Ann. Acad. Rom. Sci.
Ser. Math. Appl.
ISSN 2066-6594 Vol. 13, No. 1-2/2021

RESILIENT HYBRID-TRIGGERED CONTROL FOR NETWORKED STOCHASTIC SYSTEMS UNDER DENIAL-OF-SERVICE ATTACKS*

Ning Zhao† Huiyan Zhang‡ Peng Shi§

Abstract

This paper investigates the stabilization problem for stochastic networked control systems under periodic denial-of-service (DoS) jamming attacks. First, the resilient hybrid-triggered communication scheme is developed to reduce the network transmission data and improve the utilization efficiency, where a Bernoulli distribution is used to characterize the switching protocol between time-triggered scheme and event-triggered scheme. Then, a resilient hybrid-driven control protocol is designed, and a new switched stochastic system is constructed. Sufficient conditions of the mean-square exponential stability are derived for the underlying system under DoS attacks. Furthermore, a co-design scheme of the feedback gain and the hybrid-triggering parameter is obtained by solving linear matrix inequalities. Finally, a satellite control system is employed to illustrate the virtue and applicability of the proposed approach.

MSC: 60H35

*Accepted for publication in revised form on December 9-th, 2020

†zhaoning@hrbeu.edu.cn College of Intelligent Systems Science and Engineering, Harbin Engineering University, Harbin 150001, Heilongjiang, China

‡huiyanzhang@ctbu.edu.cn National Research Base of Intelligent Manufacturing Service, Chongqing Technology and Business University, Chongqing 400067 (Corresponding author.)

§peng.shi@adelaide.edu.au School of Electrical and Electronic Engineering, University of Adelaide, SA 5005, Australia

keywords: Networked control systems, periodic denial-of-service attacks, resilient hybrid-driven communication scheme, mean-square exponential stability.

1 Introduction

The long-distance transmission characteristics of the network contribute to the networked control systems (NCSs) penetrate into every corner of social life, such as smart home, automotive automation, unmanned aerial vehicles, intelligent transportation system and so on [1, 2, 3, 4, 5, 6, 7, 8]. However, the widely open network environment means the exposure of some system nodes and data transmission channels, which leads to a widespread existence of security problems [9]. In particular, cyber attacks, that can be roughly divided into denial of service (DoS) attacks [10] and deception attacks [11], have become major disrupters to threaten network reliability, which aim to degrade the performance of the NCSs by breaking and/or modifying the transmitted data over network. Owing to the real-time requirements of the controlled system in network environment, security problems of NCS have been extensively attracted by the scholars.

As stated in [12], DoS, as a more frequent and harmful network attack, is one of the priority problems in NCS security. Its main purpose is to interrupt the signal transmission path, resulting in measure channel (sensor-to-controller) and/or control channel (controller-to-actuator) cannot send the state/output information or control signal in real time with receivers. Based on the attacked network, some theoretical results have been reported to preserve the security of NCS, see [13, 14, 15, 16]. From the point of attackers, using the techniques of switched systems, security control problem on the duration and frequency of DoS attacks was considered by using linear matrix inequalities (LMIs) in [13]. The resilient filtering problem for NCSs under intermittent DoS attacks was solved in [14]. The interactive decision-making process of attackers and smart grid security strategies were simulated by game theory in [15] and security issues in remote state estimation of cyber-physical systems were considered in [16]. For the problem of NCS security under periodic DoS attacks, the literature [12] considered the defense of DoS attacks with known period upper bound from the perspective of security control, and obtained sufficient conditions for the controlled system to be asymptotically stable.

Recently, taking the limited communication bandwidth into consideration, event-triggered scheme (ETS) has been introduced in many interesting studies, leading to a growing number of important publications (see [17, 2, 18] and the references therein). Many of the mentioned literature above, only the pre-set trigger mechanism is used to study the performance of the system, however, the trade-off between network resource and system performance is not considered. Optimizing the method of data transmission in NCS is one of the problems to be solved, especially when the network is attacked. In particular, under the bad influence of DoS attack, how to reduce the network communication burden and reasonably and intelligently select the transmission signal to ensure the performance of the system has become an urgent problem to be solved. To tackle this problem, the literature [11] has proposed a hybrid-drive communication scheme, which contains time-triggered scheme (TTS) and ETS. However, this scheme is only applicable to the stabilization problem of NCS under stochastic deception attacks. Then, how to design a new communication scheme to remove the impact of DoS jamming attacks and then ensure the stability of stochastic NCS is an open problem.

Motivated by the problem above, contributions of this paper are generalized as follows:

- A resilient hybrid-triggered communication scheme (RHTCS) is proposed to remove the impact of DoS attacks and make full use of network resources. Affected by the sampling period and DoS attacks, the stability of the considered system may not be guaranteed under ETS, while the proposed RHTCS can effectively ensure the system security.

- The model of switching stochastic system is established under RHTCS and periodic DoS jamming attacks. On the basis of this model, the criteria of stability and controller design are obtained by solving LMIs.

Notation: $(\Omega, \mathcal{F}, \mathbb{P})$ denotes a probability space, in which Ω stands for the sample space, $\mathcal{F}$ is the σ-algebra of subsets of the sample space and $\mathbb{P}$ represents the probability measure on Ω. Let $\mathbb{R}^{n\times m}$ be a set of real $n \times m$ matrices. For a real symmetric matrix $\mathcal{R} \in \mathbb{R}^{n\times n}$, $\mathcal{R} > 0$ ($\mathcal{R} \geq 0$) represents that $\mathcal{R}$ is positive definite (semidefinite). The sign $\mathrm{He}(\mathcal{R})$ stands for $\mathcal{R}+\mathcal{R}^T$. The symbol $*$ indicates the symmetric term in a symmetric block matrix. Define a norm $||\varphi||_h = \sup\limits_{-h\leq s\leq 0} ||\varphi(s)||$, where $||\cdot||$ denotes the Euclidian norm of $\mathbb{R}^n$.

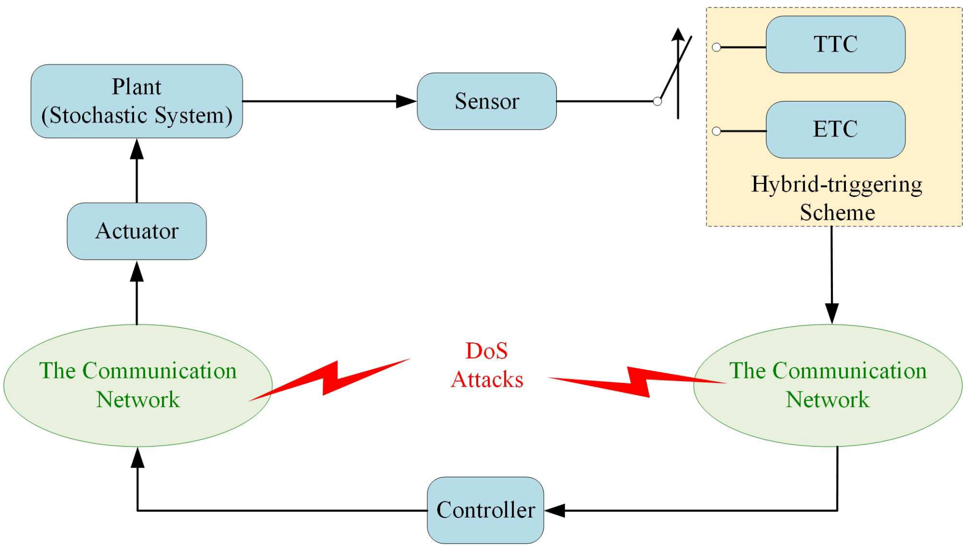

Figure 1: The framework of an NCS under DoS attacks

2 Problem formulation and Preliminaries

2.1 System description

Consider a stochastic system on the probability space $(\Omega, \mathcal{F}, \mathbb{P})$:

$$\mathrm{d}x(t) = [Ax(t) + Bu(t)]\mathrm{d}t + Ex(t)\mathrm{d}\varpi(t),\ t \geq 0, \tag{1}$$

where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$ and $\varpi(t)$ are the system state, the control input and a one-dimensional Brownian motion on the probability space, respectively and $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$ and $E \in \mathbb{R}^{n\times n}$ are known matrices. The Brownian motion $\varpi(t)$ satisfies $\mathbf{E}\{\mathrm{d}\varpi(t)\} = 0$ and $\mathbf{E}\{\mathrm{d}^2\varpi(t)\} = \mathrm{d}t$. Assume that the pair (A, B) is controllable.

As shown in Figure 1, when the signal is not attacked during network transmission, the general form of controller is designed as follows:

$$u(t) = Kx(t_jh),\ t \in [t_jh, t_{j+1}h), \tag{2}$$

where $t_jh(j \in \{0, 1, 2, ...\}, t_0 = 0)$, denotes the sampling instant of successful arrival at the controller and h represents the sampling period. K is the controller feedback gain to be designed.

2.2 Periodic DoS attacks and control law

As seen in Figure 1, considering the type of DoS attacks, its mathematical expression is shown as follows [12]:

$$\mathcal{S}_{DoS}(t) = \begin{cases} 1, \ t \in [nT, nT + \widetilde{T}), \\ 0, \ t \in [nT + \widetilde{T}, (n+1)T), \end{cases} \tag{3}$$

where $n \in \mathbb{N}$, $T > 0$ and $\widetilde{T}$ represent the period number, the period of the jammer and the sleeping time of the jammer, respectively, with $\widetilde{T} \in [\widetilde{T}_{\min}, T)$ ($\widetilde{T}_{\min} > 0$ is a constant). Therefore, the interval $\cup_{n\in\mathbb{N}}[nT, nT+\widetilde{T})$ indicates that DoS attacks are sleeping, and the interval $\cup_{n\in\mathbb{N}}[nT+\widetilde{T}, (n+1)T)$ implies that DoS attacks are active. As mentioned in [12], $\widetilde{T}$ does not require time-invariant. Therefore, when we assume that $\widetilde{T} = \widetilde{T}_{\min}$, which implies that the attacker maintains a worse-case jamming scenario.

In the interval $\cup_{n\in\mathbb{N}}[nT + \widetilde{T}, (n + 1)T)$, the released data cannot successfully arrive at the controller, and the control input cannot successfully reach the actuator too. Thus, under periodic DoS jamming attacks (3), the control input $u(t)$ can be indicated as

$$u(t) = \begin{cases} Kx(t_{j,n+1}h), \ t \in [t_{j,n+1}h, t_{j+1,n+1}h) \cap [nT, nT + \widetilde{T}), & \text{(4a)} \\ 0, \ t \in [nT + \widetilde{T}, (n + 1)T). & \text{(4b)} \end{cases}$$

where $\{t_{j,n+1}h\}$, $j \in \mathcal{J}_n = \{0, 1, ..., j_n\}$ ($j_n = \max\{j \in \mathbb{N} | nT+\widetilde{T} \geq t_{j,n+1}h\}$), stand for the successful control update instants ($t_{0,n+1}h \triangleq nT$), which are determined by the novel RHTCS.

2.3 A resilient hybrid-triggered communication scheme design

As seen in Figure 1, a RHTCS, that is composed of two trigger mechanisms, is presented to achieve tradeoff between performance and communication under DoS attacks. The switching of the two schemes satisfies a Bernoulli distribution.

When TTS is chosen during signal transmission, the sampling instants are $t_{j,n+1}h = jh$. Define $\tau_{j,n}(t) = t - t_{j,n+1}h$, for (4a), we have

$$u(t) = Kx(t - \tau_{j,n}(t)), \tag{5}$$

where $\tau_{j,n}(t) \in [0, h)$.

When no attack occurs and ETS is selected during signal transmission, whether the sampled data can reach the controller will depend on the following form of event triggering mechanism [19]:

$$e^T(t)\Psi_1 e(t) \le \sigma x^T(t_j h)\Psi x(t_j h), \tag{6}$$

where $e((t_j+i)h) = x(t_j h) - x((t_j+i)h)$, $\Psi > 0$ is a weighting matrix to be determined and $\sigma \in [0,1)$ is a constant to be designed. The next control update instants $t_{j+1}h$ can be obtained by

$$t_{j+1}h = t_j h + \min_{i\ge 1}\{jh | e^T((t_j+i)h)\Psi e((t_j+i)h) > \sigma x^T(t_j h)\Psi x(t_j h)\}. \tag{7}$$

Since the network is blocked by periodic DoS attacks, the traditional ETS (7) cannot achieve the stability of the considered system. Motivated by [18], a resilient event-triggered mechanism is introduced to remove the impact of DoS attacks. Its triggering instant is determined by the following condition:

$$t_{j,n+1}h \in \{t_{j_r}h \ satisfing \ (6) | t_{j_r}h \in [nT, nT+\widetilde{T})\} \cup \{nT\}, n, r, j_r \in \mathbb{N}. \tag{8}$$

For convenience, for $n \in \mathbb{N}$, let $\mathcal{D}_{1,n} \triangleq [nT, nT+\widetilde{T})$, $\mathcal{D}_{2,n} \triangleq [nT + \widetilde{T}, (n+1)T)$ and $\mathcal{G}_{j,n} \triangleq [t_{j,n+1}h, t_{j+1,n+1}h)(j \in \mathcal{J}_n)$. Then the time interval $\mathcal{G}_{j,n} \cap \mathcal{D}_{1,n}$ can be rewritten as

$$\begin{array}{ll} \mathcal{G}^i_{j,n} & = [t_{k,n+1}h + (i-1)h, t_{k,n+1}h + ih), i = 1, \ldots, \varsigma_{j,n}, \\ \mathcal{G}^{\varsigma_{j,n}+1}_{j,n} & = [t_{k,n+1}h + \varsigma_{j,n}h, t_{k+1,n+1}h), \\ \mathcal{G}^i_{j_n,n} & = [t_{j_n,n+1}h + (i-1)h, t_{j_n,n+1}h + ih), i = 1, \ldots, \varsigma_{j_n,n}, \\ \mathcal{G}^{\varsigma_{j_n,n}+1}_{j_n,n} & = [t_{j_n,n+1}h + \varsigma_{j_n,n}h, nT + \tilde{T}), \end{array} \tag{9}$$

where $j \in \mathcal{J}_n - \{j_n\}$, $\varsigma_{j,n} \triangleq \max\{k \in \mathbb{N} | t_{j,n+1}h + kh < t_{j+1,n+1}h\}$ and $\varsigma_{j_n,n} \triangleq \max\{k \in \mathbb{N} | t_{j_n,n+1}h + kh < nT + \tilde{T}\}$. Similarly, we divide the time interval $\mathcal{D}_{2,n}$ into the following subintervals: $\mathcal{D}_{2,n} = \cup_{i=1}^{\varsigma_{j_n+1,n}+1}\mathcal{G}^i_{j_n+1,n}$, where $\mathcal{G}^1_{j_n+1,n} = [nT + \tilde{T}, t_{j_n,n+1}h + \varsigma_{j_n,n}h + h)$, $\mathcal{G}^i_{j_n+1,n} = [t_{j_n,n+1}h + \varsigma_{j_n,n}h + (i-1)h, t_{j_n,n+1}h + \varsigma_{j_n,n}h + ih)$ with $i = 2, ..., \varsigma_{j_n+1,n} + 1$ and $\varsigma_{j_n+1,n} \triangleq \max\{i \in \mathbb{N} | t_{j_n,n+1}h + \varsigma_{j_n,n}h + ih < (n+1)T\}$.

Now, we define two piecewise functions: $\theta_{j,n}(t) = t - t_{j,n+1}h - l_{j,n}h$, $t \in \mathcal{G}^{l_{j,n}+1}_{j,n}$ with $l_{j,n} = 0, 1, .., \varsigma_{j,n}$ and $j \in \mathcal{J} \cup \{j_n+1\}$, $e_{j,n}(t) = x(t_{j,n+1}h) - x(t_{j,n+1}h + \bar{l}_{j,n}h), t \in \mathcal{G}^{\bar{l}_{j,n}+1}_{j,n}$ with $\bar{l}_{j,n} = 0, 1, .., \varsigma_{j,n}$ and $j \in \mathcal{J}$. According to the definitions of $\theta_{j,n}(t)$ and $e_{j,n}(t)$, we know $\theta_{j,n}(t) \in [0, h), t \in \mathcal{G}_{j,n} \cap$

$\mathcal{D}_{1,n}$. Then, the next released system state that satisfies the event-triggered condition can be expressed as:

$$x(t_{j,n+1}h) = x(t - \theta_{j,n}(t)) + e_{j,n}(t), t \in \mathcal{G}_{j,n} \cap \mathcal{D}_{1,n}. \quad (10)$$

Then, according to (6), it follows that

$$e^T_{j,n}(t)\Psi e_{j,n}(t) \leq \sigma(e_{j,n}(t) + x(t - \theta_{j,n}(t)))^T \Psi(e_{j,n}(t) + x(t - \theta_{j,n}(t))). \quad (11)$$

and for (4a), we have

$$u(t) = K[x(t - \theta_{j,n}(t)) + e_{j,n}(t)]. \quad (12)$$

Under RHTCS, the controller based on (5) and (12) is expressed as follows:

$$u(t) = \beta(t)Kx(t - \tau_{j,n}(t)) + (1 - \beta(t))K[x(t - \theta_{j,n}(t)) + e_{j,n}(t)], \quad (13)$$

where $\beta(t) \in \{0, 1\}$ depends on Bernoulli distribution. Its mathematical expectation and mathematical variance are $\bar{\beta}$ and $\nu^2 = \bar{\beta}(1-\bar{\beta})$, respectively.

Remark 1. *In some existing results [11, 20], these only use a hybrid-drive communication scheme to solve the stabilization problem of NCS under deception attacks. Different from the aforementioned results, this paper proposes a novel RHTCS to solve the security problem of NCS under periodic DoS jamming attacks.*

Based on (4) and (13), system (1) can be written as

$$\begin{aligned} \mathrm{d}x(t) &= [Ax(t) + \beta(t)BKx(t - \tau_{j,n}(t)) + (1 - \beta(t))BK \\ &\quad \times(x(t - \theta_{j,n}(t)) + e_{j,n}(t))]\mathrm{d}t + Ex(t)\mathrm{d}\varpi(t), t \in \mathcal{G}^k_{j,n} \cap \mathcal{D}_{1,n}, \\ \mathrm{d}x(t) &= Ax(t)\mathrm{d}t + Ex(t)\mathrm{d}\varpi(t),\ t \in \mathcal{D}_{2,n}. \end{aligned} \quad (14)$$

In order to construct a unified form of the system model, we define

$$\rho(t) = \begin{cases} 1,\ t \in \mathbb{Z}[-h, 0] \cup (\cup_{n\in\mathbb{N}}\mathcal{D}_{1,n}) \\ 2,\ t \in \cup_{n\in\mathbb{N}}\mathcal{D}_{2,n}, \end{cases} \quad \text{and } t_{l,n} = \begin{cases} nT,\ l = 1, \\ nT + \tilde{T},\ l = 2, \end{cases}$$

which implies $\mathcal{D}_{l,n} = [t_{l,n}, t_{3-l,n+l-1})$, $\rho(t_{l,n}) = l$ and $\rho(t^-_{l,n}) = 3 - l$.

As the definition of $\rho(t)$, the following switched stochastic system can be described as

$$\begin{aligned} \mathrm{d}x(t) &= [A_l x(t) + \beta(t)\mathcal{B}_l x(t - \tau_{j,n}(t)) + (1 - \beta(t))\mathcal{B}_l(x(t - \theta_{j,n}(t)) \\ &\quad +e_{j,n}(t))]\mathrm{d}t + Ex(t)\mathrm{d}\varpi(t),\ t \in [t_{l,n}, t_{3-l,n+l-1}),\ n \in \mathbb{N}, l = 1, 2, \\ x(t) &= \varphi(t),\ t \in [-h, 0], \end{aligned} \quad (15)$$

where $A_l = A$, $\mathcal{B}_1 = BK$ and $\mathcal{B}_2 = 0$.

The objective of this paper is to design the controller under DoS attacks, such that system (15) is mean-square exponentially stable.

3 Stability analysis

System (15) implies the overall dynamics of NCS in Figure 1, and the criterion of mean-square exponentially stable is given in Theorem 1.

Theorem 1. *Assume the parameters T, $\tilde{T}$ in* (3)*, and control gain matrix $K \in \mathbb{R}^{n\times m}$ be known. For given scalars $\sigma \in (0,1)$, $\bar{\beta} \in [0,1]$, $\alpha_l > 0$, $\mu_l > 0, l = 1,2,$ and $h > 0$, satisfying*

$$\lambda := \alpha_1\tilde{T} - \alpha_2(T - \tilde{T}) - 2(\alpha_1 + \alpha_2)h - \ln(\mu_1\mu_2) > 0, \tag{16}$$

if there exist symmetric matrices $\Psi > 0$, $P_l > 0$, $Q_{lj} > 0$, $R_{lj} > 0$ and $Z_{lj} > 0$, $j \in \{1,2\}$ and appropriate dimension matrices M_{ld}, N_{ld}, $d \in \{1,2,3\}$, such that for $l = 1,2$, the following LMIs hold:

$$P_1 \le \mu_2 P_2,\ P_2 \le \mu_1 e^{2(\alpha_1+\alpha_2)h} P_1,\ \zeta_{lj} \le \mu_{(3-l)j}\zeta_{(3-l)j},\ \zeta \in \{Q,R,Z\}, \tag{17}$$

$$\Xi_1 = \begin{bmatrix} \Xi_{111} & \Xi_{112} & \Xi_{113}(k) & \Xi_{114} & \Xi_{115} \\ * & \Xi_{122} & 0 & 0 & 0 \\ * & * & \Xi_{133} & 0 & 0 \\ * & * & * & \Xi_{144} & 0 \\ * & * & * & * & \Xi_{155} \end{bmatrix} < 0, \tag{18}$$

$$\Xi_2 = \begin{bmatrix} \Xi_{211} & \Xi_{212} & \Xi_{213}(k) & \Xi_{214} \\ * & \Xi_{222} & 0 & 0 \\ * & * & \Xi_{233} & 0 \\ * & * & * & \Xi_{244} \end{bmatrix} < 0, \tag{19}$$

where

$$\begin{aligned}
\Xi_{l11} &= \Xi_{l1} + \Xi_{l2} + \Xi_{l2}^T,\ \Xi_{l1} = \begin{bmatrix} \Upsilon_{l11} & \Upsilon_{l12} \\ \Upsilon_{l12}^T & \Upsilon_{l22} \end{bmatrix}, \\
\Upsilon_{112} &= \begin{bmatrix} \Upsilon_{11} & \bar{\beta}P_1\mathcal{B}_1 & (1-\bar{\beta})P_1\mathcal{B}_1 & 0 & (1-\bar{\beta})P_1\mathcal{B}_1 \end{bmatrix}, \\
\Upsilon_{212} &= \begin{bmatrix} \Upsilon_{21} & 0_{n\times 3n} \end{bmatrix},\ \Upsilon_{l11} = \mathrm{He}(P_l A_l) + (-1)^{l-1}2\alpha_l P_l + (Q_{l1} + Q_{l2}), \\
\Upsilon_{122} &= \mathrm{diag}\{0, \sigma\Psi, -e^{-2\alpha_1 h}(Q_{11} + Q_{12}), (\sigma - 1)\Psi\} + \sigma\mathrm{He}(I_1^T\Psi I_2) \\
I_1 &= \begin{bmatrix} 0 & I & 0_{n\times 2n} \end{bmatrix},\ I_2 = \begin{bmatrix} 0_{n\times 3n} & I \end{bmatrix},\ \Upsilon_{222} = \mathrm{diag}\{0, 0, -Q_{21} - Q_{22}\}, \\
\Xi_{l2} &= [\Xi_{l2}^1 \ \ \Xi_{l2}^2],\ \Xi_{l2}^1 = M_{l1} + M_{l3} + N_{l1} + N_{l3}, \\
\Xi_{12}^2 &= [-M_{12} - M_{13} \quad -N_{11} + N_{12} \ \ -M_{11} + M_{12} - N_{12} - N_{13}\ 0], \\
\Xi_{22}^2 &= [-M_{22} - M_{23} \quad -N_{21} + N_{22} \ \ -M_{21} + M_{22} - N_{22} - N_{23}], \\
\Xi_{l12} &= \begin{bmatrix} \sqrt{h}M_{l3} & \sqrt{h}N_{l3} \end{bmatrix},\ \Xi_{l22} = \mathrm{diag}\{-e^{2(l-2)\alpha_l h}R_{l2}, -e^{2(l-2)\alpha_l h}Z_{l2}\},
\end{aligned}$$

$$\begin{aligned}
\varXi_{l13}(1) &= \begin{bmatrix} \sqrt{h}M_{l1} & \sqrt{h}N_{l1} \end{bmatrix},\ \varXi_{l13}(2) = \begin{bmatrix} \sqrt{h}M_{l2} & \sqrt{h}N_{l1} \end{bmatrix},\\
\varXi_{l13}(3) &= \begin{bmatrix} \sqrt{h}M_{l1} & \sqrt{h}N_{l2} \end{bmatrix},\ \varXi_{l13}(4) = \begin{bmatrix} \sqrt{h}M_{l2} & \sqrt{h}N_{l2} \end{bmatrix},\\
\varXi_{l33} &= \mathrm{diag}\{-e^{2(l-2)\alpha_l h}R_{l1}, -e^{2(l-2)\alpha_l h}Z_{l1}\},\\
\varXi_{l14}^T &= [\varXi_{l14}^1\ \varXi_{l14}^2],\ \bar{\varXi}_{214}^2 = 0_{3n\times 2n},\\
\varXi_{l14}^1 &= \begin{bmatrix} \sqrt{h}P_lA_l & \sqrt{h}\bar{\beta}P_l\mathcal{B}_l \\ \sqrt{h}P_lA_l & \sqrt{h}\bar{\beta}P_l\mathcal{B}_l \\ P_lE & 0 \end{bmatrix},\\
\varXi_{114}^2 &= \begin{bmatrix} (1-\bar{\beta})\sqrt{h}P_1\mathcal{B}_1 & 0 & (1-\bar{\beta})\sqrt{h}P_1\mathcal{B}_1 \\ (1-\bar{\beta})\sqrt{h}P_1\mathcal{B}_1 & 0 & (1-\bar{\beta})\sqrt{h}P_1\mathcal{B}_1 \\ 0 & 0 & 0 \end{bmatrix},\\
\varXi_{115}^T &= \begin{bmatrix} 0 & \nu\sqrt{h}P_1\mathcal{B}_1 & -\nu\sqrt{h}P_1\mathcal{B}_1 & 0 & -\nu\sqrt{h}P_1\mathcal{B}_1 \\ 0 & \nu\sqrt{h}\bar{\beta}P_1\mathcal{B}_1 & -\nu\sqrt{h}P_1\mathcal{B}_1 & 0 & -\nu\sqrt{h}P_1\mathcal{B}_1 \end{bmatrix},\\
\varXi_{l44} &= \mathrm{diag}\{-(R_{l1}+R_{l2})^{-1}, -(Z_{l1}+Z_{l2})^{-1}, -P_l\},\ \varXi_{155} = \varXi_{144},
\end{aligned}$$

then system (15) *is mean-square exponentially stable.*

Proof. The following Lyapunov-Krasovskii functional is constructed:

$$\begin{aligned}
&V_{\rho(t)}(t) = x^T(t)P_{\rho(t)}x(t) + \int_{t-h}^{t} f(t,s)x^T(s)Q_{\rho(t)1}x(s)\mathrm{d}s \\
&+ \int_{t-h}^{t} f(t,s)x^T(s)Q_{\rho(t)2}x(s)\mathrm{d}s + \int_{-h}^{0}\int_{t+v}^{t} f(t,s)g^T(s)R_{\rho(t)1}g(s)\mathrm{d}s\mathrm{d}v \\
&+ \int_{-h}^{0}\int_{t+v}^{t} f(t,s)g^T(s)R_{\rho(t)2}g(s)\mathrm{d}s\mathrm{d}v + \int_{-h}^{0}\int_{t+v}^{t} f(t,s)g^T(s)Z_{\rho(t)1}g(s)\mathrm{d}s\mathrm{d}v \\
&+ \int_{-h}^{0}\int_{t+v}^{t} f(t,s)g^T(s)Z_{\rho(t)2}g(s)\mathrm{d}s\mathrm{d}v \qquad (20)
\end{aligned}$$

where $f(t,s) := e^{(-1)^{\rho(t)}2\alpha_{\rho(t)}(t-s)}$, and $g(s) = Ax(s)+\beta(s)\mathcal{B}_{\rho(t)}x(s-\tau_{j,n}(s))+(1-\beta(s))\mathcal{B}_{\rho(t)}(x(s-\theta_{j,n}(s))+e_{j,n}(s))$. Let $\mathcal{A}_l = A_lx(t)+\bar{\beta}\mathcal{B}_lx(t-\tau_{j,n}(t))+(1-\bar{\beta})\mathcal{B}_l[x(t-\theta_{j,n}(t))+e_{j,n}(t)]$, $\widetilde{\mathcal{B}}_l = \mathcal{B}_lx(t-\tau_{j,n}(t))-\mathcal{B}_l[x(t-\theta_{j,n}(t))+e_{j,n}(t)]$ and $\mathcal{Z}_l = h(R_{l1}+R_{l2})+h(Z_{l1}+Z_{l2})$.

For $\rho(t) = 1$, the weak infinitesimal operator $\mathcal{L}$, using the Leibniz-Newton formula, Young's inequality, Jenson inequality and (11), we have

$$\begin{aligned}\mathbf{E}\{\mathcal{L}V_1(t)\} \leq{}& \xi_1^T(t)\big[-2\alpha_1 V_1(t) + \Xi_{111} + e^{2\alpha_1 h}(\tau_{j,n}(t)M_{11}R_{11}^{-1}M_{11}^T \\ &+ (h-\tau_{j,n}(t))M_{12}R_{11}^{-1}M_{12}^T + hM_{13}R_{12}^{-1}M_{13}^T + \theta_{j,n}(t)N_{11}Z_{11}^{-1}N_{11}^T \\ &+ (h-\theta_{j,n}(t))N_{12}Z_{11}^{-1}N_{12}^T + hN_{13}Z_{12}^{-1}N_{13}^T)\big]\xi_1(t) + x^T(t)E^TPEx(t) \\ &+ \mathcal{A}_1^T\mathcal{Z}_1\mathcal{A}_1 + \nu^2\widetilde{\mathcal{B}}^T\mathcal{Z}_1\widetilde{\mathcal{B}},\end{aligned}$$

in which $\xi_1(t) = [x^T(t)\ x^T(t-\tau_{j,n}(t))\ x^T(t-\theta_{j,n}(t))\ x^T(t-h)\ e_{j,n}^T(t)]^T$. Using Lemma 1 in [21] and Schur complement formula to $\Xi_1 < 0$ in (18), we can obtain that

$$\mathbf{E}\{\mathcal{L}V_1(t) + 2\alpha_1 V_1(t)\} \leq 0,$$

which implies that

$$\mathbf{E}\{V_1(t)\} \leq e^{-2\alpha_1(t-t_{1,n})}\mathbf{E}\{V_1(t_{1,n})\},\ t \in [t_{1,n}, t_{2,n}). \tag{21}$$

Similarly, for $\rho(t) = 2$, we can get that

$$\begin{aligned}\mathbf{E}\{\mathcal{L}V_2(t)\} \leq{}& \xi_2^T(t)[2\alpha_2 V_2(t) + \Xi_{211} + \tau_{j,n}(t)M_{21}R_{21}^{-1}M_{21}^T \\ &+ (h-\tau_{j,n}(t))M_{21}R_{21}^{-1}M_{21}^T + hM_{23}R_{22}^{-1}M_{23}^T + \theta_{j,n}(t)N_{21}Z_{21}^{-1}N_{21}^T \\ &+ (h-\theta_{j,n}(t))N_{22}Z_{21}^{-1}N_{22}^T + hN_{23}Z_{22}^{-1}N_{23}^T]\xi_2^T(t) \\ &+ x^T(t)E^TPEx(t) + \mathcal{A}_2^T\mathcal{Z}_2\mathcal{A}_2,\end{aligned}$$

in which $\xi_2(t) = [x^T(t)\ x^T(t-\tau_{j,n}(t))\ x^T(t-\theta_{j,n}(t))\ x^T(t-h)]^T$. According to Lemma 1 in [21] and $\Xi_2 < 0$, we can deduce that

$$\mathbf{E}\{\mathcal{L}V_2(t) - 2\alpha_2 V_2(t)\} \leq 0,$$

which means that

$$\mathbf{E}\{V_2(t)\} \leq e^{2\alpha_2(t-t_{2,n})}\mathbf{E}\{V_2(t_{2,n})\},\ t \in [t_{2,n}, t_{1,n+1}).$$

Based on the analysis above, let

$$V(t) = \begin{cases} V_1(t),\ t \in [t_{1,n}, t_{2,n}), \\ V_2(t),\ t \in [t_{2,n}, t_{1,n+1}), \end{cases}$$

we have

$$\mathbf{E}\{V(t)\} \leq \begin{cases} e^{-2\alpha_1(t-t_{1,n})}\mathbf{E}\{V_1(t_{1,n})\},\ t \in [t_{1,n}, t_{2,n}), \\ e^{2\alpha_2(t-t_{2,n})}\mathbf{E}\{V_2(t_{2,n})\},\ t \in [t_{2,n}, t_{1,n+1}). \end{cases} \tag{22}$$

Case 1: if $t \in [t_{1,n}, t_{2,n})$, integrating (17) and (22) yields

$$\begin{aligned}\mathbf{E}\{V(t)\} &\leq e^{-2\alpha_1(t-t_{1,n})}\mathbf{E}\{V_1(t_{1,n})\}\\ &\leq \mu_2 e^{-2\alpha_1(t-t_{1,n})}\mathbf{E}\{V_1(t_{1,n}^-)\}\\ &\leq \mu_2 e^{-2\alpha_1(t-t_{1,n})}e^{\alpha_2(t_{1,n}-1-t_{2,n-1})}\mathbf{E}\{V_2(t_{2,n-1})\}\\ &\leq e^{(\alpha_1+\alpha_2)}\mu_1\mu_2 e^{-\alpha_1(t-t_{1,n})}e^{\alpha_2(t_{1,n}^{-1}-t_{2,n-1})}\mathbf{E}\{V_1(t_{2,n-1}^-)\}\\ &\vdots\\ &\leq e^{\lambda n}V_1(t_{1,0}).\end{aligned} \tag{23}$$

Notice that $t \leq t_{2,n} = nT + \widetilde{T}$, then $n \geq \frac{t-\widetilde{T}}{T}$. Substituting this inequality into (23) yields

$$\mathbf{E}\{V(t)\} \leq e^{\lambda\frac{1-\widetilde{T}}{T}}e^{-\frac{\lambda}{T}t}V_1(0). \tag{24}$$

Case 2: if $t \in [t_{1,n}, t_{2,n})$, similarly, integrating (17) and (22) yields

$$\mathbf{E}\{V(t)\} \leq \frac{1}{\mu_2}e^{\lambda}e^{-\frac{\lambda}{T}t}V_1(0). \tag{25}$$

Finally, we have $\mathbf{E}\{||x(t)||^2\} \leq \frac{\kappa\varepsilon d_3}{d_1}e^{-\frac{\lambda}{T}t}||\varphi||_h^2$, where $\kappa = \max\{e^{\lambda\frac{\widetilde{T}}{T}}, \frac{1}{\mu_2}e^{\lambda}\}$ and $d_3 = d_2 + \lambda_{\max}(hQ_{11} + hQ_{12}) + \lambda_{\max}(\frac{h^2}{2}(R_{11} + R_{12}) + \frac{h^2}{2}(Z_{11} + Z_{12})))$ with $d_2 = \max_{j\in\{1,2\}}\{\lambda_{\max}(P_j)\}$. Therefore, system (15) is mean-square exponentially stable. This proof is completed. □

According to Theorem 1, the state feedback gain matrix K and the weighted matrix Ψ are obtained by the following theorem.

Theorem 2. *Assume the parameters T, $\tilde{T}$. For given scalars $\sigma \in (0,1)$, $\bar{\beta} \in [0,1]$, $\varepsilon_{1l} > 0$, $\varepsilon_{2l} > 0$, $\chi_{lk} > 0$, $k = 1,2$, $\alpha_l > 0$ and $\mu_l > 1$, $l = 1,2$, and $h > 0$, satisfying (16), if there exist symmetric matrices $\bar{\Psi} > 0$, $Y_l > 0$, $\bar{Q}_{lj} > 0$, $\bar{R}_{lj} > 0$ and $\bar{Z}_{lj} > 0, j \in \{1,2\}$, and appropriate dimension* *matrices X, $\bar{M}_{ld}$, $\bar{N}_{ld}$, $d \in \{1,2,3\}$, such that the following LMIs hold:*

$$\begin{bmatrix} -\mu_2 Y_2 & Y_2 \\ * & -Y_1 \end{bmatrix} \leq 0, \tag{26}$$

$$\begin{bmatrix} -\mu_1 e^{2(\alpha_1+\alpha_2)h} Y_1 & Y_1 \\ * & -Y_2 \end{bmatrix} \leq 0, \tag{27}$$

$$\begin{bmatrix} -\mu_{3-l}\bar{\zeta}_{(3-l)k} & Y_{3-l} \\ * & \chi_{lk}^2 \bar{\zeta}_{lk} - 2\chi_{lk} Y_l \end{bmatrix} \leq 0,$$
$$\bar{\zeta} \in \{\bar{Q}, \bar{R}, \bar{Z}\},\ k \in \{1,2\}, \tag{28}$$

$$\bar{\Xi}_1 = \begin{bmatrix} \bar{\Xi}_{111} & \bar{\Xi}_{112} & \bar{\Xi}_{113}(k) & \bar{\Xi}_{114} & \bar{\Xi}_{115} \\ * & \bar{\Xi}_{122} & 0 & 0 & 0 \\ * & * & \bar{\Xi}_{133} & 0 & 0 \\ * & * & * & \bar{\Xi}_{144} & 0 \\ * & * & * & * & \bar{\Xi}_{155} \end{bmatrix} < 0, \tag{29}$$

$$\bar{\Xi}_2 = \begin{bmatrix} \bar{\Xi}_{211} & \bar{\Xi}_{212} & \bar{\Xi}_{213}(k) & \bar{\Xi}_{214} \\ * & \bar{\Xi}_{222} & 0 & 0 \\ * & * & \bar{\Xi}_{233} & 0 \\ * & * & * & \bar{\Xi}_{244} \end{bmatrix} < 0, \tag{30}$$

where $\bar{\Xi}_1$ and $\bar{\Xi}_2$ are, respectively, obtained from Ξ_1 and Ξ_2 by replacing Ψ, $P_l A_l$, $P_l \mathcal{B}_l$, Q_{lj}, R_{lj}, Z_{lj} M_{ld}, N_{ld}, $P_l E$, $-(R_{l1}+R_{l2})^{-1}$, $-(Z_{l1}+Z_{l2})^{-1}$, and P_l with $\bar{\Psi}$, $A_l Y_l$, $\mathcal{B}_l X$, $\bar{Q}_{lj}$, $\bar{R}_{lj}$, $\bar{Z}_{lj}$, $\bar{M}_{ld}$, $\bar{N}_{ld}$, EY_l, $-2\varepsilon_{1l} Y_l + \varepsilon_{1l}^2 (R_{l1} + R_{l2})$, $-2\varepsilon_{2l} Y_l + \varepsilon_{2l}^2 (Z_{l1} + Z_{l2})$ and Y_l, then the switched system is mean-square exponentially stable. Furthermore, the control gain K and resilient hybrid-driven weight matrix Ψ are given by $K = XY_1^{-1}$ and $\Psi = Y_1^{-1}\bar{\Psi}Y_1^{-1}$.

Proof. First, let $Y_l = P_l^{-1}$, $S_1 = \text{diag}\{S_3, Y_1, Y_1, Y_1, Y_1, I, I\}$, $S_3 = \text{diag}\{Y_1, Y_1, Y_1, Y_1, Y_1, Y_1\}$, $S_2 = \text{diag}\{S_4, Y_2, Y_2, Y_2, Y_2, I, I, I\}$, $S_4 = \text{diag}\{Y_2, Y_2, Y_2, Y_2, Y_2\}$, then pre- and post-multiply Ξ_1 in (18) with S_1, pre- and post-multiply $\bar{\Xi}_2$ in (18) with S_2, and let $\bar{F}_{lk} = Y_l F_{lk} Y_l$, $F \in \{Q, R, Z\}$, $\bar{U}_{lj} = S_{l+2} U_{lj} Y_l$, $U \in \{M, N\}$, $l \in \{1,2\}$, $k \in \{1,2\}$, $j \in \{1,2,3\}$, $X = KY_1$ and $\bar{\Psi} = Y_1 \Psi Y_1$. Then $(R_{l1}+R_{l2})^{-1} = Y_l(\bar{R}_{l1}+\bar{R}_{l2})^{-1} Y_l \geq 2\varepsilon_{1l} Y_l - \varepsilon_{1l}^2 (\bar{R}_{l1}+\bar{R}_{l2})$, $(Z_{l1} + Z_{l2})^{-1} = Y_l(\bar{Z}_{l1} + \bar{Z}_{l2})^{-1} Y_l \geq 2\varepsilon_{2l} Y_l - \varepsilon_{2l}^2 (\bar{Z}_{l1} + \bar{Z}_{l2})$. Similarly, (30) guarantees that (19) holds. Furthermore, applying the Schur complement formula, (27) and (28) can ensure that (17) holds. This proof is completed. □

Remark 2. *In contrast to the existing result [18], we use the necessary and sufficient condition for transforming nonlinear matrix inequalities into LMIs and introduce more slack matrices, so Theorem 2 is less conservative* *than Theorem 3 in [18], which means that our method makes the stability of system* (15) *easier to be guaranteed.*

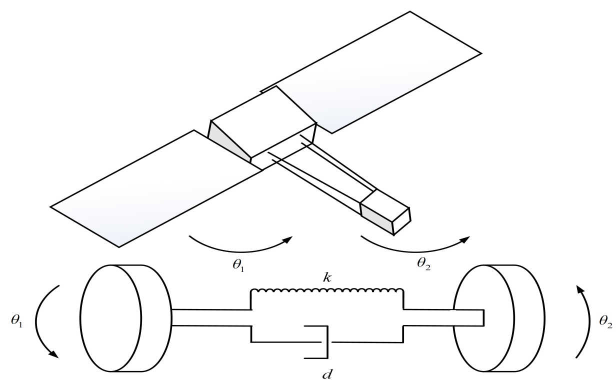

Figure 2: Structure of the satellite systems

4 An illustrative example

In this section, a satellite control system (see Figure 2) is used to illustrate the effectiveness of the proposed control strategy. The plant's state-space representation is shown by (also see [22]):

$$\dot{x}(t) = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k}{J_1} & \frac{k}{J_1} & -\frac{d}{J_1} & \frac{d}{J_1} \\ \frac{k}{J_2} & -\frac{k}{J_1} & \frac{d}{J_2} & -\frac{d}{J_2} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ \frac{1}{J_1} \\ 0 \\ 0 \end{bmatrix} u(t), \tag{31}$$

where $k = 0.09$ and $d = 0.04$ are torque constant of a spring and viscous damping in two rigid bodies (the main body and the instrumentation module), respectively, $J_1 = 1$ and $J_2 = 1$ are the moments of inertia of the two bodies. The state $x(t) = [x_1(t)\ x_2(t)\ x_3(t)\ x_4(t)] = [\theta_1(t)\ \dot{\theta}_1(t)\ \theta_2(t)\ \dot{\theta}_2(t)]$, where $\theta_1(t)$ and $\theta_2(t)$ are the yaw angles for the two bodies. Furthermore, the matrix E is chosen as $0.1I$. Let $T = 2s$, $\tilde{T} = 1.8s$, $\alpha_1 = 0.16$, $\alpha_2 = 0.5$, $\mu_1 = \mu_2 = 1.05$, $h = 0.1s$, by a simple calculation, we have $\lambda = 0.1464$, which means that (16) holds.

In the following, two schemes (ETS and RHTCS) are considered to demonstrate the effectiveness and advantage of the obtained results .

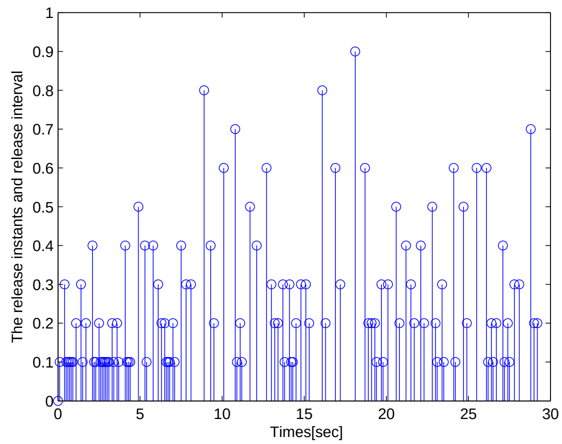

Figure 3: Release instants and intervals in Case 1

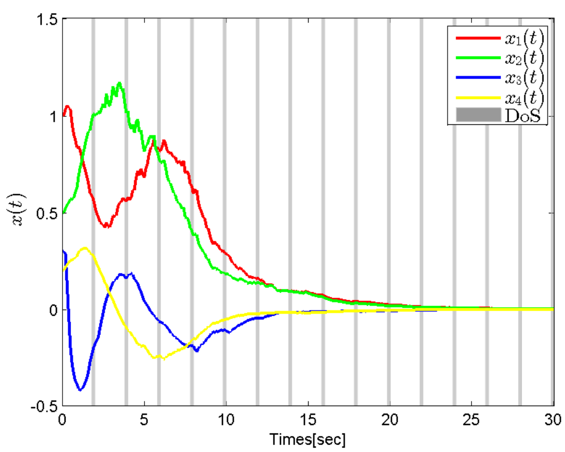

Figure 4: State responses $x(t)$ in Case 1

Scheme 1: ETS is selected, that is, $\beta(t) = 0$ for all $t \geq 0$. According to Theorem 2, the controller feedback gain of system (15) and event-triggering

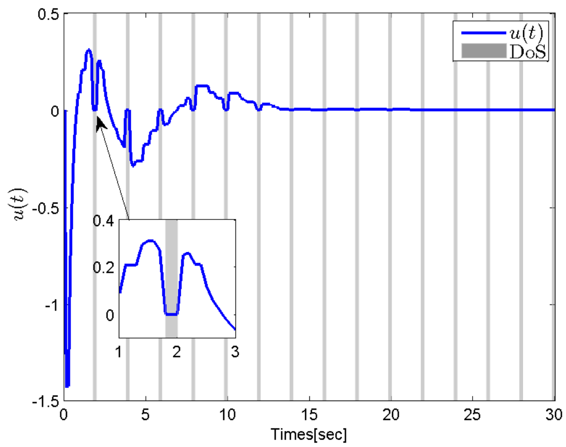

Figure 5: Control input $u(t)$ in Case 1

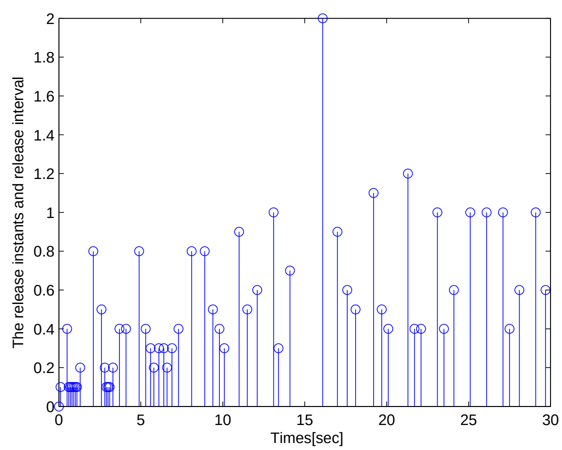

Figure 6: Release instants and intervals in Case 2

matrix under DoS jamming attacks are obtained:

$$K = \begin{bmatrix} -0.8645 & 0.4669 & -1.6018 & -0.7631 \end{bmatrix},$$

$$\Psi = 10^5 \times \begin{bmatrix} 0.7740 & -0.4238 & 1.4431 & 0.7027 \\ -0.4238 & 0.2332 & -0.7912 & -0.3855 \\ 1.4431 & -0.7912 & 2.7007 & 1.3130 \\ 0.7027 & -0.3855 & 1.3130 & 0.6497 \end{bmatrix}.$$

The response of $x(t)$, event-triggered instants and released intervals, and control input $u(t)$ are depicted in Figures 3–5, respectively. However, as shown in Table 1, the conditions of Theorem 2 in [18] cannot find a set of feasible solutions, which verifies the statement of Remark 2.

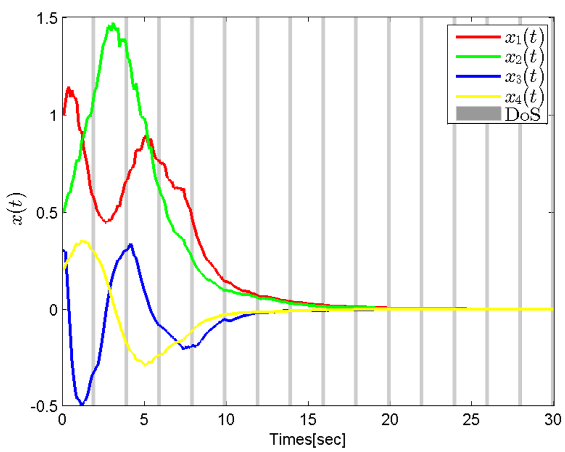

Figure 7: State responses $x(t)$ in Case 2

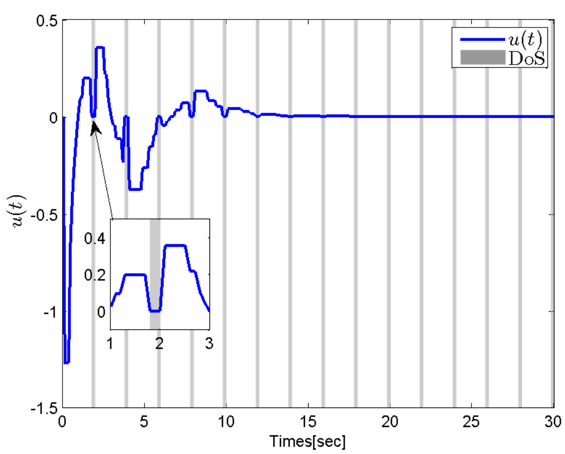

Figure 8: Control input $u(t)$ in Case 2

Scheme 2: When the trigger mechanism is selected as RHTCS, that is, $\bar{\beta} \in (0, 1)$. Let $\bar{\beta} = 0.3$, applying Theorem 2, the controller feedback gain

Table 1: Whether conditions are feasible for different parameters h.

Sample period h	0.09	0.1	0.12
Theorem 2 in [18]	feasible	-	-
Theorem 2 with $\bar{\beta} = 0$	feasible	feasible	-
Theorem 2 with $\bar{\beta} = 0.3$	feasible	feasible	feasible

and weight matrix under DoS jamming attacks are presented:

$$K = \begin{bmatrix} -1.0000 & 0.5983 & -1.9303 & -0.7077 \end{bmatrix},$$

$$\Psi = 10^9 \times \begin{bmatrix} 0.2654 & -0.1601 & 0.5152 & 0.1940 \\ -0.1601 & 0.0967 & -0.3108 & -0.1170 \\ 0.5152 & -0.3108 & 1.0010 & 0.3765 \\ 0.1940 & -0.1170 & 0.3765 & 0.1426 \end{bmatrix}.$$

Figure 6 represents the graph of event-triggered instants and released intervals. The state response is depicted in Figure 7. Figure 8 gives the curves of control input $u(t)$.

Consider $h = 0.12$, and other parameters remain unchanged. As shown in Table 1, when the trigger condition is selected as ETS, we cannot find a set of feasible solutions by using Theorem 2. However, using RHTCS, we can find a set of feasible solutions to ensure that the system is stable by employing LMIs (27)-(30) in Theorem 2. This illustrates that compared with ETS, the proposed RHTCS can ensure the stability of the system more effectively. In addition, when $h = 0.1$, the number of data transmission by TTS, ETS and RHTCS are 300, 59, 112, respectively. This clearly shows that compared with TTS, the proposed RHTCS reduces the burden of network bandwidth even more. Therefore, the RHTCS achieves a trade-off between network resource and system performance.

5 Conslusion

In this paper, the controller synthesis problem for the resilient hybrid-triggering NCSs under periodic DoS jamming attacks has been solved. A resilient hybrid-triggered control strategy has been designed to achieve a trade-off between network resources and system performance. Based on the scheme, sufficient conditions have been obtained to ensure the mean-square exponential stability of the switched stochastic system. In addition, the co-design strategy of controller gain and the parameter matrix of the strategy have been given. Finally, the efficiency and advantages of the proposed scheme have been verified by a practical example.

Acknowledgment

This work is dedicated to Prof Vasile Dragan's 70th birthday, and supported by National Natural Science Foundation of China (61773131, 62003062), Australia Research Council (DP170102644), Science and Technology Research Project of Chongqing Municipal Education Commission (KJZD-M201 900801, KJQN2019 00831), Chonqqing Natural Science Foundation (cstc2020 jcyj-msxmX0077), High-level Talents Research Project of CTBU (1953013, 1956030, ZDPTTD201918).

References

[1] P. Papadimitratos, A. L. Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *IEEE Communications Magazine*, vol. 47, no. 11, pp. 84–95, 2009.

[2] P. Shi, H. Wang, and C. C. Lim, "Network-based event-triggered control for singular systems with quantizations," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 2, pp. 1230–1238, 2015.

[3] P. Shi and Q. Shen, "Cooperative control of multi-agent systems with unknown state-dependent controlling effects," *IEEE Transactions on Automation Science and Engineering*, vol. 12, no. 3, pp. 827–834, 2015.

[4] X. Lv, J. Fei, and Z. Feng, "State feedback control for uncertain networked control systems with disturbances," *International Journal of Innovative Computing, Information and Control*, vol. 13, no. 3, pp. 751–765, 2017.

[5] M. Gao, S. Jiang, and F. Pan, "Fault detection for time-delayed networked control systems with sensor saturation and randomly occurring faults," *International Journal of Innovative Computing, Information and Control*, vol. 14, no. 4, pp. 1511–1525, 2018.

[6] D. Wang, X. Mei, R. Weng, Z. Qu, and L. Zhang, "Hybrid filter design of Ffault detection for networked linear systems with variable packet

dropout rate," *IET Control Theory and Applications*, vol. 13, no. 9, pp. 1239–1245, 2019.

[7] B. Rana, I. Mohammad and N. A. Hamad, "A multi-agent system model for controlling traffic congestions", *ICIC Express Letters, Part B: Applications*, vol. 10, no. 9, pp. 841-847, 2019.

[8] M. A. Sayeed and R. Shree, "Optimizing unmanned aerial vehicle assisted data collection in cluster based wireless sensor network", *ICIC Express Letters*, vol. 13, no. 5, pp. 367-374, 2019.

[9] R. A. Gupta and M. Chow, "Networked control system: overview and research trends," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2527–2535, 2010.

[10] H. Song, P. Shi, W. Zhang, C. Lim, and L. Yu, "Distributed H_∞ estimation in sensor networks with two-channel stochastic attacks," *IEEE Transactions on Cybernetics*, vol. 50, no. 2, pp. 465–475, 2020.

[11] J. Liu, Z. Wu, D. Yue, and J. H. Park, "Stabilization of networked control systems with hybrid-driven mechanism and probabilistic cyber attacks," *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* vol. 51, no. 2, pp. 943–953, 2021.

[12] H. S. Foroush and S. Martnez, "On triggering control of single-input linear systems under pulse-width modulated DoS signals," *SIAM Journal on Control and Optimization*, vol. 54, no. 6, pp. 3084–3105, 2016.

[13] A. Lu and G. Yang, "Input-to-state stabilizing control for cyber-physical systems with multiple transmission channels under denial of service," *IEEE Transactions on Automatic Control*, vol. 63, no. 6, pp. 1813–1820, 2018.

[14] R. Ma, P. Shi, Z. Wang, and L. Wu, "Resilient filtering for cyber-physical systems under denial-of-service attacks," *International Journal of Robust and Nonlinear Control*, vol. 30, no. 5, pp. 1754–1769, 2020.

[15] S. Backhaus, R. Bent, J. Bono, R. Lee, B. Tracey, D. Wolpert, D. Xie, and Y. Yildiz, "Cyber-physical security: a game theory model of humans interacting over control systems," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 2320–2327, 2013.

[16] Y. Li, L. Shi, P. Cheng, J. Chen, and D. E. Quevedo, "Jamming attacks on remote state estimation in cyber-physical systems: a game-theoretic approach," *IEEE Transactions on Automatic Control*, vol. 60, no. 10, pp. 2831–2836, 2015.

[17] L. Wu, Y. Gao, J. Liu, and H. Li, "Event-triggered sliding mode control of stochastic systems via output feedback," *Automatica*, vol. 82, pp. 79–92, 2017.

[18] S. Hu, D. Yue, X. Xie, X. Chen, and X. Yin, "Resilient event-triggered controller synthesis of networked control systems under periodic DoS jamming attacks," *IEEE Transactions on Cybernetics*, vol. 49, no. 12, pp. 4271–4281, 2019.

[19] L. Wu, X. Su, and P. Shi, "Sliding mode control with bounded L_2-gain performance of markovian jump singular time-delay systems," *Automatica*, vol. 48, pp. 1929–1933, 2012.

[20] J. Liu, Y. Gu, X. Xie, D. Yue, and J. H. Park, "Hybrid-driven-based H_∞ control for networked cascade control systems with actuator saturations and stochastic cyber attacks," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 49, no. 12, pp. 2452–2463, 2019.

[21] E. Tian, D. Yue, and Y. Zhang, "Delay-dependent robust H_∞ control for T–S fuzzy system with interval time-varying delay," *Fuzzy Sets and Systems*, vol. 160, no. 12, pp. 1708–1719, 2009.

[22] H. Gao, T. Chen, and J. Lam, "A new delay system approach to network-based control," *Automatica*, vol. 44, no. 1, pp. 39–52, 2008.