Resilient Sampled-Data Event-Triggered Control for Switched Systems Under Denial of Service Attacks

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Abstract: This paper focuses on the asynchronous event-triggered control problem for networked switched systems with denial-of-service (DoS) attacks. To counteract the negative influence of DoS attacks and permit the system frequent switching to occur within between event-triggered intervals, the resilient event-triggered mechanism (ETM) is established. The delayed switching system model is constructed to describe the sampling period, resilient ETM and DoS attacks. A piecewise Lyapunov functional is established to analyse the exponentially stable of the switched system. Meanwhile, a coordinated design method is given for the controller gains and event-triggered parameters. Finally, the networked continuous stirred tank reactor system is used to verify the feasibility of method.

Keywords: Switched systems; resilient event-triggered mechanism; denial-of-service attacks

1 Introduction

Switched systems have been widely used in practical applications because of their inherent characteristics, such as electrical systems [1], intelligent transportation systems [2], aircraft control [3] and so on. Their characteristic is that the subsystems stability and the entire system stability are not necessarily related, and need to rely on appropriate switching rule can be made to the system stable. Therefore, a suitable switching rule is selected in switched systems as important. In the last decades, the dwell time (DT) [4] and average dwell time (ADT) [5] are usually used to constrain the switching rules. When switching occurs, the switching delay may lead to mode mismatch between subsystems and subcontrollers, which is called asynchronous phenomenon. This phenomenon will cause the system to perform worse or perhaps become unstable, which has been a hot topic of interest in switched systems [6].

Networked control systems (NCSs) have become popular worldwide with the development of network technology [7], but the opening of the network environment can result in information being subjected to dangerous network attacks. So the issue of network security has become a focus of attention. Network attacks against NCSs are classified as denial-of-service (DoS) attacks and deception attacks [8]. The objective of the DoS attack is to disruption of data transmission and the aim of a deception attack is to modify the data of transmission. Among the above attacks, DoS attacks have received a lot of attention due to their inherent characteristics [9]. In [10], the DoS attacks exist in a periodic manner, switching back and forth between active and inactive intervals according to a fixed schedule. The stability analysis of the system in the existence of aperiodic DoS attacks that are limited in frequency and duration were discussed in [11]. In essence, DoS attacks can prevent data transmission in the sensor and the controller channel or the controller and the actuator channel, or in two channels synchronously [12]. In addition to network security issues, how to conserve network resources is also a hot topic for network control systems.

As stated in [13], it shows that the time-triggered mechanism transmits unnecessary data and therefore wastes a lot of network resources. To utilize network resources more efficiently, the event-triggered mechanism (ETM) is introduced, which will decrease unnecessary data transmission, and the frequency of control updates thus improving the utilization of resources [14]. For NCSs, numerous event-triggered schemes have been developed for networked systems. For example, a new switching signal was designed to solve the asynchronous phenomenon between the subsystem and the controller using the ETM [15]. A dynamic adaptive event-triggering control problems were addressed in [16]. The work in [17] designed a dynamic event-triggered communication strategy to defend against the frequency of control updates and resist aperiodic DoS attacks. The event-triggered control (ETC) of switched systems in the presence of dual-terminal DoS attacks was discussed in [18]. To defend against DoS attacks, a resilient dynamic ETM was proposed in [19], which effectively reduces unnecessary data packet transmissions and improves resource utilization efficiency. The event-triggered controller design for networked switching linear neutral systems was attained by constraining the minimum DT and the maximum asynchronous interval [20]. Whereas this constraint allows at most one switch to occur within the event interval which is comparatively reserved because there are cases where more than one switch can occur within the event interval [21]. So the motivation of this paper is to present a new resilient ETM to remove the maximum asynchronous interval is less than the minimum length of the switching time of two adjacent systems which is the DT constraints and compensate for the impact of DoS attacks.

In this paper, we aim to explore the problem of asynchronous ETC of switched systems under DoS attacks applying the resilient ETM. The major contributions of this paper are threefold.

1) Different from [22], the asynchronous phenomenon and DoS attacks exist simultaneously on two-channels are discussed.
2) A resilient ETM is proposed to improve resource utilization and resist the impact of DoS attacks. The mechanism eliminates the constraint that the minimum DT is greater than the maximum asynchronous interval and allows frequent switching of the system during the event interval.
3) Sufficient conditions for the exponentially stable (ES) of the underlying system are obtained using the piecewise Lyapunov functional (PLF) method. Also, the co-design framework for the event-triggered parameters and control gains is proposed using linear matrix inequalities.

Notation: Let R is the set of integer, the space of $n \times j$ real matrices is expressed as $R^{n\times j}$. $\mathrm{Q} \in R^{n\times n}, \mathrm{Q} > 0$ means Q is positive definite. $\lambda_{\max}(\mathrm{Q})(\lambda_{\min}(\mathrm{Q}))$ defines the maximum (minimum) eigenvalue of Q. In a symmetric block matrix, the symbol $*$ stands for the symmetric term.

2 Problem Formulation and Preliminaries

2.1 System Description

The linear switched system is described as

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

where $x(t) \in R^n$ is state vector and $u(t) \in R^j$ is control input. $\sigma(t):[0,\infty) \to \Xi = \{1,2,\cdots,m\}$ is the switching signal, $m \in Z$ being the quantity of subsystems. $A_m, B_m\,(m \in Z)$ are known parameter matrices.

In practice, DoS attacks may block the feedforward and feedback transmission channels separately or simultaneously. However, the latter may be more realistic

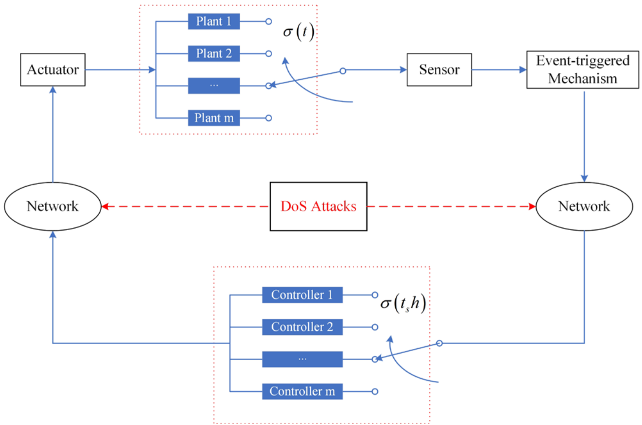

Figure 1
Framework of a switched system under DoS attacks

in the local area network. As seen in Figure 1, this paper discusses the situation where the two-ended transmission channel is attacked at the same time. When the data is successfully transmitted, the mode of the controller will change accordingly. The $\sigma(t_s h)$ determines the modes of controller which $t_s h$ is the successful transmission instant. The $\sigma(t)$ decides the mode of system and t_m updated the system mode at the switching instant.

2.2 DoS Attacks

Let $\{d^{\wp}\}_{\wp \in R_{\geq 0}}, \{d^{\wp} + \iota^{\wp}\}_{\wp \in R_{\geq 0}}$ denote the start and end instants of DoS attacks, then the $\wp$' th active and inactive interval are described as

$$D_{\wp} = \{d^{\wp}\} \cup [d^{\wp}, d^{\wp} + \iota^{\wp}), V_{\wp} = [d^{\wp} + \iota^{\wp}, d^{\wp+1}), \tag{2}$$

where $d_{off}^{\wp} = d^{\wp+1} - (d^{\wp} + \iota^{\wp})$ is DoS attacks inactive times, $d_{on}^{\wp} = \iota^{\wp}$ is DoS attacks active times.

For an arbitrarily given interval $[t_0, t)$, the sets that the entire attack active interval and entire attack inactive interval as follows

$$D(t_0, t) = \{\bigcup_{\wp \in R} D_\wp\} \bigcap [t_0, t), V\left(t_0, t\right) = [t_0, t) \setminus D(t_0, t). \tag{3}$$

For aperiodic DoS attacks, we need to fulfill the following assumptions.

Assumption 1. [15] For given constants $\gamma_0 \geq 0, \overline{R} > 0, D_0 \geq 0$ and $\overline{D} > 1$, there exist $t \in (t_0, t)$ satisfies

$$\gamma(t_0, t) \leq \gamma_0 + \frac{t - t_0}{\overline{R}},\ \left|D(t_0, t)\right| \leq D_0 + \frac{t - t_0}{\overline{D}},\ t \geq t_0 \geq 0. \tag{4}$$

Since the DoS attack start instants and end instants maybe exist between two sampling instants, it is not the expected $d^\wp$ and $d^\wp + \iota^\wp$. Therefore, the DoS interval is defined as

$$\overline{\Im}_\wp = \begin{cases} k+1, \text{ if } kh < d^\wp \leq (k+1)h \bigcap (k+1)h \in D_\wp, \\ \min\{\wp \left| \wp h \geq d^\wp, \wp h \in D_\wp\right\}, \text{ if } d^\wp > (k+1)h, \\ \text{does not exist, otherwise,} \end{cases} \tag{5}$$

with $\overline{\Im}_0 = 0$ if $d^0 = 0$. Figure 2 provides the example to show of the definition (5). If $kh < d^\wp \leq (k+1)h$ then the start instant for the DoS attack became $\overline{\Im}_\wp h = (k+1)h$ (refer to D_0 and D_4 in Figure 2). If the distance between two DoS intervals is less than the sampling period h, given a constant $l_1 \in Z$, such that $d_{off}^{l_1} < h$ (such as for D_2 and D_3 in Figure 2). Hence, the start instant of the second DoS interval is $\overline{\Im}_\wp h = \wp h$, where $\wp$ is the constrained minimum. If the sampling period h greater than the duration of DoS interval, given a constant $l_2 \in Z$, such that $d_{on}^{l_2} < h$ (such as for D_1 in Figure 2). In this case, the DoS intervals have no impact on the system, so $\overline{\Im}_\wp$ dose not exist. Additionally, we define

$$\underline{\Im}_\wp = \begin{cases} \max\{\wp \left| \wp h \leq d^\wp + \iota^\wp\right\}, & \text{if } \overline{\Im}_\wp \text{ exist,} \\ \text{does not exist,} & \text{otherwise.} \end{cases} \tag{6}$$

Therefore, if both $\overline{\Im}_\wp$ and $\underline{\Im}_\wp$ exist, then the $\wp$'th DoS active intervals can be rewritten as

$$\overline{D}_\wp = [\overline{\Im}_\wp h, (\underline{\Im}_\wp + 1)h). \tag{7}$$

Remark 1. If the DoS interval is smaller than the sampling period h, then the DoS interval does not exist. If the distance between two DoS intervals is less than the sampling period h, then these two DoS intervals can be considered as one DoS interval.

The DoS active intervals are expressed as

$$\overline{D}(t_0,t)=\{\bigcup_{\wp\in R} F_{\wp}\}\bigcap[t_0,t),\tag{8}$$

where $F_{\wp}=[\tau_{\wp},\tau_{\wp}+\psi_{\wp})$ and $\tau_{\wp+1}=\min\{\overline{\Im}_{\wp}h \,|\, \overline{\Im}_{\wp}h>\tau_{\wp},\ kh<d^{\wp}\leq(k+1)h\}$ with $\tau_0=\overline{\Im}_o h.$ $\psi_{\wp}$ is as follows

$$\psi_{\wp}=\sum_{d^{\wp}\in[\tau_{\wp},\tau_{\wp+1})}|\,\overline{D}_{\wp}\setminus\overline{D}_{\wp+1}\,|.\tag{9}$$

On the other hand, the DoS inactive intervals can be represented as

$$\overline{Y}(t_0,t)=\{\bigcup_{\wp\in N} J_{\wp-1}\}\bigcap[t_0,t),\tag{10}$$

with $J_{-1}=[0,\tau_0)$ and $J_{\wp}=[\tau_{\wp}+\psi_{\wp},\tau_{\wp+1})$. Note that $\left|\overline{D}(t_0,t)\right|\bigcup\left|\overline{Y}(t_0,t)\right|=[t_0,t)$, which that

$$\left|\overline{Y}(t_0,t)\right|=t-t_0-\left|\overline{D}(t_0,t)\right|.\tag{11}$$

Therefore, it is possible to obtain $\left|\overline{D}_{\wp}\right|\leq\left|D_{\wp}\right|+h$. With this we get

$$\left|\overline{D}(t_0,t)\right|\leq\left|D(t_0,t)\right|+h\gamma(t_0,t).\tag{12}$$

2.3 Resilient ETM

We aim to design the resilient ETM to counteract the adverse effect of aperiodic DoS attacks. First the ETM without DoS attacks is introduced as

$$\begin{aligned}t_{s+1}h=\inf\{t_sh<t\leq t_sh+\aleph \,|\, &e^T(t_sh+qh)\Omega_{\sigma(t_sh)}e(t_sh+qh)\\ &>\varsigma x^T(t_sh)\Omega_{\sigma(t_sh)}x(t_sh)\},\end{aligned}\tag{13}$$

where h is the sampling period, $e(t_sh+qh)=x(t_sh+qh)-x(t_sh),\varsigma\in(0,1)$ is a predefined parameter, $\Omega_{\sigma(t_sh)}>0$ is a weighting matrix, t_sh represent last event-triggered instant, and t_sh+qh is the current sampling time. Note that the parameter $\aleph>0$ is a positive constant that restricts the maximum asynchronous time.

If the impact of DoS attacks is considered, the ETM (13) is difficult to be guaranteed system stability. Thus, a resilient ETM can be expressed as

$$t_{s+1}h \in \{t_{s_q}h \text{ satisfying } (13) \big| t_{s_q}h \in J_{\wp}\} \cup \{\tau_{\wp}\}, \tag{14}$$

where $t_{s_q}h = t_s h + qh$. Different from ETM (13), the resilient ETM (14) will be triggered immediately at the end instant of DoS attack to eliminate the adverse impacts of the DoS attack. In addition, the resilient ETM proposed in this paper excludes Zeno phenomenon.

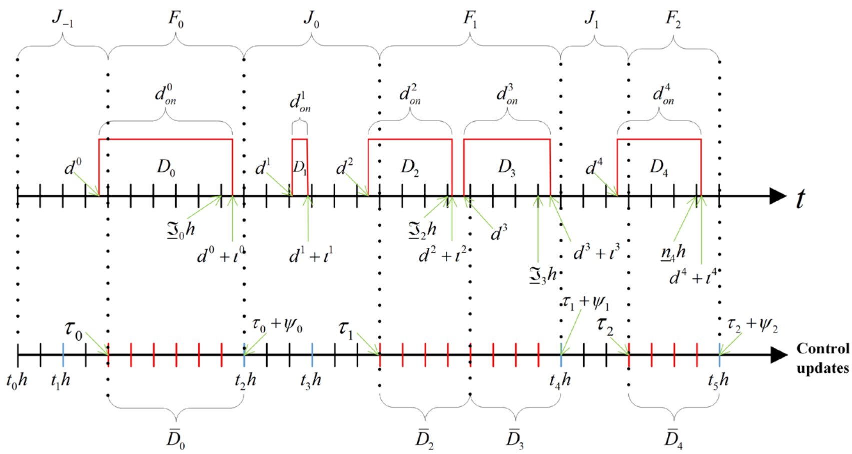

Figure 2

A schematic for periodic measurement scheme and ETC under DoS attacks intervals. Red, blue and black denote attack instants, successful transmissions and sampling instants, respectively.

2.4 Event-based Controller

Considering that when the DoS attack occurs, the controller cannot receive data. Thus, in the presence of DoS attacks (8) and resilient ETM (14), the control input under DoS attacks can be represented as

$$u(t) = \begin{cases} K_{\sigma(t_s h)} x(t_s h), \ t \in [t_s h, t_{s+1} h) \cap J_{\wp}, \\ 0, \ t \in F_{\wp}. \end{cases} \tag{15}$$

For better analysis, the time delay method is applied to split event-triggered intervals $P_{s,\wp}$ into the infinite number of sampling intervals, that is

$$P_{s,\wp} = [t_{s,\wp+1}h, t_{s+1,\wp+1}h). \tag{16}$$

Note that

$$\begin{cases} R_{s,\wp}^{q} = [t_{s,\wp+1}h + (q-1)h, t_{s,\wp+1}h + qh), \\ R_{s,\wp}^{\rho_{s,\wp}+1} = [t_{s,\wp+1}h + \rho_{s,\wp}h, t_{s+1,\wp+1}h), \end{cases} \tag{17}$$

where $\rho_{s,\wp} = \sup\{q \in R \,|\, t_{s,\wp+1}h + qh < t_{s+1,\wp+1}h\}, s \in \{0,1,\cdots s(n)\} = S,$ be triggered number.

Combining (16) and (17), the DoS inactive interval $J_{\wp}$ can be rewritten as

$$J_{\wp} = \bigcup_{s=0}^{s(n)} \bigcup_{q=1}^{\rho_{s,\wp}+1} R_{s,\wp}^{q}. \tag{18}$$

When $t \in R_{s,\wp}^{\rho_{s,\wp}+1}$, we define the artificial time-varying delay functions and the auxiliary measurement error functions as $\eta_{s,\wp}(t) = t - (t_{s,\wp+1}h + \rho_{s,\wp}h)$ and $e_{s,\wp}(t) = x(t_{s,\wp+1}h) - x(t_{s,\wp+1}h + \rho_{s,\wp}h)$, respectively.

Considering $\eta_{s,\wp}(t), e_{s,\wp}(t)$, and (15) yields that

$$u(t) = \begin{cases} K_{\sigma(t_{s,\wp+1}h)}[x(t-\eta_{s,\wp}(t)) + e_{s,\wp}(t)],\ t \in P_{s,\wp} \bigcap J_{\wp}, \\ 0,\ t \in F_{\wp}. \end{cases} \tag{19}$$

So we can get the switched system as follows:

$$\begin{cases} \dot{x}(t) = \begin{cases} A_{\sigma(t)}x(t) + B_{\sigma(t)}K_{\sigma(t_{s,\wp+1}h)}(x(t-\eta_{s,\wp}(t)) + e_{s,\wp}(t)),\ t \in J_{\wp}, \\ A_{\sigma(t)}x(t),\ t \in F_{\wp}, \end{cases} \\ x(t) = x_0(t),\ t \in [-h, 0), \end{cases} \tag{20}$$

where continuous function $x_0(t)$ is the additional initial condition for the state $x(t)$ with $x_0(0) = x_0$.

For additional analysis and design, we introduced the following definitions.

Definition 1. [15] Let $\sigma(t)$ be the switching signal and $\chi_{\sigma(t)}$ be the number of switching over $[t_0, t)$. For given scalars $\chi_0 > 0$ and $\overline{X} > 0$ such that for all $t \in (t_0, t)$ satisfies

$$\chi_{\sigma(t)}(t_0, t) \le \chi_0 + \frac{t_2 - t_1}{\overline{X}}, t_2 \ge t_1 \ge 0. \tag{21}$$

then $\overline{X}$ is the $\sigma(t)$ ADT and χ_0 is the chatter bound.

Definition 2. Given scalars $\phi > 0, \alpha > 0$, the switched systems (20) is ES, if $\| x(t) \| \leq \alpha e^{-\phi t} \| x_0 \|_h, \forall t > 0$, where ϕ is the decay rate.

The object in this article, which is based on resilient ETM (14) is to design an appropriate subcontroller for every subsystem such that systems (20) is ES in the existence of aperiodic DoS attacks (8).

3 Main Results

In this section, the stability of the switched system is discussed by using the PLF analysis method and the controller gain will be designed.

Theorem 1. Given positive scalars $\varepsilon_1 > 0, \varepsilon_2 > 0, \varepsilon_3 < 0, \mu_l \in (1, \infty), l \in \{1, 2\}$,

$\nu \in (1, \infty), \varsigma \in (0, 1), \theta \in \{1, 2, 3\}, \overline{R}, \overline{D}, \overline{X}$, sampling periods h satisfying

$$ń = 2\varepsilon_1 - \frac{\ln \nu + 2(\varepsilon_1 - \varepsilon_3)\aleph}{\overline{X}} - \frac{\beta + \ln(\mu_1 \mu_2) + 2(\varepsilon_1 + \varepsilon_2)h}{\overline{R}} - \frac{2(\varepsilon_1 + \varepsilon_2)}{\overline{D}} > 0, \qquad (22)$$

and gain matrix K_{i1}. If there exist matrices $P_{il} \in R^{n \times n} > 0, Q_{il} \in R^{n \times n} > 0$, $R_{il} \in R^{n \times n} > 0, Z_{il} \in R^{n \times n} > 0, \Omega_i \in R^{n \times n}$, and appropriate dimensions matrices $\mathcal{M}_{ilw}$, $\mathcal{S}_{ilw}$, with $w \in \{1, 2\}$ such that

$$\Pi_l = \begin{bmatrix} \Pi_{11}^l & * & * \\ \Pi_{21}^l & \Pi_{22} & * \\ \Pi_{31}^l & 0_{3n \times 2n} & \Pi_{33} \end{bmatrix} < 0, \qquad (23)$$

$$\begin{cases} P_{i1} \leq \mu_2 P_{i2}, P_{i2} \leq \mu_1 e^{2(\varepsilon_1 + \varepsilon_2)h} P_{i1}, \\ Q_{i1} \leq \mu_2 Q_{i2}, Q_{i2} \leq \mu_1 Q_{i1}, \\ R_{i1} \leq \mu_2 R_{i2}, R_{i2} \leq \mu_1 R_{i1}, \\ Z_{i1} \leq \mu_2 Z_{i2}, Z_{i2} \leq \mu_1 Z_{i1}, \end{cases} \qquad (24)$$

$$P_{il} \leq \nu P_{jl}, Q_{il} \leq \nu Q_{jl}, R_{il} \leq \nu R_{jl}, Z_{il} \leq \nu Z_{jl}, \qquad (25)$$

where

$$\Pi_{11}^{1}=\begin{bmatrix}\Gamma_1 & * & * & * \\ \Gamma_2 & \Gamma_3 & * & * \\ K_{i1}^T B_i^T P_{i1} & 0_{n\times n} & -\Omega_i & * \\ K_{i1}^T B_i^T P_{i1}+\Gamma_4 & \Gamma_5 & 0_{n\times n} & \Gamma_6+\varsigma\Omega_i\end{bmatrix},$$

$$\Pi_{21}^{1}=\begin{bmatrix}\sqrt{h}A_i & 0_{n\times n} & \sqrt{h}B_iK_{i1} & \sqrt{h}B_iK_{i1} \\ \sqrt{h}A_i & 0_{n\times n} & \sqrt{h}B_iK_{i1} & \sqrt{h}B_iK_{i1}\end{bmatrix},$$

$$\Pi_{22}=\mathrm{diag}\{-R_{il}^{-1},-Z_{il}^{-1}\},\ \Pi_{31}^{1}=\begin{bmatrix}\Pi_{311}^T & \Pi_{312}^T & \Pi_{313}^T\end{bmatrix}^T,$$

$$\Pi_{311}=\begin{bmatrix}\sqrt{h}M_{i11}^T & \sqrt{h}M_{i12}^T & 0_{2n\times 2n}\end{bmatrix},\Pi_{312}=\begin{bmatrix}\sqrt{h}N_{i11}^T & 0_{2n\times 2n} & \sqrt{h}N_{i12}^T\end{bmatrix},$$

$$\Pi_{313}=\begin{bmatrix}0_{n\times n} & \sqrt{h}S_{i11}^T & 0_{n\times n} & \sqrt{h}S_{i12}^T\end{bmatrix},$$

$$\Pi_{33}=\mathrm{diag}\{-e^{-2(2-l)\varepsilon_\theta h}Z_{il},-e^{-2(2-l)\varepsilon_\theta h}R_{il},-e^{-2(2-l)\varepsilon_\theta h}R_{il}\},$$

$$\Pi_{11}^{2}=\begin{bmatrix}\Gamma_1 & * & * \\ \Gamma_2 & \Gamma_3 & * \\ \Gamma_4 & \Gamma_5 & \Gamma_6\end{bmatrix},\Pi_{21}^{2}=\begin{bmatrix}\sqrt{h}A_i & 0_{2n\times 2n} \\ \sqrt{h}A_i & 0_{2n\times 2n}\end{bmatrix},$$

$$\Pi_{31}^{2}=\begin{bmatrix}\sqrt{h}M_{i21}^T & \sqrt{h}M_{i22}^T & 0_{n\times n} \\ \sqrt{h}N_{i21}^T & 0_{n\times n} & \sqrt{h}N_{i22}^T \\ 0_{n\times n} & \sqrt{h}S_{i21}^T & \sqrt{h}S_{i22}^T\end{bmatrix},$$

$$\Gamma_1=(-1)^{l-1}2\varepsilon_\theta P_{il}+Q_{il}+P_{il}A_i+A_i^TP_{il}+M_{il1}+M_{il1}^T+N_{il1}+N_{il1}^T,$$

$$\Gamma_2=-M_{il1}^T+M_{il2},\Gamma_3=-e^{(-1)^l 2\varepsilon_\theta h}Q_{il}-M_{il2}-M_{il2}^T-S_{il1}-S_{il1}^T,$$

$$\Gamma_4=-N_{il1}^T+N_{il2},\Gamma_5=S_{il1}^T-S_{il2},\Gamma_6=-N_{il2}-N_{il2}^T+S_{il2}+S_{il2}^T,$$

then system (20) is ES with ADT switching signal satisfying (22).

Proof. The PLF is defined as

$$\begin{aligned}V_{\sigma(t),l}(t)&=x^T(t)P_{\sigma(t),l}x(t)+\int_{t-h}^{t}\kappa_l x^T(k)Q_{\sigma(t),l}x(k)\mathrm{d}k \\ &\quad+\int_{-h}^{0}\int_{t+v}^{t}\kappa_l\dot{x}^T(k)R_{\sigma(t),l}\dot{x}(k)\mathrm{d}k\mathrm{d}v+\int_{-h}^{0}\int_{t+v}^{t}\kappa_l\dot{x}^T(k)Z_{\sigma(t),l}\dot{x}(k)\mathrm{d}k\mathrm{d}v,\end{aligned}\tag{26}$$

where $\kappa_l=e^{2(-1)^l\varepsilon_\theta(t-k)}$.

For $t\in J_\wp$ with $l=1$.

Case 1: Within $t \in [t_{s,\wp+1}h, t_{s+1,\wp+1}h)$ no system switching happens. Then the switched systems mode and controller mode are synchronous and do not change so $\theta = 1$. If we assume $\sigma(t) = i$, computing the derivation of $V_{i1}(t)$, one yields that

$$\begin{aligned}
\dot{V}_{i1}(t) &= -2\varepsilon_1 V_{i1}(t) + x^T(t)(2\varepsilon_1 P_{i1} + A_i^T P_{i1} + P_{i1}A_i + Q_{i1})x(t) \\
&\quad - e^{-2\varepsilon_1 h} x^T(t-h) Q_{i1} x(t-h) + 2x^T(t-\eta_{s,\wp}(t)) K_i^T B_i^T P_{i1} x(t) \\
&\quad + 2e_{s,\wp}^T(t) K_i^T B_i^T P_{i1} x(t) + h\dot{x}^T(t) R_{i1}\dot{x}(t) + h\dot{x}^T(t) Z_{i1}\dot{x}(t) \\
&\quad + e_{s,\wp}^T(t)\Omega_i e_{s,\wp}^T(t) - e_{s,\wp}^T(t)\Omega_i e_{s,\wp}^T(t) - \int_{t-h}^{t} e^{-2\varepsilon_1(t-k)}\dot{x}^T(k) Z_{i1}\dot{x}(k)\mathrm{d}k \\
&\quad - \int_{t-\eta_{s,\wp}(t)}^{t} e^{-2\varepsilon_1(t-k)}\dot{x}^T(k) R_{i1}\dot{x}(k)\mathrm{d}k - \int_{t-h}^{t-\eta_{s,\wp}(t)} e^{-2\varepsilon_1(t-k)}\dot{x}^T(k) R_{i1}\dot{x}(k)\mathrm{d}k \\
&\quad + 2\zeta^T(t) M_{i1}(x(t) - x(t-h) - \int_{t-h}^{t}\dot{x}(k)\mathrm{d}k) \qquad (27) \\
&\quad + 2\zeta^T(t) N_{i1}(x(t) - x(t-\eta_{s,\wp}(t)) - \int_{t-\eta_{s,\wp}(t)}^{t}\dot{x}(k)\mathrm{d}k) \\
&\quad + 2\zeta^T(t) S_{i1}(x(t-\eta_{s,\wp}(t)) - x(t-h) - \int_{t-h}^{t-\eta_{s,\wp}(t)}\dot{x}(k)\mathrm{d}k),
\end{aligned}$$

where $M_{i1} = \begin{bmatrix} M_{i11}^T & M_{i12}^T & 0_{2n\times 2n}\end{bmatrix}^T$, $N_{i1} = \begin{bmatrix} N_{i11}^T & 0_{2n\times 2n} & N_{i12}^T\end{bmatrix}^T$,

$S_{i1} = \begin{bmatrix} 0_{n\times n} & S_{i11}^T & 0_{n\times n} & S_{i12}^T\end{bmatrix}^T$, $\zeta(t) = \begin{bmatrix} x^T(t), x^T(t-h), e_{s,\wp}^T(t), x^T(t-\eta_{s,\wp}(t))\end{bmatrix}^T$.

Applying the approach in [17], we have

$$\begin{aligned}
\dot{V}_{i1}(t) &\le -2\varepsilon_1 V_{i1}(t) + \zeta^T(t)(\Pi_{11}^1 - \Pi_{21}^{1\,T}\Pi_{22}^{-1}\Pi_{21}^1 + hM_{i1}e^{2\varepsilon_1 h}Z_{i1}^{-1}M_{i1}^T + hN_{i1}e^{2\varepsilon_1 h}R_{i1}^{-1}N_{i1}^T \\
&\quad + hS_{i1}e^{2\varepsilon_1 h}R_{i1}^{-1}S_{i1}^T)\zeta(t).
\end{aligned}$$

Applying the Schur complement of the sufficient condition (23) with $l = 1$, we obtain $\dot{V}_{i1}(t) \le -2\varepsilon_1 V_{i1}(t)$, which means that

$$V_{i1}(t) \le e^{-2\varepsilon_1(t - t_{s,\wp+1}h)} V_{i1}(t_{s,\wp+1}h). \qquad (28)$$

Case 2: Within $t \in [t_{s,\wp+1}h, t_{s+1,\wp+1}h)$, system switching ℓ times. We assume $t_m < t_{s,\wp+1}h \le t_{m+1} \cdots t_{m+\ell} < t_{s+1,\wp+1}h \le t_{m+\ell+1}$. If subsystem is active in $t \in [t_{m+1}, t_{m+2})$ then $\sigma(t) = m+1$ and $t \in [t_{s,\wp+1}h, t_{m+1})$ with $\sigma(t) = m$.

For $t \in [t_{s,\wp+1}h, t_{m+1})$, similar to Case 1, the switched systems mode and controller mode are synchronous. So $\theta = 1$, we get

$$V_{m1}(t) \le e^{-2\varepsilon_1 (t - t_{s,\wp+1}h)} V_{m1}(t_{s,\wp+1}h). \tag{29}$$

For $t \in [t_{m+1}, t_{m+2})$, the subsystem mode and controller mode are asynchronous. So $\theta = 3$, then $V_{m+1,1}(t) \le e^{-2\varepsilon_3 (t - t_{m+1})} V_{m+1,1}(t_{m+1})$.

Similarly, we have

$$\begin{cases} \dot{V}_{m+2,1}(t) \le -2\varepsilon_3 V_{m+2,1}(t), & t \in [t_{m+2}, t_{m+3}), \\ \dot{V}_{m+3,1}(t) \le -2\varepsilon_3 V_{m+3,1}(t), & t \in [t_{m+3}, t_{m+4}), \\ \vdots & \vdots \\ \dot{V}_{m+\ell,1}(t) \le -2\varepsilon_3 V_{m+\ell,1}(t), & t \in [t_{m+\ell}, t_{s+1,\wp+1}h). \end{cases}$$

Based on (31), we have $V_{m+1,1}(t_{m+1}^{+}) \le \nu V_{m,1}(t_{m+1}^{-})$. Therefore $t \in [t_{m+1}, t_{s+1,\wp+1}h)$, we get

$$V_{\sigma(t),1}(t) \le \nu^{\ell} e^{-2\varepsilon_3 (t - t_{m+1})} V_{m+1,1}(t_{m+1}). \tag{30}$$

Combining (29) and (30), for all $t \in [t_{s,\wp+1}h, t_{s+1,\wp+1}h)$, we arrive at

$$V_{\sigma(t),1}(t) \le \nu^{\ell} e^{-2\varepsilon_3 N\ell - 2\varepsilon_1 (t - t_{s,\wp+1}h - \aleph\ell)} V_{m,1}(t_{s,\wp+1}h). \tag{31}$$

Remark 2. We assume that the last event-triggered successful instant in the DoS inactive interval $[\tau_{\wp} + \psi_{\wp}, \tau_{\wp+1})$ is $t_{\tilde{s},\wp+1}h.$ In the interval $[\tau_{\wp} + \psi_{\wp}, t_{\tilde{s},\wp+1}h)$, the last system switching instant is $t_{\tilde{m}}$, with $\sigma(t) = \tilde{m}.$ When $t \in [t_{\tilde{s},\wp+1}h, \tau_{\wp+1}),$ if there is no system switching, then similar to Case 1 in $t \in J_{\wp}$. Meanwhile, if there are $\breve{\ell}$ system switching, then similar to Case 2 in $t \in J_{\wp}$.

Remark 3. Because this paper uses the resilient ETM, it is triggered immediately at the end of the DoS attacks. So during the period from the DoS attacks end instant to the first system switched instant on the DoS inactive interval, system mode and controller mode are always synchronous.

For $t \in F_{\wp}$ with $l = 2$.

Case 1: No system switching in the during $F_{\wp}$. We differentiate $V_{i2}(t)$ along the trajectories of the system. It can be deduced that

$$\dot{V}_{i2}(t) \le 2\varepsilon_2 V_{i2}(t) + \zeta^T(t)(\Pi_{11}^2 - \Pi_{21}^{2\,T}\Pi_{22}^{-1}\Pi_{21}^2 + hM_{i2}Z_{i2}^{-1}M_{i2}^T + hN_{i2}R_{i2}^{-1}N_{i2}^T + hS_{i2}R_{i2}^{-1}S_{i2}^T)\zeta(t).$$

Based on (23), we obtain $\dot{V}_{i2}(t) \le 2\varepsilon_2 V_{i2}(t)$, which shows that

$$V_{i2}(t) \le e^{2\varepsilon_2(t-\tau_\wp)} V_{i2}(\tau_\wp). \tag{32}$$

Case 2: The system switches $\overline{\ell}$ times on $F_\wp$, we yields

$$\dot{V}_{\sigma(t),2}(t) \le 2\varepsilon_2 V_{\sigma(t),2}(t), t \in [\tau_\wp, t_{m+1}) \bigcup [t_{m+1} + t_{m+2}) \cdots \bigcup [t_{m+\overline{\ell}}, \tau_\wp + \psi_\wp).$$

According to (25), we have $V_{m+1,2}(t_m^+) \le \nu V_{m,2}(t_m^-)$. Then, we have

$$V_{\sigma(t),2}(t) \le \nu^{\overline{\ell}} e^{2\varepsilon_2(t-\tau_\wp)} V_{\sigma(\tau_\wp),2}(\tau_\wp). \tag{33}$$

Considering this sufficient condition (24), we easily obtain

$$\begin{cases} V_{i1}(\tau_\wp + \psi_\wp) \le \mu_2 V_{i2}((\tau_\wp + \psi_\wp)^-), \\ V_{i2}(\tau_\wp) \le \mu_1 e^{2(\varepsilon_1+\varepsilon_2)h} V_{i1}(\tau_\wp^{\ -}). \end{cases} \tag{34}$$

For $t \in F_\wp$

$$V(t) \le \frac{\nu^{\chi_{\sigma(t)}(0,t)} \beta^{\gamma(0,t)} \mu_1^{\gamma(0,t)} \mu_2^{\gamma(0,t)}}{\mu_2} e^{-2\varepsilon_1\left(t - \left|\overline{D}(0,t)\right| + 2\varepsilon_2\left|\overline{D}(0,t)\right| - \chi_{\sigma(t)}(0,t)\aleph\right) - 2\varepsilon_3\chi_{\sigma(t)}(0,t)\aleph} V_{\sigma(0),1}(0). \tag{35}$$

Similarly, for $t \in J_\wp$

$$V(t) \le \nu^{\chi_{\sigma(t)}(0,t)} \beta^{\gamma(0,t)} \mu_1^{\gamma(0,t)} \mu_2^{\gamma(0,t)} e^{-2\varepsilon_1\left(t - \left|\overline{D}(0,t)\right| + 2\varepsilon_2\left|\overline{D}(0,t)\right| - \chi_{\sigma(t)}(0,t)\aleph\right) - 2\varepsilon_3\chi_{\sigma(t)}(0,t)\aleph} V_{\sigma(0),1}(0). \tag{36}$$

Considering (4), (5), (13) and (21) into (35) and (36), one has

$$V(t) \le \begin{cases} \vartheta_1 e^{-\acute{n}t} V_{\sigma(0),1}(0), & t \in F_\wp, \\ \vartheta_2 e^{-\acute{n}t} V_{\sigma(0),1}(0), & t \in J_\wp, \end{cases} \tag{37}$$

where $\vartheta_1 = \nu^{\chi_0} \beta^{\gamma_0} \mu_1^{\gamma_0} \mu_2^{\gamma_0 - 1} e^{2\varepsilon_1(D_0 + h\gamma_0) + 2\chi_0\aleph + 2\varepsilon_2(D_0 + h\gamma_0) - 2\varepsilon_3\chi_0\aleph}$,

$\vartheta_2 = \nu^{\chi_0} \beta^{\gamma_0} \mu_1^{\gamma_0} \mu_2^{\gamma_0} e^{2\varepsilon_1(D_0 + h\gamma_0) + 2\chi_0\aleph + 2\varepsilon_2(D_0 + h\gamma_0) - 2\varepsilon_3\chi_0\aleph}$.

Considering the definition of (26), we can obtain

$$V(t) \ge \lambda_1 \| x(t) \|^2, \ V(0) \le (\lambda_2 + h\lambda_3 + (h^2/2)(\lambda_4 + \lambda_5)) \| x(0) \|_h^2, \tag{38}$$

where $\lambda_1 = \lambda_{\min}(P_{il}), \lambda_2 = \lambda_{\max}(P_{il}), \lambda_3 = \lambda_{\max}(Q_{il}), \lambda_4 = \lambda_{\max}(R_{il}), \lambda_5 = \lambda_{\max}(Z_{il})$. We can obtain form (37) and (38) that

$$\| x(t) \| \le \sqrt{\frac{\lambda_2 + h\lambda_3 + (h^2/2)(\lambda_4 + \lambda_5)}{\lambda_1} e^{-\frac{ń}{2}t}} \| x_0 \|_h . \tag{39}$$

Therefore, this means that system (20) is ES with a decay rate $\phi = \frac{ń}{2}$. Thus the proof is over.

According to Theorem 1, the co-design method of the controller gain K_{i1} and the event-triggered parameter matrix Ω_i will be proposed in Theorem 2.

Theorem 2. There exist constants $\varepsilon_1 > 0, \varepsilon_2 > 0, \varepsilon_3 < 0, \mu_l \in (1,\infty), l \in \{1,2\}$, $\nu \in (1,\infty), \nu_q > 0, \nu_r > 0, \nu_z > 0, \varsigma \in (0,1), \upsilon_{\theta l} > 0, \theta \in \{1,2,3\}, \bar{R}, \bar{D}, \bar{X}$, sampling periods *h* and satisfying (22). If there exist matrices $X_{il} \in R^{n\times n} > 0$, $\tilde{Q}_{il} \in R^{n\times n} > 0$, $\tilde{R}_{il} \in R^{n\times n} > 0, \tilde{Z}_{il} \in R^{n\times n} > 0, \tilde{\Omega}_i \in R^{n\times n}$, and appropriate dimensions matrices $\tilde{N}_{ilw}, \tilde{M}_{ilw}, \tilde{S}_{ilw}$ with $w \in \{1,2\}$ such that

$$\Theta_l = \begin{bmatrix} \Theta_{11}^l & * & * \\ \Theta_{21}^l & \Theta_{22} & * \\ \Theta_{31}^l & 0_{3n\times 2n} & \Theta_{33} \end{bmatrix} < 0, \tag{40}$$

$$\begin{bmatrix} -\mu_2 X_{2l} & X_{2l} \\ * & -X_{1l} \end{bmatrix} \le 0, \begin{bmatrix} -\mu_1 e^{2(\varepsilon_1+\varepsilon_2)h} X_{1l} & X_{1l} \\ * & -X_{2l} \end{bmatrix} \le 0,$$
$$\begin{bmatrix} -\mu_{3-i}\tilde{Q}_{(3-i)l} & X_{(3-i)l} \\ * & \upsilon_{1l}^2\tilde{Q}_{il} - 2\upsilon_{1l}X_{il} \end{bmatrix} \le 0, \begin{bmatrix} -\mu_{3-i}\tilde{R}_{(3-i)l} & X_{(3-i)l} \\ * & \upsilon_{2l}^2\tilde{R}_{il} - 2\upsilon_{2l}X_{il} \end{bmatrix} \le 0, \tag{41}$$
$$\begin{bmatrix} -\mu_{3-i}\tilde{Z}_{(3-i)l} & X_{(3-i)l} \\ * & \upsilon_{3l}^2\tilde{Z}_{il} - 2\upsilon_{3l}X_{il} \end{bmatrix} \le 0,$$

$$\begin{bmatrix} -\nu X_{jl} & X_{jl} \\ * & -X_{il} \end{bmatrix} \le 0, \begin{bmatrix} -\nu\tilde{Q}_{jl} & \tilde{Q}_{jl} \\ * & \nu_q^2\tilde{Q}_{il} - 2\nu_q X_{il} \end{bmatrix} \le 0,$$
$$\begin{bmatrix} -\nu\tilde{R}_{jl} & \tilde{R}_{jl} \\ * & \nu_r^2\tilde{R}_{il} - 2\nu_r X_{il} \end{bmatrix} \le 0, \begin{bmatrix} -\nu\tilde{Z}_{jl} & \tilde{Z}_{jl} \\ * & \nu_z^2\tilde{Z}_{il} - 2\nu_z X_{il} \end{bmatrix} \le 0, \tag{42}$$

where Θ_l is obtained from Π_l by replacing $P_{il}A_i, B_i^T P_{il}, \Omega_i, Q_{il}, R_{il}, Z_{il}, N_{ilw}, M_{ilw}$, $S_{ilw}, -R_{il}^{-1}, -Z_{il}^{-1}, K_{i1} (i = 1, 2)$ with $A_i X_{il}, B_i^T, \tilde{\Omega}_i, \tilde{Q}_{il}, \tilde{R}_{il}, \tilde{Z}_{il}, \tilde{N}_{ilw}, \tilde{M}_{ilw}, \tilde{S}_{ilw}$, $-2\upsilon_{2l} X_{il} + \upsilon_{2l}^2 \tilde{R}_{il}, -2\upsilon_{3l} X_{il} + \upsilon_{3l}^2 \tilde{Z}_{il}, Y_{i1} (i = 1, 2)$. Other parameters remain the same with those in Theorem 1. Then system (20) is ES with ADT switching signal satisfying (28). Moreover, the control gains is $K_{i1} = Y_{i1} X_{i1}^{-1}$ and weighting matrix is $\tilde{\Omega}_i = X_{i1} \Omega_i X_{i1}$.

Proof. According to Theorem 1, we define $X_{il} = P_{il}^{-1}$, Let $L_{i1} = \text{diag}\{X_{i1}, X_{i1}, X_{i1}, X_{i1}, I_n, I_n, X_{i1}, X_{i1}, X_{i1}\}$ and $L_{i2} = \text{diag}\{X_{i2}, X_{i2}, X_{i2}, I_n, I_n, X_{i2}, X_{i2}, X_{i2}\}$. Then, multiplying both sides of Π_1 in (23) with L_{i1} and L_{i1}^T, multiplying both sides of Π_2 in (23) with L_{i2} and L_{i2}^T. Introducing matrix variables $\tilde{Q}_{il} = X_{il} Q_{il} X_{il}, \tilde{R}_{il} = X_{il} R_{il} X_{il}, \tilde{\Omega}_i = X_{i1} \Omega_i X_{i1}, \tilde{M}_{ilw} = X_{il} M_{ilw} X_{il}, \tilde{\Omega}_i = X_{i1} \Omega_i X_{i1}$, $\tilde{M}_{ilw} = X_{il} M_{ilw} X_{il}$, $\tilde{N}_{ilw} = X_{il} N_{ilw} X_{il}$, $\tilde{S}_{ilw} = X_{il} S_{ilw} X_{il}$ and $Y_{il} = K_{il} X_{il}$, where $l \in \{1, 2\}, w \in \{1, 2\}$.

It is easy to conclude that

$$-Q_{il}^{-1} = -X_{il} \tilde{Q}_{il}^{-1} X_{il} \le -2\upsilon_{1l} X_{il} + \upsilon_{1l}^2 \tilde{Q}_{il}. \tag{43}$$

Similarly, we have

$$-R_{il}^{-1} = -X_{il} \tilde{R}_{il}^{-1} X_{il} \le -2\upsilon_{2l} X_{il} + \upsilon_{2l}^2 \tilde{R}_{il}, -Z_{il}^{-1} = -X_{il} \tilde{Z}_{il}^{-1} X_{il} \le -2\upsilon_{3l} X_{il} + \upsilon_{3l}^2 \tilde{Z}_{il}. \tag{44}$$

Combining (43) and (44) yields the equivalence condition that (40) is (23). Next, multiply the former inequality and the latter inequality in (24) forms left and by X_{i2} and X_{i1}, respectively. It follows that the condition (44) is equivalent to the condition (24). It is clear that (41) and (42) are sufficient conditions to ensure (24) and (25). The end of this proof.

Remark 4. Different from [22], this paper designs a novel resilient ETM to further eliminate the adverse effects caused by DoS attacks and address the asynchronous problem. Meanwhile, the stability and security of the underlying system are ensured by using the PLF approach.

4 An Illustrative Example

A networked CSTR system from [23] is utilized to prove the feasibility of the presented design approach. The CSTR is connected to two different tanks via selector valves. When CSTR is connected to different tanks, the system will have different parameters. The adoption of network communication technologies makes networked CSTR susceptible to a number of various malicious attacks. Therefore the working principle of the networked CSTR considering the DoS attacks is shown in Figure 3.

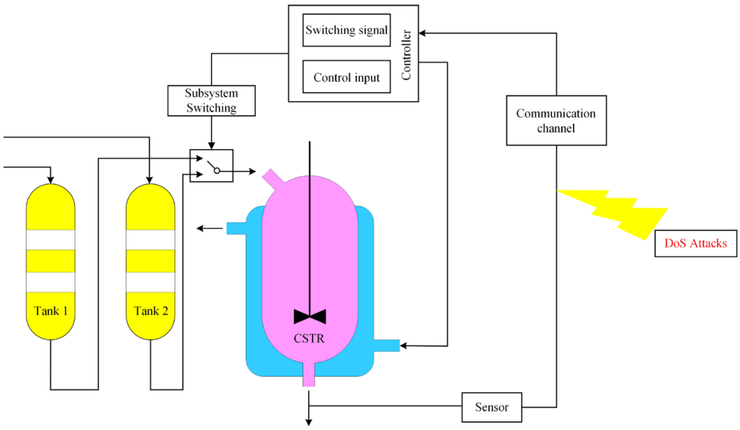

Figure 3
Framework of the networked CSTR system subject to DoS attacks

The CSTR system of differential equation model is described as the following:

$$\dot{C}_A = \frac{q_i}{V}\left(C_{Afi} - C_A\right) - k_0 e^{-\frac{E}{RT}} C_A, \dot{T} = \frac{q_i}{V}\left(T_{fi} - T\right) - k_1 e^{-\frac{E}{RT}} C_A + k_2\left(T_c - T\right), \tag{45}$$

where the parameters are given in [23]. Given the initial states $T(0) = 340\text{K}$ and $C_A(0) = 0.9\text{mol/L}$. For these two modes, $C_A^* = 0.5\text{mol/L}, T_c^* = 300\text{K}$ and $T^* = 350\text{K}$ is the unstable equilibrium point for nominal operating conditions.

Define several states as shown below $x_1 = C_A - C_A^*, x_2 = T - T^*$ and the control input $u = T_c - T_c^*$. The systems (20) matrix can be described as

$$A_1 = \begin{bmatrix} 0.5 & 1 \\ 0 & 0 \end{bmatrix}, A_2 = \begin{bmatrix} 2 & 1 \\ 0 & 0 \end{bmatrix}, B_1 = B_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

Let $\varepsilon_1 = 0.3, \varepsilon_2 = 2.5, \varepsilon_3 = -0.2, \upsilon_{1m} = 4, \upsilon_{2m} = 6, \upsilon_{3m} = 6 (m = 1, 2), h = 0.01,$

$\varsigma = 0.3, \mu_1 = 1.03, \mu_2 = 1.05, \nu = 1.2, \overline{X} = 14, \overline{R} = 15, \overline{D} = 16, \nu_q = \nu_r = \nu_z = 3,$

$\aleph = 0.5$.

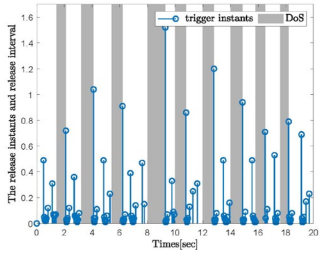

Figure 4
Triggering instants and release intervals under DoS attacks

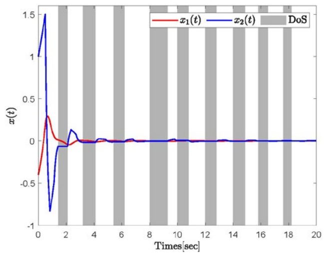

Figure 5
State responses of switched system under DoS attacks

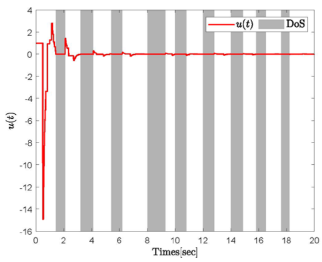

Figure 6
Control input of switched system under DoS attacks

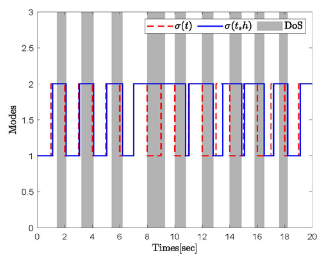

Figure 7
Switching modes of the system and the controller under DoS attacks

By calculation we can get that (28) holds. According to Theorem 2, the weight matrices and controller gain matrices are given as follows: $K_{11} = \begin{bmatrix} -21.4128 & -7.5642 \end{bmatrix}, K_{21} = \begin{bmatrix} -22.3876 & -8.2785 \end{bmatrix}$,

$$\Omega_1 = \begin{bmatrix} 1.9294 & 1.4690 \\ 1.4690 & 8.6546 \end{bmatrix}, \Omega_2 = \begin{bmatrix} 0.2734 & 0.8849 \\ 0.8849 & 9.4875 \end{bmatrix}.$$

Let is setup the original state as $x_0 = [-0.3, 0.8]$. The set of the active interval of DoS attacks to $S = \{[1.42, 2.1], [3.22, 4.1], [5.42, 6.2], [8, 9.29], [10.01, 10.79],$ $[11.99, 12.8], [14, 14.77], [15.82, 16.5], [17.6, 18.2]\}$. The triggering instants and release intervals under DoS attack in Figure 4, from which in the DoS inactive interval, the two adjacent trigger instants are less than $\aleph$ and the DoS attack is over, the output signal is immediately transmitted to the controller to compensate for the impact of the attacks. Switching systems in Figure 5 to achieve stability. Figure 6 display the control input of the switched system under DoS attacks. The system switching signal and the switching modes of controller is depicted in Figure 7 which follows that the maximum asynchronous time between the system and the controller is less than $\aleph$, and that the controller is not switching mode during the DoS active interval. Therefore, the simulation results represent a valid approach.

Conclusions

The asynchronous ETC problem of switched systems with DoS attacks has been explored in this paper. A resilient ETC strategy has been presented to defend against the impact of DoS attacks and eliminate the limitation that the minimum DT is greater than the maximum asynchronous time. Then, the stability conditions of the switched systems have been acquired by employing PLF method. In addition, a coordinated design method has been given for the event-triggered parameters and the controller gains. Finally, the feasibility of the presented approach has been confirmed by taking an example.

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