Event-Triggered Security Output Feedback Control for Networked Interconnected Systems Subject to Cyber-Attacks

Zhou Gu, Ju H. Park, Dong Yue, *Senior Member, IEEE*, Zheng-Guang Wu, and Xiangpeng Xie

***Abstract*—This article studies the security of networked interconnected systems (NISs) subject to cyber-attacks based on a new event-triggered mechanism (ETM). NISs with spatially distributed subsystems are vulnerable to cyber-attacks. With a new concept of security control, attention is focused on designing a novel ETM together with a decentralized output feedback control (DOFC) scheme such that the NIS subject to cyber-attacks is stable in secure sense. Under the proposed ETM, the average data-releasing rate over the whole operating period can be extremely decreased, thereby reducing the burden of network bandwidth, computation, and battery-supply. Moreover, during the system with external disturbance or attack on the communication network, more transmission-events can be generated than other periods. As a result, the desired control performance can be achieved. By using stochastic analysis techniques and Lyapunov stability theory, sufficient conditions are derived to obtain both the controller gains and the parameters of the ETM. Numerical simulation of chemical reactor systems is given to illustrate the advantages and effectiveness of the proposed theories and design techniques.**

***Index Terms*—Cyber attacks, event-triggered control, networked interconnected control systems.**

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I. Introduction

INTERCONNECTED systems commonly consist of a set of coupled subsystems that are physically distributed over a wide area. It has wide applications in many areas, such as, it can be found in power systems, digital communication systems, chemical processing, and urban traffic systems. Control strategies for interconnected systems are commonly based on decentralized control. Compared to the centralized control, the decentralized control has the advantages of higher flexibility, scalability, and reliability [1]. In recent years, the decentralized control scheme has been an attractive control methodology for dealing with the complex interconnected systems (see [2], [3], and the references therein).

Rapid development in the fields of digital, communication and sensing technologies has led to the emergence of networked control systems (NCSs) [4], [5]. Large-scaled interconnected systems have a common feature of spatial distribution that makes it imperative to use the network as a communication medium. In this context, the point-to-point signal transmission from local controllers to each distributed subsystems is replaced by the communication network [6]. Most of the existing literature on NCSs assumes that the quality of service (QoS) of the communication network is good enough to ensure the NCS works in a normal condition, such as [6] and [7]. However, communication networks, potentially suffering from the safety and security issues in practice, are vulnerable to attack. Attacks from the network layer may cause severe damage to control and monitoring applications. Malicious adversaries attempt to make the network unavailable to the terminal, or change the data transmitting over the network temporarily or indefinitely, thereby deteriorating the control performance and even leading disastrous consequences. Consequently, the main objective of anti-attack control is to maintain a certain control performance of the system in the event of attacks. Recently, the issue of security control for NCSs has become an emerging topic and has attracted considerable attention. Various types of attacks are investigated in security control and filtering design areas, such as denial-of-service (DoS) attacks [8], [9], replay attacks [10], and deception attacks [11]–[13]. In [8], attention was focused on the stabilization problem for NCSs with periodic DoS jamming attacks. Amin *et al.* [14] dealt with the problem of security decisions for the system with an intermittent DoS attacks. Under replay attacks, the data transmission from the operator to the actuator is maliciously or

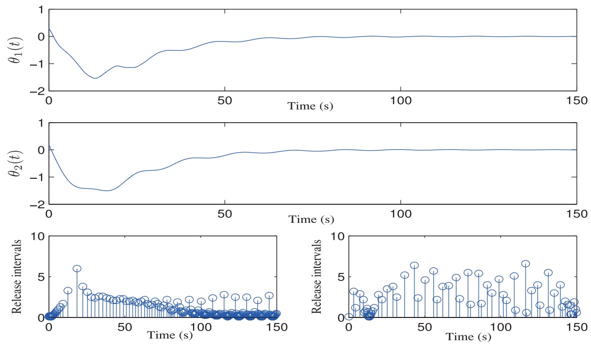

Fig. 1. State responses and data releasing sequences in [28].

fraudulently repeated.A resilient control was studied in [10] for discrete-time systems against this form of network attack. For cyber-physical systems in the presence of deception attacks, in [15] a secure state estimation based on an adaptive switched mechanism was investigated. In [16] and [17], deception attacks were modeled by norm-bounded functions that depend on the state of the system, under which resilient control was developed for NCSs and neural network systems. Distributed recursive filter against deception attacks was investigated in [18] via a gradient-based method.

Unlike a simple NCS with only one independent controller, networked interconnected system (NIS) has multiple subsystems and communication channels, which leads to a big challenge for researchers to analyze the performance of security control when the adversaries launch attacks on the network.

The control performance of an NCS with nonideal signal transmission hardly remains at the control level of the system using point-to-point connections. In recent years, there has been enormous interest in finding ways to improve the QoS of the communication network to achieve a better quality of control (QoC). Event-triggered mechanism (ETM) is a promising way in finding a balance between QoC and QoS, which has received increasing attention in NCSs and sampled-data control systems during the last decade [19]. Different from the conventional time-triggered mechanism (TTM), the control task under ETM is executed only when it is necessary for the control system, and consequently, the amount of packets released into the network is greatly reduced. Therefore, a suitable ETM for NISs can mitigate the network bandwidth.

Under ETM, the packet that violates the event-triggering condition (ETC) is identified as an important packet to the control system. Therefore, developing a suitable ETC is critical for event-trigger-based NCSs. In the existing research results, ETC is generally dependent on absolute, relative error and some other extensions. The absolute error is a difference between the values of the current data and the latest releasing data [20]; while the relative error denotes the ratio of the absolute error to the value of the latest releasing data [21]–[24]. If the error is beyond the predefined threshold, an event of data-releasing is generated. For example, in [21], a two-step design method was proposed by designing the controller first based on an assumption that the signal transmission is ideal (that is, no delay, no packet dropout), and then designing the parameters of ETC to ensure the stability of the system. Yue *et al.* [22] and Su *et al.* [25] proposed a communication scheme for a class of NCSs using TTM for data sampling and ETM for data releasing. Under unreliable links, self-triggered $\mathcal{H}_\infty$ control of networked discrete-time T–S fuzzy systems was investigated in [26]. In [27], the state estimation of multiagent agent systems with a fixed/switched topologies was studied based on a distributed event-triggered communication protocol. Zhang and Han [28] addressed the problem of decentralized ETM-based dissipative control for the system with multiple communication channels. The ETM of which the threshold depends on the bandwidth occupation was investigated for a cloud-aided active suspension control system in [29]. To make a better tradeoff between QoC and QoS, a hybrid-triggered scheme based on a random switching between TTM and ETM was introduced in [30]. Adaptive ETMs, in [31]–[33], were developed such that the generated event with a better adaption with the variation of the state.

Data releasing rate (DRR) is one of the important indicators to measure the quality of the ETM. DDR represents the ratio of the number of data-releasing to the number of data-sampling over a prescribed period. Obviously, TTM is a special case of ETM, under which the DDR is up to 100%. From the above discussion, one can know that it is an effective way to reduce the lever of DRR by using ETMs in the existing literature. Some simulation results in [28] are shown in Fig. 1. In this example, the average DRRs of nodes 1 and 2 are (237/3000) and (67/3000), respectively. Notice that the DRR of the two nodes increases as the system tends to be stable, that is to say, the controller receives more data instead during this period. Clearly, it does not fit the original design intention of ETM although the average DRR is much lower than using TTM. In fact, the controller requires more data from the controlled plant when the communication channels are attacked or the system is subject to disturbances. It is hard to fulfill this requirement by a simple ETM in the existing literature. It is still a hard task and challenge to design a resilient ETM for NCSs subject to cyber-attacks, which motives this article.

This article introduces a decentralized security output feedback control methodology and a novel ETM for a class of NISs with random cyber-attacks (RCAs). The main contributions of this article are as follows.

1) RCAs against control systems by malicious adversaries are considered. A set of random variables are introduced to characterize the behavior of attacks loaded in different communication channels.
2) A new ETM is put forward, under which the control unit can receive more information from the local subsystem to guarantee the desired control performance when the system is subjected to RCAs, while the average DRR during the whole runtime period remains a low level.
3) A decentralized security output feedback control methodology is proposed to guarantee the system is stable in secure sense.

The remainder of this article is organized as follows. The model of NISs, the ETM, the RCA, and their integration are formulated in Section II. Section III presents the design method of decentralized resilient control for NISs subject to RCA; A numerical example of a networked chemical reactor system is given in Section IV to illustrate the advantages and effectiveness of the proposed design method. Section V concludes this article.

Notation: $\mathbb{R}^n$ stands for the n-dimensional Euclidean space, $\mathbb{R}^{n\times m}$ is the set of real $n \times m$ matrices. The Euclidean vector norm is represented by $\|\cdot\|$. The matrix $R > 0$ for $R \in \mathbb{R}^{n\times n}$ means that R is real symmetric positive definite, and matrix $R < 0$ represents R is a real symmetric negative definite matrix. M^{T} represents the transpose of M. $\mathbb{E}\{\beta\}$ stands for the expectation of stochastic variable β. $\mathrm{diag}_N\{X_i\}$ represents a block diagonal matrix with N blocks on its diagonal, i.e., $\mathrm{diag}_N\{X_i\} = \mathrm{diag}\{X_1, \ldots, X_N\}$, and $\mathrm{col}_N\{x_i\}$ denotes the vector $[x_1^{\mathrm{T}}, \ldots, x_N^{\mathrm{T}}]^{\mathrm{T}}$. In a matrix, the symbol $*$ represents a symmetric term.

II. Problem Formulation

A. System Description

Consider the following interconnected systems [6]:

$$\mathbf{S} : \dot{x}(t) = Ax(t) + Bu(t) + f(t, x(t)) \tag{1}$$

which is connected by the following N subsystems:

$$\mathbf{S_i} : \begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + f_i(t, x(t)) \\ y_i(t) = C_i(t) x_i(t) \end{cases} \tag{2}$$

for $i \in \mathcal{N} \triangleq \{1, 2, \ldots, N\}$, where $x_i(t) \in \mathbb{R}^{n_i}$ ($\sum_{i=1}^N n_i = n$), $y_i(t) \in \mathbb{R}^{p_i}$ ($\sum_{i=1}^N p_i = p$) and $u_i(t) \in \mathbb{R}^{m_i}$ ($\sum_{i=1}^N m_i = m$) are the state, measured output and control input of each subsystems, respectively. $f_i(t, x(t))$ represents coupled interconnection. A_i, B_i, and C_i are known constant matrices with compatible dimensions. In (1), the state, measured output, control input, and coupled function are defined by $x(t) = \mathrm{col}_N\{x_i(t)\}$, $y(t) = \mathrm{col}_N\{y_i(t)\}$, $u(t) = \mathrm{col}_N\{u_i(t)\}$, and $f(t) = \mathrm{col}_N\{f_i(t)\}$, respectively. The matrices $A = \mathrm{diag}_N\{A_i\}$, $B = \mathrm{diag}_N\{B_i\}$, and $C = \mathrm{diag}_N\{C_i\}$. Here, we suppose $p < n$ and C is row full rank.

Assume the coupled interconnection among subsystems for $\mathbf{S_i}$ satisfies

$$||f_i(t, x(t))|| \leq \delta_i^2 ||F_i x(t)|| \tag{3}$$

where δ_i is a positive scalar and F_i is a known matrix.

Remark 1: Unlike some existing restraints on $f_i(t, x(t))$, such as in [34] and [35], $f_i(t, x(t))$, here, is related to the state of each subsystems rather than only the subsystem $\mathbf{S_i}$ itself $x_i(t)$.

B. Novel ETM

As shown in Fig. 2, the measured output of each subsystem is transmitted over the network, and then holden by zero-order hold (ZOH). Whether to transmit the current sample data or not is decided by ETM. Therefore, an evaluation is needed for each sampling data at instant $t_k h + lh$ for $l \in \mathscr{L}_k \triangleq \{0, 1, 2, \ldots, l_M\}$ after the latest releasing instant $t_k h$, where $\{t_k\}_{k=0}^{\infty}$ is a monotonically increasing subsequence, and h is a sampling period.

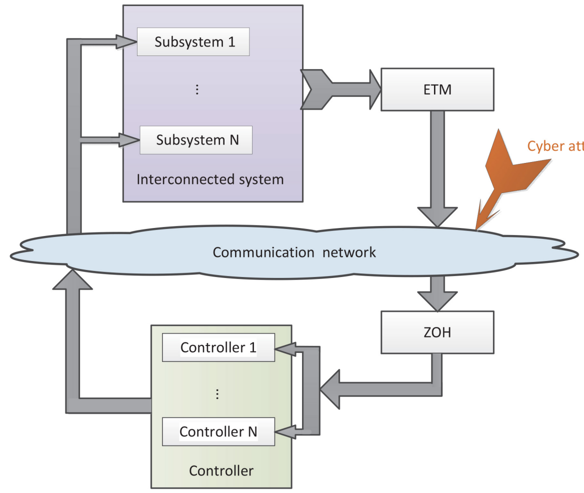

Fig. 2. Framework of networked decentralized control system.

Define $\bar{y}(t_k h, l) = (1/2)[y(t_k h) + y(t_k h + lh)]$, that is, $\bar{y}(t_k h, l)$ denotes the average value between the values of the latest released packet and the current sampling packet.

Define a set

$$\begin{aligned}\mathscr{I}_{t_k} = \Big\{ l | \varepsilon^{\mathrm{T}}(t_k, l)\bar{\Psi}\varepsilon(t_k, l) \leq \sigma\bar{y}^{\mathrm{T}}(t_k, l)\bar{\Psi}\bar{y}(t_k h, l) \\ + \varrho\sigma\big[\bar{y}^{\mathrm{T}}(t_k h, l)\bar{\Psi}\varepsilon(t_k, l) + \varepsilon^{\mathrm{T}}(t_k, l)\bar{\Psi}\bar{y}(t_k h)\big]\Big\}\end{aligned} \tag{4}$$

where $\varepsilon(t_k, l) = y(t_k h) - \bar{y}(t_k h, l)$, σ and ϱ are positive scalars, and $\bar{\Psi} > 0$ is a weighting matrix.

The next releasing instant is decided by

$$t_{k+1}h = t_k h + (l_M + 1)h \tag{5}$$

where $l_M = \max_{l \in \mathscr{I}_{t_k}} l$.

Remark 2: Different from the traditional ETC, such as in [22] and [23], here in (4), we use a mean value $\bar{y}(t_k h, l)$ to replace $y(t_k h)$. In this way, some unexpected triggering events can be avoided when there are some noise and disturbance in the measured output. In fact, it is very common in practice in signal processing by using such a median filtering approach.

Remark 3: A new item is introduced in (4). Compared to the system using the conventional ETM, more sampling packets can be transmitted over the network when the system is subject to malicious attacks or unexpected external disturbance that leads to output jitter, and consequently, a better QoC can be achieved. In the meantime, a lower average DRR can be remained throughout the runtime. These results will be demonstrated in Section IV.

Remark 4: The parameter ϱ is a weight scalar that satisfies $0 < \varrho < ([1 - \sigma]/2\sigma)$. If one sets $\varrho = 0$, the ETC in (4) reduces to a conventional one like in [22].

C. Model of Cyber-Attacks

Decentralized control is a way of physically breaking complex control problems into smaller control problems. In this article, a DOFC scheme for each subsystems is considered as follows:

$$u_i(t) = K_i y_i(t) \tag{6}$$

where K_i is the local controller gain of the subsystem $\mathbf{S}_i$ to be designed.

Remark 5: The centralized output feedback control scheme has the following form:

$$u_i^c(t) = \sum_{j=1}^{N} K_{ij} y_j(t) \tag{7}$$

which can be rewritten as

$$u_i^c(t) = \bar{K}_i y(t) \tag{8}$$

by defining $\bar{K}_i = [K_{i1}\ K_{i2}, \ldots, K_{iN}]$.

The control information transmitted over the network are vulnerable to attack. Assume the control input of the subsystem $\mathbf{S_i}$ has the following form when malicious attacks inject into the network:

$$\tilde{u}_i(t) = u_i(t_k h) + \beta_i(t) u_i^a(t_k h) \tag{9}$$

for $t \in [t_k h + \tau_k, t_{k+1} h + \tau_{k+1})$, where $u_i^a(t_k h) = a_i(t_k h) - u_i(t_k h)$, the random variable $\beta_i(t)$ with mathematical expectation $\bar{\beta}_i$ satisfies that $\beta_i(t) \in \{0, 1\}$. Here, we assume $\beta_i(t)$ and $\beta_j(t)$ are uncorrelated for $i \neq j$. $a_i(t_k h)$ denotes the attack that aims at tampering the control input at instant $t_k h$. τ_k is network induced delay that satisfies $\eta_1 \leq \tau_k \leq \bar{\tau}$. To avoid being detected from adversaries point of view, the attack is assumed to satisfy

$$\|a_i(t)\| \leq \varsigma^3 / N \tag{10}$$

where $\varsigma > 0$ is a known scalar.

Remark 6: The attack is modeled as intermittent behavior due to the following three reasons.

1) From the attacker's point of view, in general, the probability of continuous attack being detected is greater than that of random intermittent attack.
2) The attack is intercepted sometimes.
3) Since the objective of cyber-attacks is to destroy the control system, attack signals that are loaded in an abnormal manner are not always successful due to this sneaky behavior. In addition, the dropout of the attack signal may occur like a normal transmission signal.

Remark 7: In (9), $\beta_i(t)$ taking value of 1 or 0 reflects whether the packet transmitting through the ith communication channel is injected false data or not. For NISs, the probability of each subsystem being attacked is different. Therefore, a series of random variables governed by Bernoulli distribution is introduced to characterize the attack behavior.

From the above analysis, the control input against malicious attacks for the whole system can be rewritten as

$$\tilde{u}(t) = Ky(t_k h) + \Pi(t)[a(t_k h) - Ky(t_k h)] \tag{11}$$

where $\Pi(t) = \text{diag}_N\{\beta_i(t)\}$ and $K = \text{diag}_N\{K_i\}$.

D. Overall Model

Define $\chi_k^l \triangleq [\varsigma_k^l, \varsigma_k^{l+1})$, where $\varsigma_k^l = t_k h + lh + \tau_{t_k}^l$, $l \in \mathscr{L}_k$ and $\tau_{t_k}^l$ satisfies $\eta_1 \leq \tau_{t_k}^l \leq \bar{\tau}$. Inspired by [32], we divide the interval $[t_k h + \tau_k, t_{k+1} h + \tau_{k+1})$ into $l_M + 1$ subintervals. Let $[t_k h + \tau_k, t_{k+1} h + \tau_{k+1}) = \cup_{l=0}^{l_M} \chi_k^l$. Obviously, $\tau_{t_k}^l$ for $l = 0$ and $l = l_M + 1$ are network-induced delays τ_k and τ_{k+1}, respectively.

Remark 8: From (5), one can know that there are l_M successive packets are discarded before the next event is generated. As a consequence, $\tau_{t_k}^l$ for $l \in \mathscr{I}_{t_k}/0$ is not a real network-induced delay but an artificial delay.

Thus, the overall closed-loop NIS can be obtained by combining (1), (2), and (6) as

$$\begin{aligned}\dot{x}(t) &= Ax(t) + B(I - \Pi)Ky(t_k h) + B\Pi a(t_k h) + f(t) \\ &\quad + \sum_{i=1}^{N} \big(\bar{\beta}_i - \beta_i(t)\big) BL_i [Ky(t_k h) - a(t_k h)]\end{aligned} \tag{12}$$

where $\Pi = \mathbb{E}\{\Pi(t)\}$, and $L_i = \text{diag}\{\underbrace{0\ \cdots\ 0}_{i-1}\ I\ \underbrace{0\ \cdots\ 0}_{N-i}\}$.

For $t \in \chi_k^l$, defining $\eta(t) = t - (t_k h + lh)$ yields that

$$0 \leq \eta_1 \leq \eta(t) \leq h + \bar{\tau} \triangleq \eta_2. \tag{13}$$

Define $e(t_k h, l) = x(t_k h) - x(t_k h + lh)$, and the closed-loop NIS (12) can be transformed into the following time-delay systems:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + B(I - \Pi)KC[e(t_k h, l) + x(t - \eta(t))] \\ &\quad + B\Pi a(t_k h) + f(t) + \psi(t)\end{aligned} \tag{14}$$

for $t \in \chi_k^l$, where $\psi(t) = \sum_{i=1}^{N} (\bar{\beta}_i - \beta_i(t)) BL_i KC[e(t_k h, l) + x(t - \eta(t)) - a(t_k h)]$.

Before introducing the objective of this article, we give the definition of *stable in secure sense* first for NISs in (1) subject to RCAs.

Definition 1: Let a scalar ς be given. The NIS (1) under a class of RCAs that satisfy (10) is said to be stable in secure sense if there exist scalars $\varsigma > 0$ and $T(\varsigma, x_{t_0}, P)$, and matrix $P > 0$, such that $x(t) \in \mathcal{E}(P, \varsigma) \triangleq \{x(t) | x^{\mathrm{T}}(t) P x(t) \leq \varsigma^2\}$ for $\forall t \geq t_0 + T$.

The main objective of this article is to design the DOFC controller (6) and the ETM (5) such that the NIS (1) in the presence of RCAs is stable in secure sense.

III. Controller Design

In this section, we are going to design the controller of DOFC in (6) together with the ETM in (5) for the NIS (1) subject to RCAs. Sufficient conditions will be formulated in terms of a set of linear matrix inequalities.

For convenience to description, first, we define $\zeta(t) = [x^{\mathrm{T}}(t)\ \ x^{\mathrm{T}}(t - \eta_1)\ \ x^{\mathrm{T}}(t - \eta(t))\ \ x^{\mathrm{T}}(t - \eta_2)\ \ e^{\mathrm{T}}(t_k h, l)\ \ a^{\mathrm{T}}(t_k h)\ \ f^{\mathrm{T}}(t)]^{\mathrm{T}}$. Let $\mathscr{I}_i$ denote a compatible row-matrices with the ith block being an identity matrix and the others being zero matrices, for example, $\mathscr{I}_2 = [0\ \ I\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$. Then, we introduce the following lemmas will be applied in the subsequent design.

Lemma 1 [6]: Suppose $\eta(t) \in [\eta_1, \eta_2]$, $x(t) \in \mathbb{R}^n$ and there exist positive matrices $R_1 \in \mathbb{R}^{n \times n}$, $R_2 \in \mathbb{R}^{n \times n}$ and matrix $U \in \mathbb{R}^{n \times n}$. Then the following inequalities hold:

$$-\eta_1 \int_{t-\eta_1}^{t} \dot{x}^{\mathrm{T}}(s) R_1 \dot{x}(s) ds \leq \zeta^{\mathrm{T}}(t) \mathbf{R}_1 \zeta(t)$$

$$-(\eta_2 - \eta_1) \int_{t-\eta_2}^{t-\eta_1} \dot{x}^{\mathrm{T}}(s) R_2 \dot{x}(s) ds \leq \zeta^{\mathrm{T}}(t) \mathbf{R}_2 \zeta(t)$$

where

$$\mathbf{R}_1 = -(\mathscr{I}_1 - \mathscr{I}_2)^{\mathrm{T}} R_1 (\mathscr{I}_1 - \mathscr{I}_2)$$
$$\mathbf{R}_2 = -\begin{bmatrix} \mathscr{I}_2 - \mathscr{I}_3 \\ \mathscr{I}_3 - \mathscr{I}_4 \end{bmatrix}^{\mathrm{T}} \begin{bmatrix} R_2 & * \\ U & R_2 \end{bmatrix} \begin{bmatrix} \mathscr{I}_2 - \mathscr{I}_3 \\ \mathscr{I}_3 - \mathscr{I}_4 \end{bmatrix}.$$

Lemma 2: For some given positive constants $\eta_1, \eta_2, \varrho, \varsigma, \sigma, \bar{\beta}_i$ $(i \in \mathcal{N})$ and a matrix K, under the ETM (5), the NIS (1) with DFOC scheme in (6) is stable in secure sense, if there exist matrices $P > 0, \Psi > 0, Q_j > 0, R_j > 0$ $(j = 1, 2)$, matrix U and a positive scalar ϵ such that

$$\begin{bmatrix} \Gamma_1 & * & * \\ \mathcal{R}\mathcal{A}_1 & -\mathcal{R} & * \\ \Gamma_2 & 0 & -\Gamma_3 \end{bmatrix} < 0 \tag{15}$$

where

$$\Gamma_1 = \begin{bmatrix} \Gamma_{11} & * & * & * & * & * & * \\ R_1 & \Gamma_{22} & * & * & * & * & * \\ \Gamma_{31} & \Gamma_{32} & \Gamma_{33} & * & * & * & * \\ 0 & -U & \Gamma_{43} & \Gamma_{44} & * & * & * \\ \Gamma_{51} & 0 & \Gamma_{53} & 0 & \Gamma_{55} & * & * \\ \Gamma_{61} & 0 & 0 & 0 & 0 & -I & * \\ P & 0 & 0 & 0 & 0 & 0 & -\varsigma I \end{bmatrix}$$
$$\Gamma_{11} = PA + A^{\mathrm{T}}P + Q_1 + Q_2 - R_1 + \epsilon\delta^2 F^{\mathrm{T}}F + \varsigma P$$
$$\Gamma_{22} = -Q_1 - R_1 - R_2, \Gamma_{31} = C^{\mathrm{T}}K^{\mathrm{T}}(I - \Pi)B^{\mathrm{T}}P$$
$$\Gamma_{32} = R_2 + U, \Gamma_{33} = -2R_2 - U - U^{\mathrm{T}} + 4\sigma\Psi$$
$$\Gamma_{43} = \Gamma_{32}, \Gamma_{44} = -Q_2 - R_2, \Gamma_{51} = C^{\mathrm{T}}K^{\mathrm{T}}(I - \Pi)B^{\mathrm{T}}P$$
$$\Gamma_{53} = 2\kappa\Psi C, \Gamma_{55} = -(1 + \sigma - 2\kappa)\Psi, \Gamma_{61} = \Pi B^{\mathrm{T}}P$$
$$\mathcal{A}_1 = [A\ 0\ B(I - \Pi)KC\ 0\ B(I - \Pi)K\ B\Pi\ I]$$
$$\mathcal{A}_{2i} = [0\ 0\ BL_iKC\ 0\ BL_iK\ \ -2BL_i\ 0]$$
$$\Gamma_2 = \begin{bmatrix} \sqrt{\bar{\beta}_1(1 - \bar{\beta}_1)}\mathcal{R}\mathcal{A}_{21} \\ \vdots \\ \sqrt{\bar{\beta}_N(1 - \bar{\beta}_N)}\mathcal{R}\mathcal{A}_{2N} \end{bmatrix}$$
$$\mathcal{R} = \eta_1^2 R_1 + (\eta_2 - \eta_1)^2 R_2, \kappa = \sigma(1 + \varrho)$$
$$\Gamma_3 = \mathrm{diag}\{\underbrace{\mathcal{R}, \ldots, \mathcal{R}}_{N}\}, \Psi = C^{\mathrm{T}}\bar{\Psi}C.$$

Proof: Construct a Lyapunov–Krasovskill functional for system (14)

$$V(t) = x^{\mathrm{T}}(t)Px(t) + \sum_{i=1}^{2} \int_{t-\eta_i}^{t} x^{\mathrm{T}}(s)Q_i x(s)ds$$
$$+ \eta_1 \int_{t-\eta_1}^{t} \int_{s}^{t} \dot{x}^{\mathrm{T}}(v)R_1\dot{x}(v)dvds$$
$$+ (\eta_2 - \eta_1) \int_{t-\eta_2}^{t-\eta_1} \int_{s}^{t} \dot{x}^{\mathrm{T}}(v)R_2\dot{x}(v)dvds.$$

Notice that $\mathbb{E}\{\beta_i(t) - \bar{\beta}_i\} = 0, \mathbb{E}\{(\beta_i(t) - \bar{\beta}_i)^2\} = \bar{\beta}_i(1 - \bar{\beta}_i)$.

Along the trajectory of (14), taking mathematical expectation of the generator $\mathcal{L}V(t)$ yields that

$$\mathbb{E}\{\mathcal{L}V(t)\} = \mathbb{E}\{2x^{\mathrm{T}}(t)P\mathcal{A}_1\zeta(t) + x^{\mathrm{T}}(t)(Q_1 + Q_2)x(t)\}$$
$$- \mathbb{E}\left\{\sum_{i=1}^{2} x^{\mathrm{T}}(t - \eta_i)Q_i x(t - \eta_i)\right\}$$
$$+ \mathbb{E}\left\{\dot{x}^{\mathrm{T}}(t)\mathcal{R}\dot{x}(t) - \eta_1 \int_{t-\eta_1}^{t} \dot{x}^{\mathrm{T}}(s)R_1\dot{x}(s)ds\right\}$$
$$- \mathbb{E}\left\{(\eta_2 - \eta_1) \int_{t-\eta_2}^{t-\eta_1} \dot{x}^{\mathrm{T}}(s)R_2\dot{x}(s)ds\right\}. \tag{16}$$

Also, we have

$$\mathbb{E}\{\dot{x}^{\mathrm{T}}(t)\mathcal{R}\dot{x}(t)\} \leq \mathbb{E}\{\zeta^{\mathrm{T}}(t)\mathcal{A}_1^{\mathrm{T}}\mathcal{R}\mathcal{A}_1\zeta(t)\}$$
$$+ \mathbb{E}\left\{\sum_{i=1}^{N} \bar{\beta}_i(1 - \bar{\beta}_i)\zeta^{\mathrm{T}}(t)\mathcal{A}_{2i}^{\mathrm{T}}\mathcal{R}\mathcal{A}_{2i}\zeta(t)\right\}. \tag{17}$$

Recalling the definition of $\eta(t), \varepsilon(t_k, l), e(t_kh, l)$, and Ψ, the ETC (4) can be rewritten as the following equivalent form:

$$(1 + \sigma - 2\kappa)e^{\mathrm{T}}(t_kh, l)\Psi e(t_kh, l)$$
$$\leq 2\kappa e^{\mathrm{T}}(t_kh, l)\Psi x(t - \eta(t))$$
$$+ 2\kappa x^{\mathrm{T}}(t - \eta(t))\Psi e(t_kh, l)$$
$$+ 4\sigma x^{\mathrm{T}}(t - \eta(t))\Psi x(t - \eta(t)) \tag{18}$$

where the scalar κ and matrix Ψ are defined in Theorem 2.

Using Lemma 1 and combining (3), (16)–(18) follow that:

$$\mathbb{E}\{\mathcal{L}V(t)\} \leq \mathbb{E}\{\zeta^{\mathrm{T}}(t)(\Gamma_1 + \mathcal{A}_1^{\mathrm{T}}\mathcal{R}\mathcal{A}_1)\zeta(t)\}$$
$$+ \mathbb{E}\left\{\sum_{i=1}^{N} \zeta^{\mathrm{T}}(t)\bar{\beta}_i(1 - \bar{\beta}_i)\mathcal{A}_{2i}^{\mathrm{T}}\mathcal{R}\mathcal{A}_{2i}\zeta(t)\right\}.$$

From Definition 1, one knows that when $x(t) \in \mathcal{E}(P, \varsigma)$, the system is stable in secure sense.

For the case that $x(t) \notin \mathcal{E}(P, \varsigma)$, i.e., $x^{\mathrm{T}}(t)Px(t) > \varsigma^2$, we have

$$0 \leq x^{\mathrm{T}}(t)\varsigma Px(t) - a^{\mathrm{T}}(t_kh)a(t_kh) \tag{19}$$

in the light of (10).

Using Schur complement to (15), one can now prove that $\mathbb{E}\{\mathcal{L}V(t)\} < 0$ for the case that $x(t) \notin \mathcal{E}(P, \varsigma)$. From Definition 1, one can conclude that under the proposed DOFC strategy and the ETM, the NIS (1) subject to RCAs is stable in secure sense, and the proof is now complete. ■

Lemma 2 gives sufficient conditions to guarantee the NIS (1) is stable in secure sense when the system is under RCAs. Next, we are ready to design the gains of DOFC in (6) and the parameters of ETM in (5).

Theorem 1: For some given positive constants $\eta_1, \eta_2, \varrho, \varsigma, \sigma, \epsilon$, and $\bar{\beta}_i$ $(i \in \mathcal{N})$, under and the ETM in (5), the NIS (1) with the DOFC scheme in (6) is stable in secure sense, if there exist matrices $\tilde{\Psi} > 0, \tilde{Q}_j > 0$, and $\tilde{R}_j > 0$ $(j = 1, 2)$, matrices $Y, \tilde{U}$, and V such that

$$\Gamma = \begin{bmatrix} \tilde{\Gamma}_1 & * & * & * \\ \tilde{\mathcal{A}}_1 & -\tilde{\mathcal{R}}_0 & * & * \\ \tilde{\Gamma}_2 & 0 & -\tilde{\Gamma}_3 & * \\ \tilde{\Gamma}_4 & 0 & 0 & -\epsilon I \end{bmatrix} < 0 \tag{20}$$
$$CX = VC \tag{21}$$

where

$$\tilde{\Gamma}_1 = \begin{bmatrix} \tilde{\Gamma}_{11} & * & * & * & * & * & * \\ \tilde{R}_1 & \tilde{\Gamma}_{22} & * & * & * & * & * \\ \tilde{\Gamma}_{31} & \tilde{\Gamma}_{32} & \tilde{\Gamma}_{33} & * & * & * & * \\ 0 & -\tilde{U} & \tilde{\Gamma}_{43} & \tilde{\Gamma}_{44} & * & * & * \\ \tilde{\Gamma}_{51} & 0 & \tilde{\Gamma}_{53} & 0 & \tilde{\Gamma}_{55} & * & * \\ \tilde{\Gamma}_{61} & 0 & 0 & 0 & 0 & -I & * \\ I & 0 & 0 & 0 & 0 & 0 & -\varsigma I \end{bmatrix}$$

$$\tilde{\Gamma}_{11} = AX + XA^{\mathrm{T}} + \tilde{Q}_1 + \tilde{Q}_2 - \tilde{R}_1 + \varsigma X$$
$$\tilde{\Gamma}_{22} = -\tilde{Q}_1 - \tilde{R}_1 - \tilde{R}_2, \tilde{\Gamma}_{31} = C^{\mathrm{T}}Y^{\mathrm{T}}(I-\Pi)B^{\mathrm{T}}$$
$$\tilde{\Gamma}_{32} = \tilde{R}_2 + \tilde{U}, \tilde{\Gamma}_{33} = -2\tilde{R}_2 - \tilde{U} - \tilde{U}^{\mathrm{T}} + 4\sigma\tilde{\Psi}$$
$$\tilde{\Gamma}_{43} = \Gamma_{32}, \tilde{\Gamma}_{44} = -\tilde{Q}_2 - \tilde{R}_2, \tilde{\Gamma}_{51} = C^{\mathrm{T}}Y^{\mathrm{T}}(I-\Pi)B^{\mathrm{T}}$$
$$\tilde{\Gamma}_{53} = 2\kappa\tilde{\Psi}C, \tilde{\Gamma}_{55} = -(1+\sigma-2\kappa)\tilde{\Psi}, \tilde{\Gamma}_{61} = \Pi B^{\mathrm{T}}$$
$$\tilde{\Gamma}_4 = [\epsilon\delta FX \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$$
$$\tilde{\mathcal{A}}_1 = [AX \; 0 \; B(I-\Pi)YC \; 0 \; B(I-\Pi)YC \; B\Pi \; I]$$
$$\tilde{\mathcal{A}}_{2i} = [0 \; 0 \; BL_iYC \; 0 \; BL_iYC \; -BWL_i \; 0]$$
$$\tilde{\Gamma}_2 = \begin{bmatrix} \sqrt{\bar{\beta}_1(1-\bar{\beta}_1)}\tilde{\mathcal{A}}_{21} \\ \vdots \\ \sqrt{\bar{\beta}_N(1-\bar{\beta}_N)}\tilde{\mathcal{A}}_{2N} \end{bmatrix}, \; \kappa = \sigma(1+\rho)$$
$$\tilde{\Gamma}_3 = \mathrm{diag}\{\tilde{\mathcal{R}}_1, \ldots, \tilde{\mathcal{R}}_N\}, \; \tilde{\mathcal{R}}_i = -2\alpha_i X + \alpha_i^2\tilde{\mathcal{R}}$$

and the symbols not stated here are defined in Theorem 2. Furthermore, the gain of DOFC in (6) and the weight matrix of the ETC in (4) are given by

$$K = YV^{-1} \tag{22}$$
$$\bar{\Psi} = (CC^{\mathrm{T}})^{-1}CX^{-1}\tilde{\Psi}X^{-1}C^{\mathrm{T}}(CC^{\mathrm{T}})^{-1}. \tag{23}$$

Proof: By using Schur complement to (15), we have

$$\begin{bmatrix} \bar{\Gamma}_1 & * & * & * \\ \mathcal{R}\mathcal{A}_1 & -\mathcal{R} & * & * \\ \Gamma_2 & 0 & -\Gamma_3 & * \\ \Gamma_4 & 0 & 0 & -\epsilon I \end{bmatrix} < 0 \tag{24}$$

where $\bar{\Gamma}_1$ is the matrix Γ_1 in Lemma 2 by replacing Γ_{11} with $PA + A^{\mathrm{T}}P + Q_1 + Q_2 - R_1 + \varsigma P$, $\Gamma_4 = [\epsilon\delta F \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0]$.

Define $X = P^{-1}$, $\tilde{R}_j = XR_jX$, $\tilde{Q}_j = XQ_jX$ $(j = 1, 2)$, $\tilde{U} = XUX$, $\tilde{\Psi} = X\Psi X$, and $Y = KV$. Pre- and post-multiplying (15) with $\mathrm{diag}\{X, X, X, X, X, I, I, \mathcal{R}^{-1}, \mathscr{T}_N, I\}$ with $\mathscr{T}_N = \mathrm{diag}\{\underbrace{\mathcal{R}^{-1}, \ldots, \mathcal{R}^{-1}}_{N}\}$ and theirs transposes and combining (21), we have

$$\begin{bmatrix} \tilde{\Gamma}_1 & * & * & * \\ \tilde{\mathcal{A}}_1 & -\mathcal{R}^{-1} & * & * \\ \tilde{\Gamma}_2 & 0 & -\bar{\Gamma}_3 & * \\ \tilde{\Gamma}_4 & 0 & 0 & -\epsilon I \end{bmatrix} < 0 \tag{25}$$

where

$$\bar{\Gamma}_3 = \mathrm{diag}\left\{\underbrace{-\mathcal{R}^{-1}, \ldots, -\mathcal{R}^{-1}}_{N}\right\}.$$

For a positive scalar α_i, it is true that [36]

$$X(\alpha_i\mathcal{R} - P)\mathcal{R}^{-1}(\alpha_i\mathcal{R} - P)X \geq 0. \tag{26}$$

It follows that $-\mathcal{R}^{-1} \leq -2\alpha X + \alpha^2\tilde{\mathcal{R}}$, where $\tilde{\mathcal{R}} = \eta_1^2\tilde{R}_1 + (\eta_2 - \eta_1)^2\tilde{R}_2$. Obviously, (24) is a sufficient condition to guarantee (20) holds.

Since the matrix C is row full rank, then we have (23). The proof is completed. ■

Theorem 1 gives the conditions that guarantee the existence of the controller gains and the weight matrix of the ETM. Notice that (21) in Theorem 1 is not an LMI, therefore, we can not get a feasible solution from Theorem 1 by using LMI control toolbox. Next, we will introduce the following approach to get an approximate solution to this problem.

Theorem 2: For some given positive constants $\eta_1, \eta_2, \varrho, \varsigma, \sigma, \epsilon, \bar{\beta}_i$ $(i \in \mathcal{N})$ and an enough small positive scalar φ, under the ETM (5), the NIS (1) with the DOFC scheme (6) is stable in secure sense, if there exist matrices $\tilde{\Psi} > 0, \tilde{Q}_j > 0$, and $\tilde{R}_j > 0$ $(j = 1, 2)$, matrices $Y, \tilde{U}$, and V such that the following LMIs hold:

$$\Gamma < 0 \tag{27}$$
$$\begin{bmatrix} -\varphi I & * \\ CX - VC & -I \end{bmatrix} < 0 \tag{28}$$

where the symbols are of the same definition with these in Theorem 1. Furthermore, the gain of DOFC in (6) and the weight matrix of the ETC in (4) are given by

$$K = YV^{-1} \tag{29}$$
$$\bar{\Psi} = \left(CC^{\mathrm{T}}\right)^{-1}CX^{-1}\tilde{\Psi}X^{-1}C^{\mathrm{T}}\left(CC^{\mathrm{T}}\right)^{-1}. \tag{30}$$

Proof: Notice that (21) is equivalent to

$$\mathrm{trace}(CX - VC)^{\mathrm{T}}(CX - VC) = 0. \tag{31}$$

Assume φ is an enough small positive constant. By using Schur complement, (31) turns to be an optimization problem in (28). This completes the proof. ■

IV. Illustrative Example

In this section, we consider a chemical reactor recycle system [37] to manifest the advantages and effectiveness of our proposed method. The input to be recycled is separated from the yields for the recycling, then do the separation operation and finally travel through the pipes. As shown in Fig. 3, the chemical rector system is composed of two subsystems. Each subsystem has three reactors, i.e., (1A, 1B, 1C) and (2A, 2B, 2C).

By linearization technique, the whole system can be modeled by the following dynamics:

$$\begin{cases} \dot{C}_{1A} = -k_{1A}C_{1A} + \frac{1-R_{1B}}{V_{1A}}C_{1B} + f_1^1(C_{1,2}) \\ \dot{C}_{1B} = -k_{1B}C_{1B} + \frac{1-R_{1C}}{V_{1B}}C_{1C} + f_1^2(C_{1,2}) \\ \dot{C}_{1C} = -k_{1C}C_{1C} + \frac{R_{1A}}{V_{1C}}C_{1A} + \frac{R_{1B}}{V_{1C}}C_{1B} + \frac{G_1}{V_{1C}}u_1(t) \\ \qquad + f_1^3(C_{1,2}) \\ \dot{C}_{2A} = -k_{2A}C_{2A} + \frac{1-R_{2B}}{V_{2A}}C_{2B} + f_2^1(C_{1,2}) \\ \dot{C}_{2B} = -k_{2B}C_{2B} + \frac{1-R_{2C}}{V_{2B}}C_{2C} + f_2^2(C_{1,2}) \\ \dot{C}_{2C} = -k_{2C}C_{2C} + \frac{R_{2A}}{V_{2C}}C_{2A} + \frac{R_{2B}}{V_{2C}}C_{2B} + \frac{G_2}{V_{2C}}u_2(t) \\ \qquad + pf_2^3(C_{1,2}) \end{cases}$$

where C_{iA}, C_{iB}, and C_{iC} denote the concentration of the ith produce stream; $f_i^j(C_{1,2})$ denotes the coupled interconnection

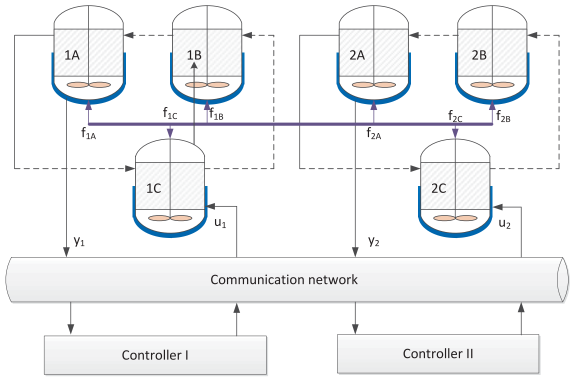

Fig. 3. Networked chemical reactor system.

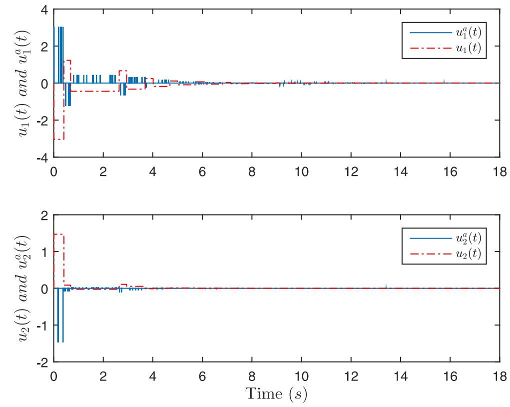

Fig. 4. Sequence of random cyber attacks laid on the NIS.

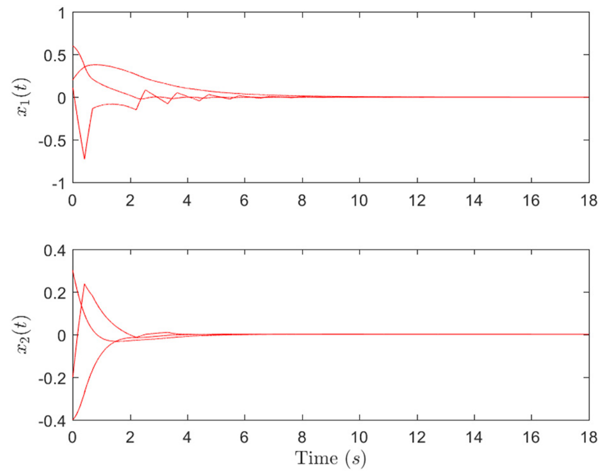

Fig. 5. State response of the each subsystem.

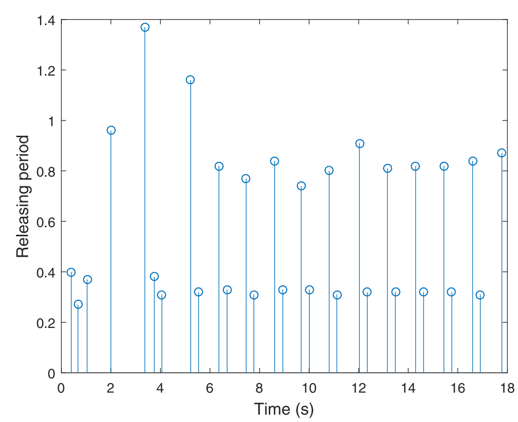

Fig. 6. Releasing period in time sequence under the ETM.

with $C_{1,2} \triangleq [C_{1A}\ C_{1B}\ C_{1C}\ C_{2A}\ C_{2B}\ C_{2C}]^{\mathrm{T}}$; R_{iA}, R_{iB}, and R_{iC} are the recycle flow rate; k_{iA}, k_{iB}, and k_{iC} are the reaction constants; G_i are the feed rates; V_{iA}, V_{iB}, and V_{iC} are the volume of the reactors for $i = 1, 2; j = 1, 2, 3$.

Choose $k_{1A} = k_{1B} = k_{1C} = 0.5, R_{1A} = R_{1B} = R_{1C} = 0.5, V_{1A} = V_{1B} = V_{1C} = 0.5$, and $k_{2A} = k_{2B} = k_{2C} = 0.8, R_{2A} = R_{2B} = R_{2C} = 0.4, V_{2A} = V_{2B} = V_{2C} = 0.6$, and $G_1 = G_2 = 0.5$.

Defining $x_i = [C_{iA}\ C_{iB}\ C_{iC}]^{\mathrm{T}}$, the subsystem $\mathbf{S_i}$ can be written in the form of (1) in which the coupled interconnection function satisfies

$$||f_i(t, x(t))|| \le 0.1^2||F_i x(t)||$$

for $i = 1, 2$ with $F_1 = \mathrm{diag}\{0.5, 0.8, 1, 0.8, 0.1, 0.2\}$ and $F_2 = \mathrm{diag}\{0.3, 0.4, 0.8, 0.4, 0.5, 0.6\}$, and the measured output of the subsystem $\mathbf{S_i}$ is

$$y_i(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \end{bmatrix} x_i(t) \quad i = 1, 2.$$

Obviously, the system is a nonself-regulating process since there are two positive poles in the system. As shown in Fig. 3, the control signal, in this article, is transmitted over a communication network. We choose the sampling period $h = 0.01$ s, and the bound of the network-induced delay are $\eta_1 = 1$ ms and $\bar{\tau} = 10$ ms. The parameters of ETM are selected as $\sigma = 0.1$ and $\varrho = 0.2$.

Suppose the system is attacked by RCAs. The probabilities of the attack on each subsystems are $\beta_1 = 0.01$ and $\bar{\beta}_2 = 0.1$, respectively, and $\varsigma = 0.1$ in (10). Fig. 4 shows the sequences of successful attacks laid on the both subsystems.

From Theorem 2, we can obtain the DOFC gains of both subsystems in (6)

$$K_1 = \begin{bmatrix} -0.5485 & -4.1833 \end{bmatrix}$$
$$K_2 = \begin{bmatrix} -0.2155 & -2.5582 \end{bmatrix}$$

and the weight matrices of ETM

$$\bar{\Psi}_1 = \begin{bmatrix} 0.0018 & 0.0011 \\ 0.0011 & 0.0520 \end{bmatrix}$$
$$\bar{\Psi}_2 = \begin{bmatrix} 0.0004 & -0.0003 \\ -0.0003 & 0.0031 \end{bmatrix}.$$

Under the attacks shown in Fig. 4, with the initial states $\phi_1(t) = [0.2\ 0.6\ 0.1]^{\mathrm{T}}$ and $\phi_2(t) = [0.3\ \ -0.4\ \ -0.2]^{\mathrm{T}}$, we can get the state response of the each subsystem by using the DOFC scheme and the ETM with the above parameters, which are depicted in Fig. 5. It can be seen that the system tends to be stable after 8 s although the system is subjected to RCAs. Owing to the proposed ETM, the sequence of data-releasing instants is depicted in Fig. 6. The average data releasing period (DRP) is computed as 0.59 s, which is larger than the sampling period $h = 0.02$ s and the average DRR is up to 1.67%. It is clear that the proposed DOFC scheme is an effective

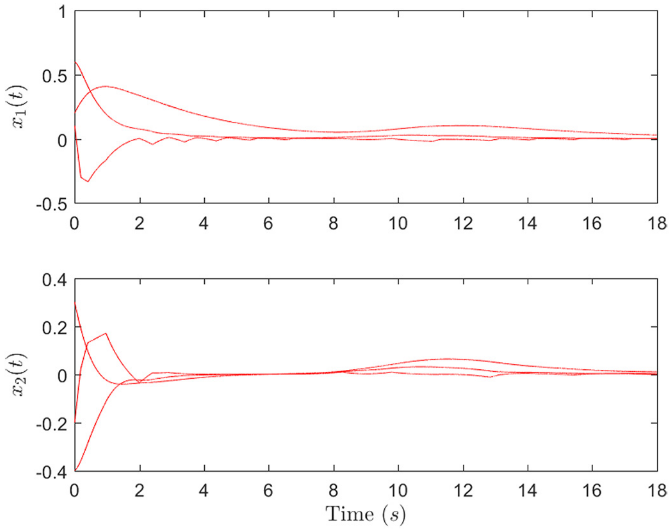

Fig. 7. State responses of the system under Case I.

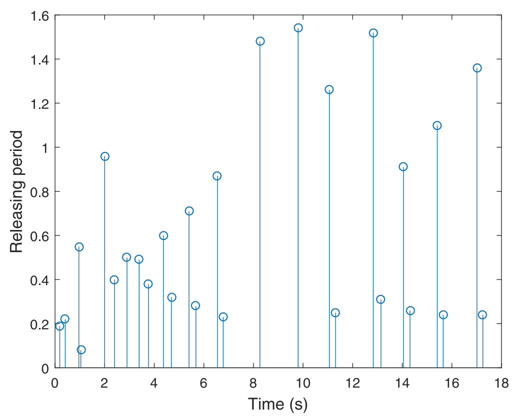

Fig. 8. Releasing period in time sequence under Case I.

approach against the cyber attacks. Moreover, a fair amount of "redundant" sampling data is rejected thanks to the proposed ETM, and accordingly, the communication and computation resources can be saved.

Next, we will further illustrate the advantages of the proposed ETM from two aspects: 1) control performance and 2) DRR. To do so, a disturbance is exerted to both the subsystems from 8 s to 12 s. Under this disturbance, we study the response of the each system under the following two cases.

Case I: The conventional ETM like in [22], that is, let $\varrho = 0$ in (4).

Case II: The proposed ETM in (5) with $\sigma = 0.1$ and $\varrho = 0.2$.

As mentioned in Remark 3, the proposed ETM (under case II) is much more sensitive to external disturbances or attacks than the conventional ETM (under case I), more sampled data are transmitted over the network being the input of the controller. One can clearly see that during 8–12 s the average releasing rate of the sampled data in Fig. 10 (using the proposed ETM) is higher than the one in Fig. 8 (using the conventional ETM).

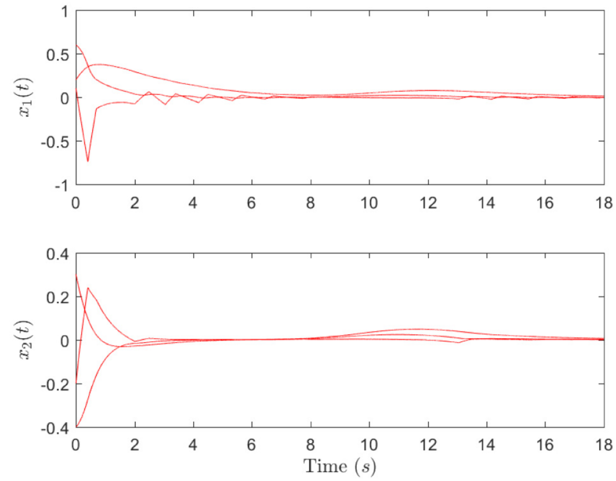

Fig. 9. State responses of the system under Case II.

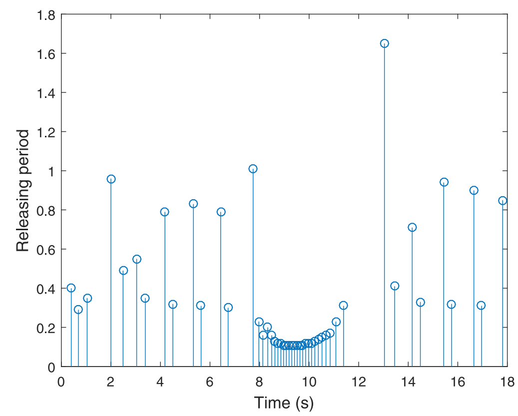

Fig. 10. Releasing period in time sequence under Case II.

It is known from the above discussion that the controller of the system with the proposed ETM receives more information from the plant in the event of external disturbance or cyber-attacks than that of the system with the conventional ETM. Therefore, a better control performance can be obtained by using the proposed ETM. Figs. 7 and 9 reveal that the system under both cases can be stabilized, however, it is noticed that the control performance of the system under case II shown in Fig. 9 is better than the one under case I shown in Fig. 7.

If one chooses a centralized control strategy as discussed in Remark 5, the controller gains and the weight matrix of the centralized ETM can also be got from Theorem 2 as follows:

$$\bar{K}_1 = \begin{bmatrix} -0.5518 & -4.1696 & -0.0037 & -0.0204 \end{bmatrix}$$
$$\bar{K}_2 = \begin{bmatrix} 0.0009 & -0.1627 & -0.2500 & -2.1851 \end{bmatrix}$$
$$\bar{\Psi} = \begin{bmatrix} 0.0022 & 0.0012 & 0 & 0 \\ 0.0012 & 0.0620 & 0 & 0.0005 \\ 0 & 0 & 0.0007 & -0.0003 \\ 0 & 0.0005 & -0.0003 & 0.0042. \end{bmatrix}$$

The state responses of the event-triggered system using the centralized output feedback control scheme is depicted in Fig. 11. Compared with the DOFC scheme, the centralized output feedback control scheme may achieve a similar results.

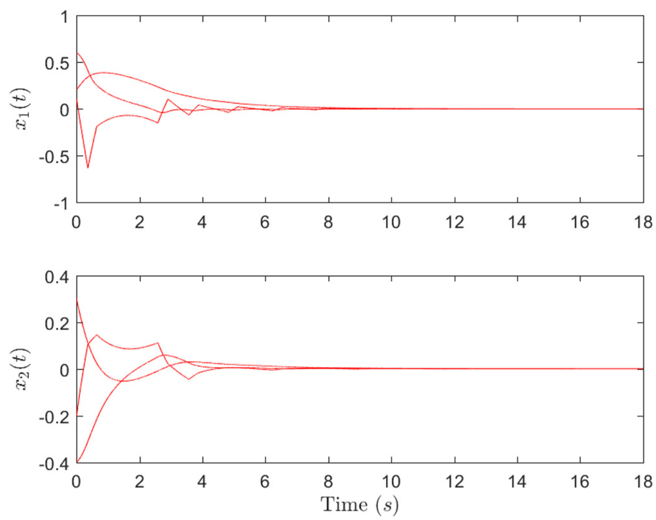

Fig. 11. State responses of the system with centralized control scheme.

However, this control strategy has poor reliability. If a communication channel is subjected to a continuous attack, the QoC of the whole system will be deteriorated. Therefore, from the perspective of security and reliability, the decentralized control strategy is better than the centralized control strategy for NISs.

V. Conclusion

This article has investigated the problem of secure control of NISs subject to RCAs in multiple channels. By using the proposed ETM, more communication and computation resources can be saved. Moreover, the DRR of the system during the attack or disturbance period is higher than that during the other period, thereby improving the security and QoC of NISs. Taking RCAs in multiple channels and ETM into account, sufficient conditions have been developed on the basis of Lyapunov stability theory to ensure NISs are stable in secure sense. An illustrative example is given to demonstrate the usefulness of the event-triggered DOFC scheme for the chemical reactor recycle system subject to RCAs.

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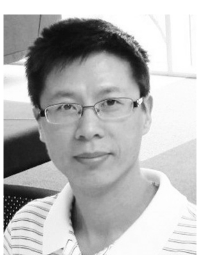

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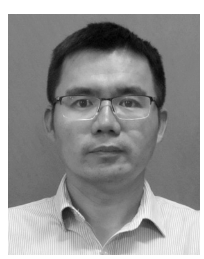

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