) = 0$ , we can get  $\tilde{x}(t) = 0$ , which means that DoS jamming signal is active and the signal communication is denied no matter whether deception attacks take place or not.

In the presence of DoS attacks, the transmitted data are interrupted in the active period  $\mathcal{W}_{2,n}$ , thus, the event-triggering condition (5) is not suitable as before. Motivated by [49], the previous adaptive event-triggered condition (5) is modified for adapting the DoS attacks. In the following, the event-triggered instant of the modified AETM is presented [48]:

$$t_{k,n}h = \{t_{k_a}h \text{ satisfying (5)} | t_{k_a}h \in \mathcal{W}_{1,n}\} \cup \{H_n\} \quad (9)$$

where  $k$  is the number of triggering instants in  $a$ th attack period of DoS attacks, and  $k \in \{1, \dots, k(n)\} \triangleq \mathcal{D}(n)$ ,  $k(n) = \sup\{k \in \mathcal{N} | t_{k,n}h \leq H_n + \mu_n\}$ ;  $t_{k_a}, k_a, n, a \in \mathcal{N}$ .

For convenience,  $\forall n \in \mathcal{N}$ , let  $\mathcal{C}_{k,n} \triangleq [t_{k,n}h, t_{k+1,n}h)$ ,  $t_{0,n}h \triangleq H_n$ . Further, the time interval  $\mathcal{C}_{k,n}$  is divided into

$$\mathcal{C}_{k,n} = \bigcup_{\tau=1}^{\psi_{k,n}} \mathcal{O}_{k,n}^{\tau} \cup \mathcal{O}_{k,n}^{\psi_{k,n}+1} \quad (10)$$

where  $k \in \mathcal{D}(n)$ ,  $n \in \mathcal{N}$ ,  $\psi_{k,n} \triangleq \inf\{\tau \in \mathcal{N} | t_{k,n}h + \tau h \leq t_{k,n+1}h\}$ , and  $\mathcal{O}_{k,n}^{\tau} = [t_{k,n}h + (\tau - 1)h, t_{k,n}h + \tau h)$ ,  $\tau \in \{1, 2, \dots, \psi_{k,n}\}$ ,  $\mathcal{O}_{k,n}^{\psi_{k,n}+1} = [t_{k,n}h + \psi_{k,n}h, t_{k+1,n}h)$ .

Notice that the following expression holds:

$$\mathcal{W}_{1,n} = \bigcup_{k=0}^{\mathcal{D}(n)} \{\mathcal{C}_{k,n} \cap \mathcal{W}_{1,n}\} \subseteq \bigcup_{k=0}^{\mathcal{D}(n)} \mathcal{C}_{k,n}. \quad (11)$$

According to (10) and (11), the interval  $\mathcal{W}_{1,n}$  is denoted as

$$\mathcal{W}_{1,n} = \bigcup_{k=0}^{\mathcal{D}(n)} \bigcup_{\tau=1}^{\psi_{k,n}+1} \{\mathcal{O}_{k,n}^{\tau} \cap \mathcal{W}_{1,n}\}. \quad (12)$$

As a result, define

$$\lambda_{k,n}(t) = t - t_{k,n}h - (\partial - 1)h, t \in \mathcal{O}_{k,n}^{\partial} \cap \mathcal{W}_{1,n} \quad (13)$$

and

$$\delta_{k,n}(t) = x(t_{k,n}h) - x(t_{k,n}h + (\partial - 1)h), t \in \mathcal{O}_{k,n}^{\partial} \cap \mathcal{W}_{1,n} \quad (14)$$

where  $\partial = 1, 2, \dots, \psi_{k,n} + 1$ .

From (13) and (14), it can be obtained that  $\lambda_{k,n}(t) \in [0, h)$ ,  $t \in \mathcal{C}_{k,n} \cap \mathcal{W}_{1,n}$ . Then the adaptive event-triggered sampled state  $x(t_{k,n}h)$  is presented as follows:

$$x_e(t) = x(t_{k,n}h) = \delta_{k,n}(t) + x(t - \lambda_{k,n}(t)) \quad (15)$$

with  $\delta_{k,n}(t)$  and  $\varepsilon(t)$  satisfying the following conditions:

$$\dot{\varepsilon}(t) = \frac{1}{\varepsilon(t)} \left( \frac{1}{\varepsilon(t)} - \sigma \right) \delta_{k,n}^T(t) W \delta_{k,n}(t) \quad (16)$$

$$\delta_{k,n}^T(t) W \delta_{k,n}(t) \leq \varepsilon(t) x^T(t - \lambda_{k,n}(t)) W x(t - \lambda_{k,n}(t)). \quad (17)$$

By combining (2), (4), (8), and (15), the system (2) can be expressed as

$$\dot{x}(t) = \begin{cases} \sum_{i=1}^r \sum_{j=1}^r \xi_i \xi_j \{A_i x(t) + B_j K_j [\eta(t) \delta_{k,n}(t) + \eta(t) x(t - \lambda_{k,n}(t)) + (1 - \eta(t)) h(x(t))]\} \\ t \in \mathcal{C}_{k,n} \cap \mathcal{W}_{1,n} \\ \sum_{i=1}^r \sum_{j=1}^r \xi_i \xi_j A_i x(t), t \in \mathcal{W}_{2,n} \end{cases} \quad (18)$$

where  $\xi_i$  and  $\xi_j$  stand for  $\xi_i(\phi(x))$  and  $\xi_j(\phi(\tilde{x}))$ , respectively;  $x(t) = \beta(t)$ ,  $t \in [-h, 0]$ ;  $\beta(t)$  is the supplemented initial condition of the state  $x(t)$  on  $[-h, 0]$ ,  $\beta(0) \triangleq \beta_0$ .

*Remark 6:* In the past years, the network security issue of T-S fuzzy systems has become a research hotspot due to the much attention paid to T-S fuzzy systems [1]–[3], [21]. There are most of the published literatures only concerned with single cyber-attack, however, various cyber-attacks may simultaneously occur in the real systems. To describe it more authentic, a class of multiple cyber-attacks consisting of deception attacks and DoS attacks is considered for the networked T-S fuzzy systems. Then the mathematical model (18) of T-S fuzzy systems with AETM and multiple cyber-attacks is first established.

Under the consideration of multiple attacks, this article aims at designing the controller and triggering parameters to stabilize the T-S fuzzy systems with AETM. To solve this issue, inspired by [32] and [50], the errors of the grades of memberships are assumed to satisfy the following inequalities:

$$|\xi_i(\phi(x)) - \xi_i(\phi(\tilde{x}))| \leq \varsigma_i, i \in \mathcal{D}. \quad (19)$$

Then, the following assumptions, definition, and lemma are introduced to assist us in achieving the main results.

*Assumption 2* [51]: In attack periods  $\cup_{n \in \mathcal{N}} [H_n, H_{n+1})$  of DoS attacks, there exist the following conditions:

$$\begin{cases} H_M \geq \sup_{n \in \mathcal{N}} \{H_{n+1} - H_n - \mu_n\} \\ H_m \leq \inf_{n \in \mathcal{N}} \{\mu_n\} \end{cases} \quad (20)$$

where  $H_M$  and  $H_m$  denote a uniform upper bound on the lengths of the DoS active periods  $H_{n+1} - H_n - \mu_n$  and a uniform lower bound on the lengths of the DoS sleeping periods  $\mu_n$ , respectively.

*Assumption 3* [51]: In the interval  $[0, t)$ , the number of DoS attacks sleep/active transitions is defined as  $f(t)$ . If  $c \in R_{\geq 0}$  and  $\psi_d \in R_{\geq h}$  are given, the sequence  $\{H_n, H_n + \mu_n, H_{n+1}\}_{n \in \mathcal{N}}$  of DoS attacks satisfies the following constraint:

$$f(t) \leq c + \frac{t}{\psi_d}. \quad (21)$$

*Definition 1* [52]: For known scalars  $\chi_1 > 0$  and  $\chi_2 > 0$ , if  $\mathbf{E}\{\|x(t)\|^2\} \leq \chi_1 e^{-\chi_2 t} \mathbf{E}\{\|\beta_0\|^2\}$  holds, the zero solution of (18) is regard to be EMSS with the initial condition.

*Lemma 1* [43]: For  $d(t) \in [0, d_m]$ , if  $\begin{bmatrix} Z & * \\ S & Z \end{bmatrix} \geq 0$  for any constant matrices  $Z \in R^{m_1 \times m_1}$  and  $S \in R^{m_1 \times m_1}$ , the following inequality holds:

$$-d_m \int_{t-d_m}^t \dot{x}^T(v) Z \dot{x}(v) dv \leq s^T(t) \Phi s(t) \quad (22)$$

where

$$s(t) = \begin{bmatrix} x(t) \\ x(t-d(t)) \\ x(t-d_m) \end{bmatrix}, \Phi = \begin{bmatrix} -Z & * & * \\ Z+S & -2Z-S-S^T & * \\ -S & Z+S & -Z \end{bmatrix}.$$

### III. MAIN RESULTS

The main results are presented in the form of two theorems in this section, along with their corresponding proofs. By using Lyapunov–Krasovskii stability theory and linear matrix inequality techniques, sufficient conditions to ensure the system (18) EMSS and the controller gains will be obtained in Theorems 1 and 2, respectively.

*Theorem 1:* For known DoS parameters  $H_M, H_m, c$ , and  $\psi_d$ , matrices  $K_j, L$  and scalars  $\bar{\eta} \in (0, 1)$ ,  $\sigma > 0$ ,  $h > 0$ , the system (18) is EMSS, if for some prescribed scalars  $\varpi_1 > 0$ ,  $\varpi_2 > 0$ ,  $\gamma_1 > 0$ ,  $\gamma_2 > 0$ , and  $\varsigma_i$  ( $i \in \mathcal{D}$ ), there exist symmetric matrices  $W > 0$ ,  $P_1 > 0$ ,  $P_2 > 0$ ,  $Q_1 > 0$ ,  $Q_2 > 0$ ,  $R_{11} > 0$ ,  $R_{21} > 0$ ,  $R_{12} > 0$ , and  $R_{22} > 0$ , and matrices  $M, S_{11}, S_{21}, S_{12}$ , and  $S_{22}$  with appropriate dimensions such that for  $l \in \{1, 2\}$ ,  $i, j \in \mathcal{D}$  the following inequalities hold:

$$\Gamma_{ii}^l < 0 \quad (23)$$

$$\Gamma_{ij}^l + \Gamma_{ji}^l < 0 \quad (24)$$

$$M + \Upsilon_{ij}^l > 0 \quad (25)$$

$$\vartheta > 0 \quad (26)$$

$$\begin{cases} P_1 \leq \gamma_2 P_2, P_2 \leq \gamma_1 e^{2\vartheta_1 h} P_1 \\ Q_l \leq \gamma_{3-l} Q_{3-l} \\ R_{1l} \leq \gamma_{3-l} R_{1 \ 3-l}, R_{2l} \leq \gamma_{3-l} R_{2 \ 3-l} \end{cases} \quad (27)$$

where

$$\begin{aligned} \Gamma_{ij}^l &= \Upsilon_{ij}^l + \sum_{p=1}^r \varsigma_p \left( M + \Upsilon_{ip}^l \right) \\ \Upsilon_{ij}^1 &= \begin{bmatrix} \Pi_{ij11}^1 & * & * \\ \Pi_{ij21}^1 & \Pi_{22}^1 & * \\ \Pi_{ij31}^1 & \Pi_{ij32}^1 & \Pi_{33}^1 \end{bmatrix} < 0 \\ \Pi_{ij11}^1 &= \begin{bmatrix} v_{i11} & * & * \\ v_{ij21} & v_{22} & * \\ v_{31} & v_{32} & -g_1(Q_1 + R_{11} + S_{11}) \end{bmatrix} \\ v_{i11} &= 2\varpi_1 P_1 + P_1 A_i + A_i^T P_1 + Q_1 \\ &\quad - g_1 R_{11} - g_1 R_{21}, v_{ij21} = \bar{\eta} K_j^T B_i^T P_1 + v_{32} \\ v_{22} &= g_1(-2R_{11} - S_{11} - S_{11}^T - 2R_{21} - S_{21} - S_{21}^T) \\ &\quad - \sigma W, v_{31} = -g_1 S_{11} - g_1 S_{21} \\ v_{32} &= g_1(R_{11} + S_{11} + R_{21} + S_{21}), g_1 = e^{-2\varpi_1 h} \\ \Pi_{ij21}^1 &= \begin{bmatrix} \bar{\eta} K_j^T B_i^T P_1 & 0 & 0 \\ \bar{\eta}_1 K_j^T B_i^T P_1 & 0 & 0 \\ L & 0 & 0 \end{bmatrix} \\ \Pi_{22}^1 &= \text{diag}\{W, -\bar{\eta}_1 I, -\bar{\eta}_1 I\}, \bar{\eta}_1 = 1 - \bar{\eta} \\ \Pi_{ij31}^1 &= \begin{bmatrix} h P_1 A_i & h \bar{\eta} P_1 B_i K_j & 0 \\ 0 & h \rho P_1 B_i K_j & 0 \end{bmatrix} \\ \Pi_{ij32}^1 &= \begin{bmatrix} h \bar{\eta} P_1 B_i K_j & h \bar{\eta}_1 P_1 B_i K_j & 0 \\ h \rho P_1 B_i K_j & -h \rho P_1 B_i K_j & 0 \end{bmatrix} \\ \Pi_{33}^1 &= \text{diag}\{-P_1(R_{11} + R_{21})^{-1} P_1, \end{aligned}$$

$$\left. \begin{aligned} &- P_1(R_{11} + R_{21})^{-1} P_1 \right\}, \rho = \sqrt{\bar{\eta}(1 - \bar{\eta})} \\ \Upsilon_{ij}^2 &= \begin{bmatrix} v_{i11} & * & * & * \\ v_{21} & v_{22} & * & * \\ v_{31} & v_{31} & v_{33} & * \\ h P_2 A_i & 0 & 0 & v_{44} \end{bmatrix} < 0 \end{aligned}$$

$$v_{i11} = -2\varpi_2 P_2 + P_2 A_i + A_i^T P_2 + Q_2 - R_{12} - R_{22}$$

$$v_{21} = R_{12} + S_{12} + R_{22} + S_{22}$$

$$v_{22} = -2R_{12} - S_{12} - S_{12}^T - 2R_{22} - S_{22} - S_{22}^T$$

$$v_{31} = -S_{12} - S_{22}, v_{32} = R_{12} + S_{12} + R_{22} + S_{22}$$

$$v_{33} = -e^{2\varpi_2 h} Q_2 - R_{12} - R_{22}$$

$$v_{44} = -P_2(R_{12} + R_{22})^{-1} P_2, \vartheta_1 = \varpi_1 + \varpi_2$$

$$\vartheta = \frac{2}{\psi_d} (\varpi_1 H_m - \varpi_2 H_M - \vartheta_1 h) - \frac{1}{\psi_d} \ln(\gamma_1 \gamma_2).$$

*Proof:* Construct the following time-varying Lyapunov functional for system (18):

$$\begin{aligned} V_{\theta(t)}(t) &= x^T(t) P_{\theta(t)} x(t) + \int_{t-h}^t x^T(v) \omega(\cdot) Q_{\theta(t), x(v)} dv \\ &\quad + h \int_{-h}^0 \int_{t+s}^t \dot{x}^T(v) \omega(\cdot) R_{1\theta(t)} \dot{x}(v) dv ds \\ &\quad + h \int_{-h}^0 \int_{t+s}^t \dot{x}^T(v) \omega(\cdot) R_{2\theta(t)} \dot{x}(v) dv ds \end{aligned} \quad (28)$$

where  $P_{\theta(t)} > 0$ ,  $Q_{\theta(t)} > 0$ ,  $R_{1\theta(t)} > 0$ ,  $R_{2\theta(t)} > 0$ , and  $\omega(\cdot) \triangleq e^{(-1)^{\theta(t)} 2\varpi_{\theta(t)}(t-v)}$ ,  $\theta(t) \in \{1, 2\}$ .

Then two cases of  $\theta(t) = 1$  and  $\theta(t) = 2$  will be discussed in the following, respectively.

When  $\theta(t) = 1$ , calculating the derivation and mathematical expectation of  $V_1(t)$  for  $t \in \mathcal{W}_{1,n}$ ,  $n \in \mathcal{N}$ , notice that we can obtain that

$$\begin{aligned} \mathbf{E}\{\dot{V}_1(t)\} &\leq -2\varpi_1 \mathbf{E}\{V_1(t)\} + 2\varpi_1 x^T(t) P_1 x(t) \\ &\quad + 2x^T(t) P_1 \dot{x}(t) + x^T(t) Q_1 x(t) \\ &\quad - x^T(t-h) e^{-2\varpi_1 h} Q_1 x(t-h) \\ &\quad + \mathbf{E}\{\dot{x}^T(t) \mathcal{R} \dot{x}(t)\} - h \int_{t-h}^t \dot{x}^T(v) e^{-2\varpi_1 h} R_{11} \dot{x}(v) dv \\ &\quad - h \int_{t-h}^t \dot{x}^T(v) e^{-2\varpi_1 h} R_{21} \dot{x}(v) dv \end{aligned} \quad (29)$$

where  $\mathbf{E}\{\dot{x}^T(t) \mathcal{R} \dot{x}(t)\} = \mathbb{A}_{1ij}^T \mathcal{R} \mathbb{A}_{1ij} + \rho^2 \mathbb{A}_{2ij}^T \mathcal{R} \mathbb{A}_{2ij}$ ,  $\mathbb{A}_{1ij} = A_i x(t) + (1 - \bar{\eta}) B_i K_j h(x(t)) + \bar{\eta} B_i K_j [x(t - \lambda_{k,n}(t)) + \delta_{k,n}(t)]$ ,  $\mathbb{A}_{2ij} = B_i K_j [h(x(t)) + x(t - \lambda_{k,n}(t)) + \delta_{k,n}(t)]$ , and  $\mathcal{R} = h^2(R_{11} + R_{21})$ .

According to (6) and (5), one can acquire the constraint of AETM

$$x^T(t - \lambda_{k,n}(t)) W x(t - \lambda_{k,n}(t)) - \sigma \delta_{k,n}^T(t) W \delta_{k,n}(t) > 0. \quad (30)$$

By using Lemma 1, we have

$$-h \int_{t-h}^t \dot{x}^T(v) R_{11} \dot{x}(v) dv \leq s_1^T(t) \Phi_{1S_1}(t) \quad (31)$$

$$-h \int_{t-h}^t \dot{x}^T(v) R_{21} \dot{x}(v) dv \leq s_1^T(t) \Phi_{2S_1}(t) \quad (32)$$

where

$$s_1(t) = \begin{bmatrix} x(t) \\ x(t - \lambda_{k,n}(t)) \\ x(t - h) \end{bmatrix}$$

$$\Phi_l = \begin{bmatrix} -R_{l1} & * & * \\ R_{l1} + S_{l1} & -2R_{l1} - S_{l1} - S_{l1}^T & * \\ -S_{l1} & R_{l1} + S_{l1} & -R_{l1} \end{bmatrix}, l = 1, 2.$$

According to the inequality (7) in Assumption 1, it yields that

$$x^T(t)L^T Lx(t) - h^T(x(t))h(x(t)) \geq 0. \quad (33)$$

Then by combining (29)–(33) and utilizing Schur complement, it is easy to obtain that

$$\mathbf{E}\{\dot{V}_1(t)\} \leq -2\varpi_1 \mathbf{E}\{V_1(t)\} + \zeta_1^T(t)\Upsilon_{ij}^1 \zeta_1(t) \quad (34)$$

where  $\zeta_1(t) = [x^T(t) \quad x^T(t - \lambda_{k,n}(t)) \quad x^T(t - h) \quad \delta_{k,n}^T(t) \quad h^T(x(t)) \quad I \quad I \quad I]^T$ . According to  $\Upsilon_{ij}^1 < 0$ , then it yields that  $\mathbf{E}\{\dot{V}_1(t)\} \leq -2\varpi_1 \mathbf{E}\{V_1(t)\}$  holds for  $t \in \mathcal{W}_{1,n}$ .

When  $\theta(t) = 2$ ,  $t \in \mathcal{W}_{2,n}$ ,  $n \in \mathcal{N}$ , by taking the derivation and expectation of  $V_2(t)$  and utilizing the similar approach above-mentioned, we can get

$$\mathbf{E}\{\dot{V}_2(t)\} \leq 2\varpi_2 \mathbf{E}\{V_2(t)\} + \zeta_2^T(t)\Upsilon_{ij}^2 \zeta_2(t) \quad (35)$$

where  $\zeta_2(t) = [x^T(t) \quad x^T(t - \lambda_{k,n}(t)) \quad x^T(t - h) \quad I]^T$ . By using  $\Upsilon_{ij}^2 < 0$ , it can be deduced that  $\mathbf{E}\{\dot{V}_2(t)\} \leq 2\varpi_2 \mathbf{E}\{V_2(t)\}$  holds for  $t \in \mathcal{W}_{2,n}$ .

Define  $H_{l,n} = \begin{cases} H_n, & l = 1, \\ H_n + \mu_n, & l = 2 \end{cases}$ , then we can get  $\mathcal{W}_{l,n} = [H_{l,n}, H_{3-l, l-1+n})$ . Therefore, it yields that  $t \in [H_{l,n}, H_{3-l, l-1+n})$ ,  $l \in \{1, 2\}$

$$\mathbf{E}\{V_l(t)\} \leq e^{2(-1)^l \varpi_l (t - H_{l,n})} \mathbf{E}\{V_l(H_{l,n})\}. \quad (36)$$

Then we have

$$\mathbf{E}\{V(t)\} \leq \begin{cases} e^{-2\varpi_1(t - H_{1,n})} \mathbf{E}\{V_1(H_{1,n})\} \\ t \in [H_{1,n}, H_{2,n}) \\ e^{2\varpi_2(t - H_{2,n})} \mathbf{E}\{V_2(H_{2,n})\} \\ t \in [H_{2,n}, H_{1,1+n}). \end{cases} \quad (37)$$

Note that the inequalities in (27) hold, then the following inequalities can be obtained by simple calculations:

$$\begin{cases} \mathbf{E}\{V_1(H_{1,n})\} \leq \gamma_2 \mathbf{E}\{V_2(H_{1,n}^-)\} \\ \mathbf{E}\{V_2(H_{2,n})\} \leq \gamma_1 e^{2\vartheta_1 h} \mathbf{E}\{V_1(H_{2,n}^-)\} \end{cases} \quad (38)$$

where  $\vartheta_1 = \varpi_1 + \varpi_2$ .

If  $t \in [H_{1,n}, H_{2,n})$ , by combining (37) and (38), one has

$$\begin{aligned} \mathbf{E}\{V(t)\} &\leq \gamma_2 e^{-2\varpi_1(t - H_{1,n})} \mathbf{E}\{V_2(H_{1,n}^-)\} \\ &\leq \gamma_2 e^{-2\varpi_1(t - H_{1,n}) + 2\varpi_2(H_{1,n} - H_{2,n-1})} \\ &\quad \times \mathbf{E}\{V_2(H_{2,n-1})\} \\ &\leq \dots \leq e^{f(t)} \mathbf{E}\{V_1(0)\} \end{aligned} \quad (39)$$

where  $f(t) = 2(c + [t/\psi_d])(\vartheta_1 h + \varpi_2 H_M - 2\varpi_1 H_m) + (c + [t/\psi_d]) \ln(\gamma_1 \gamma_2)$ . Due to the inequality (26) holding, it is easy to acquire that

$$\mathbf{E}\{V(t)\} \leq e^{\epsilon_1} e^{-\nu t} \mathbf{E}\{V_1(0)\} \quad (40)$$

where  $\epsilon_1 = 2c(2\vartheta_1 h + \varpi_2 H_M - \varpi_1 H_m) + c \ln(\gamma_1 \gamma_2)$  and  $\nu = (1/\psi_d)(-\vartheta_1 h - \varpi_2 H_M + \varpi_1 H_m) - (1/2\psi_d) \ln(\gamma_1 \gamma_2)$ .

Similarly, by combining inequality (26), we can get

$$\mathbf{E}\{V(t)\} \leq \frac{1}{\gamma_2} e^{\epsilon_2} e^{-\nu t} \mathbf{E}\{V_1(0)\} \quad (41)$$

where  $\epsilon_2 = (c + 1)[2\vartheta_1 h + 2\varpi_2 H_M - 2\varpi_1 H_m + \ln(\gamma_1 \gamma_2)]$ .

Define  $\mathcal{C} = \max\{e^{\epsilon_1}, (1/\gamma_2)e^{\epsilon_2}\}$ , it yields that

$$\mathbf{E}\{V(t)\} \leq \mathcal{C} e^{-\nu t} \mathbf{E}\{V_1(0)\}. \quad (42)$$

It follows from the definition of  $V(t)$  that:

$$\begin{cases} \mathbf{E}\{V(t)\} \geq \chi_{\min} \mathbf{E}\{\|x(t)\|^2\} \\ \mathbf{E}\{V_1(0)\} \leq \chi_{\max} \mathbf{E}\{\|\beta_0\|^2\} \end{cases} \quad (43)$$

where  $\chi_{\min} = \min\{\vartheta_{\min}(P_i)\}$  and  $\chi_{\max} = \max\{\vartheta_{\max}(P_i)\} + h\vartheta_{\max}(Q_1) + (h^2/2)\vartheta_{\max}(R_{11} + R_{21})$ .

Combining (42) and (43), one can obtain the following inequality holds for all  $t \geq 0$ :

$$\mathbf{E}\{\|x(t)\|^2\} \leq \frac{\mathcal{C}\chi_{\max}}{\chi_{\min}} e^{-\frac{\nu}{2}t} \mathbf{E}\{\|\beta_0\|^2\}. \quad (44)$$

In addition, considering the difference between  $\xi_i(\phi(x))$  and  $\xi_j(\phi(\tilde{x}))$ , we introduce a slack matrix  $M$  which satisfies the following equality [50]:

$$\sum_{i=1}^r \sum_{j=1}^r \xi_i(\phi(x)) (\xi_j(\phi(\tilde{x})) - \xi_j(\phi(x))) M = 0. \quad (45)$$

Then by using Schur complement, it yields that  $\mathbf{E}\{\dot{V}_1(t)\} < 0$  can be guaranteed by inequality (46)

$$\sum_{i=1}^r \sum_{j=1}^r \xi_i(\phi(x)) \xi_j(\phi(\tilde{x})) \Upsilon_{ij}^1 < 0. \quad (46)$$

If  $M + \Upsilon_{ij}^1 > 0$ , substituting (45) and (46), we have

$$\begin{aligned} \mathbf{E}\{\dot{V}_1(t)\} &\leq \sum_{i=1}^r \sum_{j=1}^r \xi_i(\phi(x)) \\ &\quad \times \left[ \xi_j(\phi(\tilde{x})) \Upsilon_{ij}^1 + (\xi_j(\phi(\tilde{x})) - \xi_j(\phi(x))) (M + \Upsilon_{ij}^1) \right] \\ &\leq \sum_{i=1}^r \sum_{j=1}^r \xi_i(\phi(x)) \xi_j \left( \phi(\tilde{x}) \left( \Upsilon_{ij}^1 + \sum_{p=1}^r \varsigma_p (M + \Upsilon_{ip}^1) \right) \right) \\ &= \sum_{i=1}^r \sum_{j=1}^r \xi_i^2(\phi(x)) \Gamma_{ii}^1 + \sum_{i=1}^r \sum_{i < j \leq r} \xi_i(\phi(x)) \xi_j(\phi(\tilde{x})) \\ &\quad \times (\Gamma_{ij}^1 + \Gamma_{ji}^1) \end{aligned} \quad (47)$$

where  $\Gamma_{ij}^1 = \Upsilon_{ij}^1 + \sum_{p=1}^r \varsigma_p (M + \Upsilon_{ip}^1)$ .

Combining the inequalities (45) and (46) in Theorem 1, it yields that inequality (47) holds, furthermore, one can get  $\mathbf{E}\{\dot{V}_1(t)\} < 0$ . Besides, under the help of the same method, it can be deduced that  $\mathbf{E}\{\dot{V}_2(t)\} < 0$ . Notice that the inequality (44) holds, then by using Definition 1, we can obtain that the system (18) is EMSS. That completes the proof. ■

The sufficient conditions are acquired in Theorem 1 to guarantee the system (18) EMSS. Based on Theorem 1, the controller gains of T-S fuzzy systems with AETM and multiple cyber-attacks are derived in the following Theorem 2.

**Theorem 2:** The DoS parameters  $H_M, H_m, c$ , and  $\psi_d$ , matrix  $L$  and scalars  $\bar{\eta} \in (0, 1)$ ,  $\sigma > 0$ ,  $h > 0$ ,  $\varrho_l > 0$ , and  $\varrho_{2l} > 0$  ( $l = 1, 2$ ) are given. The system (18) is EMSS, if for some prescribed scalars  $\varpi_1 > 0$ ,  $\varpi_2 > 0$ ,  $\gamma_1 > 0$ ,  $\gamma_2 > 0$ , and  $\varsigma_i$  ( $i \in \mathcal{D}$ ), there exist symmetric matrices  $\tilde{W} > 0$ ,  $X_1 > 0$ ,  $X_2 > 0$ ,  $\tilde{Q}_1 > 0$ ,  $\tilde{Q}_2 > 0$ ,  $\tilde{R}_{11} > 0$ ,  $\tilde{R}_{21} > 0$ ,  $\tilde{R}_{12} > 0$ , and  $\tilde{R}_{22} > 0$ , and matrices  $Y_j, \tilde{M}, \tilde{S}_{11}, \tilde{S}_{21}, \tilde{S}_{12}$ , and  $\tilde{S}_{22}$  with appropriate dimensions such that inequality (26) holds and for  $l \in \{1, 2\}$ ,  $i, j \in \mathcal{D}$  the following linear matrix inequalities hold:

$$\tilde{\Gamma}_{ii}^l < 0 \quad (48)$$

$$\tilde{\Gamma}_{ij}^l + \tilde{\Gamma}_{ji}^l < 0 \quad (49)$$

$$\tilde{M} + \tilde{\Upsilon}_{ij}^l > 0 \quad (50)$$

$$\begin{bmatrix} -\gamma_2 X_2 & * \\ X_2 & -X_1 \end{bmatrix} \leq 0 \quad (51)$$

$$\begin{bmatrix} -\gamma_1 e^{2\vartheta_1 h} X_1 & * \\ X_1 & -X_2 \end{bmatrix} \leq 0 \quad (52)$$

$$\begin{bmatrix} -\gamma_{3-l} \tilde{Q}_{3-l} & * \\ X_{3-l} & -2\varrho_{2l} X_l + \varrho_{2l}^2 \tilde{Q}_l \end{bmatrix} \leq 0 \quad (53)$$

$$\begin{bmatrix} -\gamma_{3-l} \tilde{R}_{1 \ 3-l} & * \\ X_{3-l} & -2\varrho_l X_l + \varrho_l^2 \tilde{R}_{1 \ 3-l} \end{bmatrix} \leq 0 \quad (54)$$

$$\begin{bmatrix} -\gamma_{3-l} \tilde{R}_{2 \ 3-l} & * \\ X_{3-l} & -2\varrho_l X_l + \varrho_l^2 \tilde{R}_{2 \ 3-l} \end{bmatrix} \leq 0 \quad (55)$$

where

$$\begin{aligned} \tilde{\Gamma}_{ij}^l &= \tilde{\Upsilon}_{ij}^l + \sum_{p=1}^r \varsigma_p (\tilde{M} + \tilde{\Upsilon}_{ip}^l) \\ \tilde{\Upsilon}_{ij}^1 &= \begin{bmatrix} \tilde{\Pi}_{ij11}^1 & * & * \\ \tilde{\Pi}_{ij21}^1 & \tilde{\Pi}_{22}^1 & * \\ \tilde{\Pi}_{ij31}^1 & \tilde{\Pi}_{ij32}^1 & \tilde{\Pi}_{33}^1 \end{bmatrix} < 0 \\ \tilde{\Pi}_{ij11}^1 &= \begin{bmatrix} a_{i11} & * & * \\ a_{ij21} & a_{22} & * \\ a_{31} & a_{32} & -g_1 (\tilde{Q}_1 + \tilde{R}_{11} + \tilde{S}_{11}) \end{bmatrix} \\ a_{i11} &= 2\varpi_1 X_1 + A_i X_1 + X_1 A_i^T + \tilde{Q}_1 - g_1 \tilde{R}_{11} \\ &\quad - g_1 \tilde{R}_{21}, a_{ij21} = \bar{\eta} Y_j^T B_i^T + a_{32} \\ a_{22} &= g_1 (-2\tilde{R}_{11} - \tilde{S}_{11} - \tilde{S}_{11}^T - 2\tilde{R}_{21} - \tilde{S}_{21} - \tilde{S}_{21}^T) \\ &\quad - \sigma \tilde{W}, a_{31} = -g_1 \tilde{S}_{11} - g_1 \tilde{S}_{21} \\ a_{32} &= g_1 (\tilde{R}_{11} + \tilde{S}_{11} + \tilde{R}_{21} + \tilde{S}_{21}), g_1 = e^{-2\varpi_1 h} \\ \tilde{\Pi}_{ij21}^1 &= \begin{bmatrix} \bar{\eta} Y_j^T B_i^T & 0 & 0 \\ \bar{\eta}_1 Y_j^T B_i^T & 0 & 0 \\ LX_1 & 0 & 0 \end{bmatrix} \\ \tilde{\Pi}_{22}^1 &= \text{diag}\{\tilde{W}, -\bar{\eta}_1 I, -\bar{\eta}_1 I\}, \bar{\eta}_1 = 1 - \bar{\eta} \\ \tilde{\Pi}_{ij31}^1 &= \begin{bmatrix} hA_i X_1 & h\bar{\eta} B_i Y_j & 0 \\ 0 & h\rho B_i Y_j & 0 \end{bmatrix}, \rho = \sqrt{\bar{\eta}(1 - \bar{\eta})} \\ \tilde{\Pi}_{ij32}^1 &= \begin{bmatrix} h\bar{\eta} B_i Y_j & h\bar{\eta}_1 B_i Y_j & 0 \\ h\rho B_i Y_j & -h\rho B_i Y_j & 0 \end{bmatrix} \\ \tilde{\Pi}_{33}^1 &= \text{diag}\{-2\varrho_1 X_1 + \varrho_1^2 (\tilde{R}_{11} + \tilde{R}_{21}), \\ &\quad - 2\varrho_1 X_1 + \varrho_1^2 (\tilde{R}_{11} + \tilde{R}_{21})\} \end{aligned}$$

$$\tilde{\Upsilon}_{ij}^2 = \begin{bmatrix} \mathbf{a}_{i11} & * & * & * \\ \mathbf{a}_{21} & \mathbf{a}_{22} & * & * \\ \mathbf{a}_{31} & \mathbf{a}_{31} & \mathbf{a}_{33} & * \\ hA_i X_2 & 0 & 0 & \mathbf{a}_{44} \end{bmatrix} < 0$$

$$\mathbf{a}_{i11} = -2\varpi_2 X_2 + A_i X_2 + X_2 A_i^T + \tilde{Q}_2 - \tilde{R}_{12} - \tilde{R}_{22}$$

$$\mathbf{a}_{21} = \tilde{R}_{12} + \tilde{S}_{12} + \tilde{R}_{22} + \tilde{S}_{22}$$

$$\mathbf{a}_{22} = -2\tilde{R}_{12} - \tilde{S}_{12} - \tilde{S}_{12}^T - 2\tilde{R}_{22} - \tilde{S}_{22} - \tilde{S}_{22}^T$$

$$\mathbf{a}_{31} = -\tilde{S}_{12} - \tilde{S}_{22}, \mathbf{a}_{32} = \tilde{R}_{12} + \tilde{S}_{12} + \tilde{R}_{22} + \tilde{S}_{22}$$

$$\mathbf{a}_{33} = -e^{2\varpi_2 h} \tilde{Q}_2 - \tilde{R}_{12} - \tilde{R}_{22}$$

$$\mathbf{a}_{44} = -2\varrho_2 X_2 + \varrho_2^2 (\tilde{R}_{21} + \tilde{R}_{22}), \vartheta_1 = \varpi_1 + \varpi_2.$$

Moreover, the controller gains are derived

$$K_j = Y_j X_1^{-1}, j \in \mathcal{D}. \quad (56)$$

*Proof:* Owing to  $(R - \varrho^{-1}P)R^{-1}(R - \varrho^{-1}P) \geq 0$ , we have

$$-PR^{-1}P \leq -2\varrho P + \varrho^2 R. \quad (57)$$

Namely,

$$-P_1(R_{11} + R_{21})^{-1}P_1 \leq -2\varrho_1 P_1 + \varrho_1^2 (R_{11} + R_{21}).$$

Then, replacing the terms in  $\Pi_{33}^1$  with  $-2\varrho_1 P_1 + \varrho_1^2 (R_{11} + R_{21})$ , it yields that  $\Pi_{33}^1 = \text{diag}\{-2\varrho_1 P_1 + \varrho_1^2 (R_{11} + R_{21}), -2\varrho_1 P_1 + \varrho_1^2 (R_{11} + R_{21})\}$ .

Let  $X_1 = P_1^{-1}$ ,  $\Psi_1 = \text{diag}\{X_1, X_1, \dots, X_1, I, X_1, X_1\}$ , then

multiplying  $\Psi_1$  and  $\Psi_1^T$  on both sides of  $\Upsilon_{ij}^1$ , respectively. Define  $Y_j = K_j X_1$ ,  $\tilde{Q}_1 = X_1 Q_1 X_1$ ,  $\tilde{R}_{11} = X_1 R_{11} X_1$ ,  $\tilde{R}_{21} = X_1 R_{21} X_1$ ,  $\tilde{S}_{11} = X_1 S_{11} X_1$ ,  $\tilde{S}_{21} = X_1 S_{21} X_1$ , and  $\tilde{W} = X_1 W X_1$ , then we can obtain  $\tilde{\Upsilon}_{ij}^1$ . Adopting the similar approach in Theorem 1, a slack matrix  $\tilde{M}$  satisfying the following equality is introduced:

$$\sum_{i=1}^r \sum_{j=1}^r \xi_i(\phi(x)) (\xi_j(\phi(\tilde{x})) - \xi_j(\phi(x))) \tilde{M} = 0. \quad (58)$$

Combining (48) and (49), it is easy to get that  $\mathbf{E}\{\dot{V}_1(t)\} < 0$ .

Besides, set  $X_2 = P_2^{-1}$ ,  $\Psi_2 = \text{diag}\{X_2, X_2, X_2, X_2\}$ , then multiplying the both sides of  $\Upsilon_{ij}^2$  with  $\Psi_2$  and  $\Psi_2^T$ . Denote  $\tilde{Q}_2 = X_2 Q_2 X_2$ ,  $\tilde{R}_{12} = X_2 R_{12} X_2$ ,  $\tilde{R}_{22} = X_2 R_{22} X_2$ ,  $\tilde{S}_{12} = X_2 S_{12} X_2$ ,  $\tilde{S}_{22} = X_2 S_{22} X_2$ , then  $\tilde{\Upsilon}_{ij}^2$  can be obtained. Further,  $\mathbf{E}\{\dot{V}_2(t)\} < 0$  can be derived with the same method.

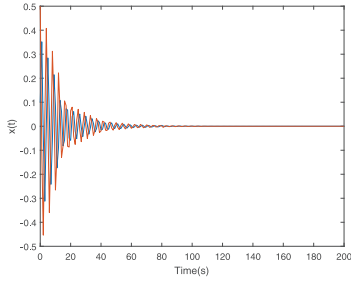
For the first inequality in (27), using the Schur complement, then remultiplying and post-multiplying its both sides by  $\Phi$  and  $\Phi^T$  ( $\Phi = \text{diag}\{X_2, X_2\}$ ), it yields that (51) holds. Similar operation to the rest four inequalities in (27), one can get that inequalities (52)–(55) hold. According to the analysis of Theorem 1, the system (18) is EMSS. Moreover, notice that  $Y_j = K_j X_1$ , then the controller gains are designed as  $K_j = Y_j X_1^{-1}$  ( $j \in \mathcal{D}$ ). ■

#### IV. SIMULATION EXAMPLES

In this section, two simulation examples are given to demonstrate the feasibility of the designed algorithm.

*Example 1:* Consider the following nonlinear mass–spring system [53]:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -0.01x_1 - 0.67x_1^3 + u \end{cases} \quad (59)$$


 Fig. 2. Response of  $x(t)$  in case 1.

where  $x_1 \in [-1, 1]$ . Choose the fuzzy membership function  $\xi_1(x_1) = 1 - x_1^2$  and  $\xi_2(x_1) = 1 - \xi_1(x_1)$ . Then the nonlinear system (59) can be approximated by the following T-S fuzzy model:

RULE 1: IF  $x_1$  is  $\xi_1$ , THEN  $\dot{x}(t) = A_1x(t) + B_1u(t)$   
 RULE 2: IF  $x_1$  is  $\xi_2$ , THEN  $\dot{x}(t) = A_2x(t) + B_2u(t)$  where

$$A_1 = \begin{bmatrix} 0 & 1 \\ -0.01 & 0 \end{bmatrix}, A_2 = \begin{bmatrix} 0 & 1 \\ -0.68 & 0 \end{bmatrix}, B_1 = B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

Set  $H_m = 1.3$  s,  $\gamma_1 = \gamma_2 = 1.02$ ,  $h = 0.01$  s and  $\varpi_1 = 0.08$ ,  $\varpi_2 = 1.02$ .

In the following, two cases are discussed according to the different values of  $\bar{\eta}$  which denotes the probability of deception attacks not occurring in T-S fuzzy systems. By setting  $\bar{\eta} \in [0, 1)$  or  $\bar{\eta} = 1$ , the performances of T-S fuzzy systems under multiple cyber-attacks or single cyber-attack are studied in Cases 1 and 2, respectively.

*Case 1:* Set  $\bar{\eta} = 0.94$  and  $H_M = 1.26$ , which means that T-S fuzzy systems are subjected to multiple cyber-attacks, concretely, the occurring probability of deception attacks is 0.06 and the upper bound on the lengths of the DoS active periods is 1.26 s. Let  $\sigma = 0.2$ ,  $\varrho_l = 0.2$ ,  $\varrho_{2l} = 0.2$  ( $l = 1, 2$ ),  $\varsigma_1 = 1$ , and  $\varsigma_2 = 1$ . Choose the deception attack function  $h(x(t)) = [-\tanh^T(0.15x_1(t)) - \tanh^T(0.05x_2(t))]^T$ , which satisfies inequality (7) in Assumption 1 with  $L = \text{diag}\{0.15, 0.05\}$ . By solving a set of linear matrix inequalities in Theorem 2 through MATLAB, we can get

$$\begin{cases} Y_1 = [-5.3692 & -6.6582] \\ Y_2 = [-4.2147 & -6.4049] \\ X_1 = \begin{bmatrix} 17.9866 & -13.8400 \\ -13.8400 & 127.5211 \end{bmatrix}. \end{cases}$$

By calculating the equality (56) in Theorem 2, the controller gains are obtained as follows:

$$\begin{cases} K_1 = [-0.3695 & -0.0923] \\ K_2 = [-0.2978 & -0.0826]. \end{cases}$$

The initial parameter of system (18) is chosen as  $x_0 = [0.1 \ 0.5]^T$ , then by applying MATLAB, the simulation results are exhibited. The state response of the system is presented in Fig. 2. Fig. 3(a) shows the occurring instants of deception attacks. The DoS jamming signal with  $H_M = 1.26$  and  $H_m = 1.3$  is exhibited in Fig. 3(b). The release instants and intervals of AETM are shown in Fig. 4(a). Fig. 4(b) exhibits the response of controller input. In view of the above analysis, it can be concluded that the system with multiple cyber-attacks

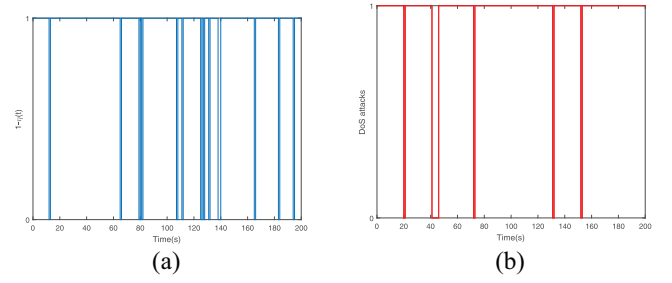


Fig. 3. Situation of multiply attacks in case 1. (a) Occurring instants of deception attacks. (b) Signal of DoS attacks.

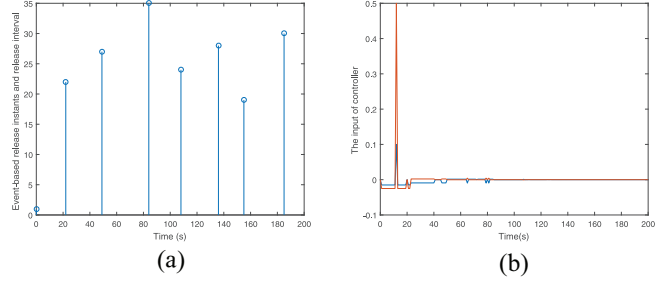


Fig. 4. (a) Release instants and intervals and (b) response of controller input in case 1.

and AETM is EMSS and the designed controller for T-S fuzzy systems with multiple cyber-attacks is feasible.

*Case 2:* Set  $\bar{\eta} = 1$  and  $H_M = 1.26$ , which means that the deception attacks do not occur, namely, only the DoS attacks take place in the T-S fuzzy systems with AETM. Let  $\sigma = 0.2$ ,  $\varrho_l = 0.2$ ,  $\varrho_{2l} = 0.2$  ( $l = 1, 2$ ),  $\varsigma_1 = 1$ , and  $\varsigma_2 = 1$ . Through solving the linear matrix inequalities of Theorem 2 in MATLAB, it yields that

$$\begin{cases} Y_1 = [-20.6243 & -11.4383] \\ Y_2 = [-20.6743 & -11.3851] \\ X_1 = \begin{bmatrix} 5.1945 & -5.8545 \\ -5.8545 & 24.0761 \end{bmatrix}. \end{cases}$$

According to the equality (56) in Theorem 2, the controller gains are calculated as

$$\begin{cases} K_1 = [-6.2069 & -1.9844] \\ K_2 = [-6.2167 & -1.9846]. \end{cases}$$

Given the initial state  $x_0 = [0.1 \ 0.5]^T$  of system (18), the results are obtained by using MATLAB. Fig. 5(b) presents the signal of DoS attacks. The release instants and release intervals of the transmission signals are exhibited in Fig. 6(a). By comparing Fig. 4(a) with Fig. 6(a), the release time intervals in case 2 have increased in comparison with the ones in case 1 due to the absence of deception attacks. Fig. 6(b) stands for the response of controller input. Fig. 5(a) shows the state response of  $x(t)$ , which means that the system under single cyber-attack performs well. According to the aforementioned analysis, one can draw the conclusions that the algorithm of adaptive event-triggered controller design is effective for T-S fuzzy systems under no matter single cyber-attack or multiple cyber-attacks.



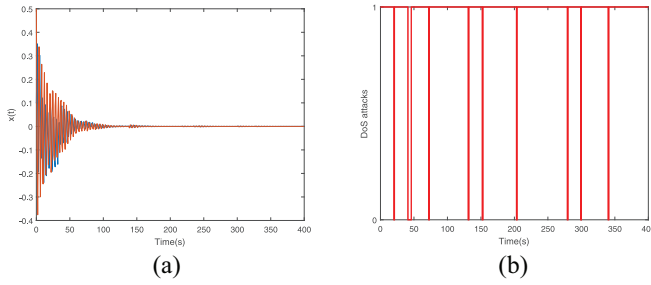


Fig. 5. State response, signal of DoS attacks in case 2. (a) Response of  $x(t)$ . (b) Signal of DoS attacks.

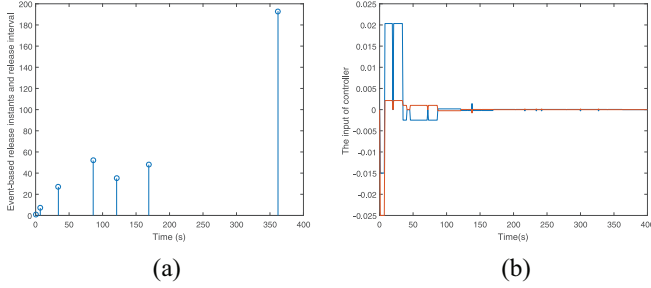


Fig. 6. (a) Release instants and intervals and (b) response of controller input in case 2.

TABLE I  
CONTROLLER GAINS WITH DIFFERENT  $h$  AND  $\sigma$

$h$	$\sigma$	$K_1, K_2$	
0.01	0.02	$K_1 = [-0.4114 \quad 0.0044]$	$K_2 = [-0.4120 \quad 0.0050]$
0.05	0.02	$K_1 = [-0.0261 \quad -0.0016]$	$K_2 = [-0.0263 \quad -0.0013]$
0.1	0.02	$K_1 = [-0.0038 \quad -0.0020]$	$K_2 = [-0.0038 \quad -0.0017]$
0.01	0.2	$K_1 = [-0.3846 \quad 0.0047]$	$K_2 = [-0.3863 \quad 0.0044]$
0.05	0.2	$K_1 = [-0.0232 \quad -0.0014]$	$K_2 = [-0.0232 \quad -0.0012]$
0.1	0.2	$K_1 = [-0.0035 \quad -0.0018]$	$K_2 = [-0.0035 \quad -0.0015]$
0.01	0.5	$K_1 = [-0.3500 \quad 0.0040]$	$K_2 = [-0.3515 \quad 0.0051]$
0.05	0.5	$K_1 = [-0.0261 \quad -0.0016]$	$K_2 = [-0.0264 \quad -0.0013]$
0.1	0.5	$K_1 = [-0.0035 \quad -0.0017]$	$K_2 = [-0.0035 \quad -0.0016]$

*Example 2:* Consider the system (2) with the following system matrices:

$$A_1 = \begin{bmatrix} -1 & 0 \\ -1 & -0.5 \end{bmatrix}, A_2 = \begin{bmatrix} -1 & 0 \\ -1.2 & -1 \end{bmatrix}, B_1 = B_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

The deception attack function is chosen as  $h(x(t)) = [-\tanh^T(0.15x_1(t)) \quad -\tanh^T(0.05x_2(t))]^T$ , which satisfies inequality (7) in Assumption 1 with  $L = \text{diag}\{0.15, 0.05\}$ . Choose the fuzzy membership function  $\xi_1(x_1) = 1 - x_1^2$ ,  $\xi_2(x_1) = 1 - \xi_1(x_1)$ . The initial parameter of system (18) is  $x_0 = [0.1 \quad 0.5]^T$ .

Set the parameters  $H_M = 1.26$ ,  $H_M = 1.78$ ,  $\gamma_1 = \gamma_2 = 1.02$ ,  $\varpi_1 = 0.08$ ,  $\varpi_2 = 1.02$ ,  $\varsigma_1 = \varsigma_2 = 1$ ,  $\varrho_l = 0.01$ , and  $\varrho_{2l} = 0.01$  ( $l = 1, 2$ ).

$h$  and  $\sigma$  are chosen as different values, then the controller gains can be derived under the help of MATLAB, which is presented in Table I.

For the purpose of testifying the advantages of the proposed method, the following comparisons between AETM and event-triggering mechanism in [25] are presented.

TABLE II  
NUMBER OF TRANSMITTED DATA PACKET IN 50 S WITH SAMPLING PERIOD  $h = 0.01$

	$\sigma = 0.02$	$\sigma = 0.2$	$\sigma = 0.5$
packets transmitted in this paper	20	30	35
packets transmitted in [25]	190	70	48

TABLE III  
NUMBER OF TRANSMITTED DATA PACKET IN 50 S WITH SAMPLING PERIOD  $h = 0.05$

	$\sigma = 0.02$	$\sigma = 0.2$	$\sigma = 0.5$
packets transmitted in this paper	14	25	32
packets transmitted in [25]	172	69	47

TABLE IV  
NUMBER OF TRANSMITTED DATA PACKET IN 50 S WITH SAMPLING PERIOD  $h = 0.1$

	$\sigma = 0.02$	$\sigma = 0.2$	$\sigma = 0.5$
packets transmitted in this paper	12	20	27
packets transmitted in [25]	169	65	47

Under the circumstances of different sampling periods  $h$  and  $\sigma$ , the numbers of transmitted data packets are recorded, respectively, which are shown in Tables II–IV.

From Tables II–IV, one can see that under AETM adopted in this article, the number of transmitted data packets is obviously less than the number of data packets transmitted with the event triggering mechanism in [25]. This indicates that the utilization of AETM in this article can further economize the limited bandwidth and improve the utilization of communication resources.

In short, the AETM proposed in this article can effectively save the network resources when keeping the desired system performance.

## V. CONCLUSION

In this article, the security control for T–S fuzzy systems with AETM and multiple cyber-attacks has been investigated. A multiple cyber-attacks model, where deception attacks and DoS attacks are considered at the same time, is first constructed for T–S fuzzy systems. In order to mitigate the communication pressure, the AETM is adopted where the event-triggered condition can be dynamically adjusted by the states of both the system and the communication network. Then an algorithm of controller design for T–S fuzzy systems is first proposed with AETM and multiple cyber-attacks. By the use of Lyapunov stability theory, sufficient conditions are achieved that ensure the system is EMSS. Moreover, the controller gains are acquired in terms of linear matrix inequalities. Finally, the algorithm of controller design for T–S fuzzy systems is testified to be feasible by the simulation examples. In the future, the attack detection will be considered for improving system performance subject to cyber-attacks. Besides, with the wide application of machine learning, the reinforcement learning will be introduced to optimize the event-triggered control strategy for further saving limited network resources.

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