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Research Article

Robust H_∞ Fault Detection for Networked Control Systems with Markov Time-Delays and Data Packet Loss in Both S/C and C/A Channels

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This paper investigates the robust H∞ fault detection problem for networked control systems with Markov time-delays and data packet loss in both S/C and C/A channels. First, the time-delay from sensor to controller (S/C) and the time-delay from sensor to actuator (C/A) are described by two different Markov chains. Two random variables obeying the Bernoulli distribution are used to describe the packet loss between the sensor and the controller together between the controller and the actuator. Based on this, a fault detection filter is constructed and the closed-loop system mathematical model is established. Then, the solution method of the fault detection filter and controller gain matrix is given. The relationship between the probability of successful packet transmission and the ability to suppress external disturbance is obtained. Finally, simulation verifies the effectiveness of the proposed method.

1. Introduction

Networked control systems (NCSs) have the merits of low cost, easy expansion, and maintenance and are widely used in aerospace, telemedicine, and other fields [1, 2]. However, the introduction of the network inevitably causes time-delay, data packet loss, and other phenomena [3, 4], which makes the performance of the control system degrade and even leads to system instability. The failure analyses of NCSs are more complicated than the traditional point-to-point control system [5–7]. NCSs fault detection (FD) has received extensive attention and has achieved a lot of research results.

The networks in a typical NCS exist not only between the sensor and the controller (S/C) but also between the controller and the actuator (C/A), and both networks have time-delay and data packet loss. However, most of the existing literatures only consider time-delay or data packet loss, or only consider time-delay and data packet loss in S/C or C/A channel. The existing research results on NCSs FD could be divided into the following three categories.

The first category only considered the time-delay. For example, in literature [8], the time-delay was transformed into the system uncertainty matrix and the H_∞ state observer was designed for NCSs. In order to make a compromise between system robustness and FD sensitivity, a threshold optimization method for FD was proposed; in literature [9], for NCSs with time-delay, the control input was treated as external input to the system, and the closed-loop systems were modeled as Markov jump linear systems. The residual generator of the system was constructed, and the FD problem is transformed into the H_∞ filtering problem. The sufficient conditions for the existence of FD filter were given in the term of Linear Matrix Inequality (LMI), and the corresponding solution method was given; in literature [10], the sum of S/C delay and C/A delays was modelled as a Markov chain and closed-loop NCSs were modelled as Markov jump linear systems. The sufficient conditions for the existence of FD filter were given. The solution to the system performance optimization problem was given; in literature [11], two independent Markov chains described S/C and C/A time-delay, respectively. The H_∞ FD problem of NCSs was researched under the condition that the time-delay transition probabilities were partly unknown. The FD filter was given in the terms of matrix inequalities. The solution method of filter gain matrix was also given by the idea of cone complement linearization (CCL).

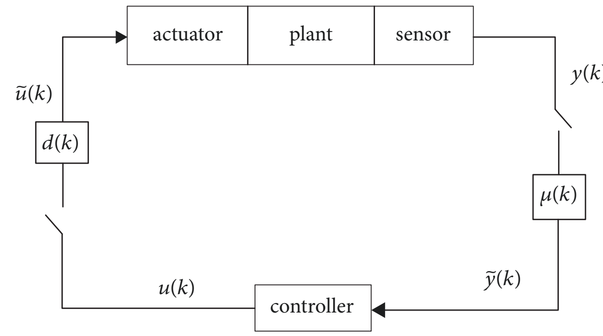

Figure 1: Structure of NCSs with time-delay and data packet loss in both S/C channel and C/A channels.

The second category only considered data packet loss. For example, considering the data packet loss in S/C and C/A channel, the problem of robust FD of NCSs in the presence of external disturbance was researched in literature [12]. The sufficient conditions for the existence of the FD filter gain matrix were given which made the error system to be mean square exponential stable and achieve the given robust H_∞ disturbance suppression level; in literature [13], considering the packet loss in S/C and C/A channels, NCSs were modeled as Markov jump systems with four different modes, and a residual generator was constructed to convert the corresponding fault detection problem into the H_∞ filtering problem. The fault detection filter was designed by using Markov jump linear system theory.

The third category only considered the time-delay and data packet loss in S/C or C/A channels. For example, the FD filter was designed in literature [14], and the FD issue was transformed to the filter design problem for the Markov jump systems with time-delay, but only the time-delay and data packet loss of the S/C channel were considered; in literature [15], for a class of networked switching control systems with short time-delay and data packet loss, an observer-based residual generator was constructed. The stability of the system was analyzed by combining the Lyapunov function method and the average dwell time method. The adaptive threshold of the fault filter was given, but, for the data packet loss, only the C/A side was considered; in literature [16], for the NCSs with short time-delay and data packet loss, the sufficient conditions for the existence of the FD filter which made the closed-loop system stable and achieve a given H_∞ attenuation performance were given in terms of LMI. Although the time-delays in S/C and C/A channels were considered, but the data packet loss in C/A channel was ignored.

In summary, the current research on NCSs FD is still not sufficient. The FD of NCSs with time-delay and data packet loss in both S/C and C/A channels needs further research which motivates our investigation. Different from the existing literature, this paper considers time-delay and data packet loss in both S/C and C/A channels. The sufficient conditions for the existence of state feedback controller and FD filter gain matrices are obtained in the form of matrix inequalities to ensure that the closed-loop systems are stochastically stable and satisfy given the H_∞ disturbance suppression level. The co-design method of the controller and fault filter is proposed.

2. Problem Formulations

The structure of the NCSs considered in this paper is shown Figure 1 where the switch closure indicates that the packet transmission is successful, and the opening indicates that the data packet loss occurs. $\mu(k)$ and $d(k)$ denote the S/C and C/A time-delay and take value from $\Upsilon = \{0, \ldots, \mu\}$, and $\Theta = \{0, \ldots, d\}$, the transition probability matrix is $G = [\lambda_{ij}]$, $H = [\pi_{rs}]$, respectively, where λ_{ij} and π_{rs} are defined as $\lambda_{ij} = \text{Prob}\{\mu(k+1) = j \mid \mu(k) = i\}$, $\pi_{rs} = \text{Prob}\{d(k+1) = s \mid d(k) = r\}$, where $\sum_{j=0}^{\mu} \lambda_{ij} = 1$, $\sum_{s=0}^{d} \pi_{rs} = 1$, $\lambda_{ij} \geq 0$, $\pi_{rs} \geq 0$.

The random variable $\alpha(k)$ and $\beta(k)$ taking value from $\{0, 1\}$ denotes the data packet loss in S/C channel and C/A channel, respectively. When the random variable takes the value of 1, it indicates that the data packet transmission is successful; otherwise, it indicates that the data packet transmission fails, and the following characteristics are satisfied:

$$\begin{aligned}
&\text{Prob}\{\alpha(k) = 1\} = E\{\alpha(k)\} = a, \\
&\text{Prob}\{\alpha(k) = 0\} = 1 - a, \\
&\text{Var}\{\alpha(k)\} = E\{(\alpha(k) - a)^2\} = (1 - a)a = b^2, \\
&\text{Prob}\{\beta(k) = 1\} = E\{\beta(k)\} = c, \\
&\text{Prob}\{\beta(k) = 0\} = 1 - c, \\
&\text{Var}\{\beta(k)\} = E\{(\beta(k) - c)^2\} = (1 - c)c = e^2.
\end{aligned}$$

The NCSs state equation can be given as follows:

$$\begin{aligned}
x(k+1) &= A_p x(k) + B_p \tilde{u}(k) + B_d d(k) + B_f f(k) \\
y(k) &= C_p x(k)
\end{aligned} \tag{1}$$

where $x(k) \in R^w$ is the state vector, $\tilde{u}(k) \in R^h$ is the control input vector, $y(k) \in R^g$ is the output vector, $d(k) \in R^p$ is the external disturbance signal with limited energy, and $f(k) \in R^q$ is the system fault signal. A_p, B_p, B_d, B_f, C_p are known real matrixes with appropriate dimensions.

Considering the time-delay and data packet loss, $\tilde{y}(k)$ and $\tilde{u}(k)$ can be described as

$$\tilde{y}(k) = \alpha(k)\, y(k-\mu(k)) \tag{2}$$

$$\tilde{u}(k) = \beta(k)\, u(k-d(k)) \tag{3}$$

The following FD filter is constructed at the controller side of the NCSs:

$$\begin{aligned} \hat{x}_{k+1} &= A_p\hat{x}(k) + B_p u(k) \\ &\quad + L\left(\tilde{y}(k) - \alpha(k)\,\hat{y}(k-\mu(k))\right) \\ \hat{y}(k) &= C_p\hat{x}(k) \\ r(k) &= V\left(\tilde{y}(k) - \alpha(k)\,\hat{y}(k-\mu(k))\right) \end{aligned} \tag{4}$$

where $\hat{x}(k) \in R^w$ is the state vector of the filter, $\hat{y}(k) \in R^g$ is the output vector of the filter, $r(k) \in R^q$ is the residual vector, V is the residual gain matrix, and L is the filter gain matrix to be determined.

Remark 1. Due to the existence of time-delay and data packet loss in C/A channel, the control input of controlled plant is $\tilde{u}(k)$ rather than that of the filter input $u(k)$, which makes the stability analyses complicated to some extent.

The following feedback control law is used:

$$u(k) = K\hat{x}(k) \tag{5}$$

The state estimation error and residual error are defined as follows:

$$e(k) = x(k) - \hat{x}(k) \tag{6}$$

$$r_e(k) = r(k) - f(k) \tag{7}$$

Define augmented vectors:

$$\begin{aligned} \phi(k) &= \left[x^T(k) \quad e^T(k)\right]^T, \\ \omega(k) &= \left[d^T(k) \quad f^T(k)\right]^T \end{aligned} \tag{8}$$

The closed-loop system equations can be obtained from (1)-(7):

$$\begin{aligned} \phi_{k+1} &= \left(A + B_1 K I_1\right)\phi(k) + \alpha(k)\, I_2 L C \phi(k-\mu(k)) \\ &\quad + \beta(k)\, B_2 K I_1 \phi(k-d(k)) + B_\omega \omega(k) \\ r_e(k) &= \alpha(k)\, V C \phi(k-\mu(k)) - I_3\omega(k) \\ \phi(k) &= \upsilon(k), \quad k \in \{-\max(\mu, d), \ldots, 0\} \end{aligned} \tag{9}$$

where

$$\begin{aligned} A &= \begin{bmatrix} A_p & 0 \\ 0 & A_p \end{bmatrix}, \\ B_1 &= \begin{bmatrix} 0 \\ -B_p \end{bmatrix}, \\ B_2 &= \begin{bmatrix} B_p \\ B_p \end{bmatrix}, \\ B_\omega &= \begin{bmatrix} B_d & B_f \\ B_d & B_f \end{bmatrix}, \\ C &= \begin{bmatrix} 0 & -C_p \end{bmatrix}, \\ I_1 &= \begin{bmatrix} I & -I \end{bmatrix} \in R^{n\times 2n}, \\ I_2 &= \begin{bmatrix} 0 \\ I \end{bmatrix} \in R^{2n\times n}, \\ I_3 &= \begin{bmatrix} 0 & I \end{bmatrix} \in R^{q\times(p+q)}. \end{aligned} \tag{10}$$

Definition 1 ([17]). For $\omega(k) = 0$, the closed-loop system (9) is stochastically stable, if for any initial condition $\phi(0)$, and any initial time-delay mode $\mu(0) \in \Upsilon$, $d(0) \in \Theta$, there exists positive-definite matrix Q such that

$$E\left\{\sum_{k=0}^{\infty} \|\phi(k)\|^2 \mid \phi(0), \mu(0), d(0)\right\} < \phi^T(0)\, Q\phi(0). \tag{11}$$

The object of this paper is to design the filter (4) and the feedback control law (5) for NCSs with time-delay and data packet loss in both S/C and C/A channels such that

(1) when $\omega(k) = 0$, system (9) is stochastically stable;

(2) under system zero initial conditions, the residual error $r_e(k)$ satisfies the following H_∞ performance:

$$E\left\{\sum_{k=0}^{\infty} r_e^T(k)\, r_e(k)\right\} \le \gamma^2 E\left\{\sum_{k=0}^{\infty} \omega^T(k)\,\omega(k)\right\} \tag{12}$$

One step of FD is the residual evaluation stage including residual evaluation function and the threshold. In this paper, the evaluation function $J(k)$ and the threshold J_{th} are selected as follows:

$$J(k) = E\left\{\sum_{\rho=l_0}^{l_0+k} \sqrt{r^T(\rho)\, r(\rho)}\right\} \tag{13}$$

$$J_{th} = \sup_{\omega(k)\in L_2, f(k)=0} E\left\{\sum_{\rho=l_0}^{l_0+L_0} \sqrt{r^T(\rho)\, r(\rho)}\right\} \tag{14}$$

where l_0 denotes the initial evaluation time instant; L_0 denotes the evaluation time steps.

The occurrence of fault can be detected by comparing $J(k)$ and J_{th}:

$$\begin{aligned} J(k) &\le J_{th} \Longrightarrow \text{alarm for fault}, \\ J(k) &> J_{th} \Longrightarrow \text{no fault}. \end{aligned} \tag{15}$$

A lemma used in this paper to deal with matrix inequalities is given as follows.

Lemma 2 ([18]). *For any positive-definite matrix R, two scalars δ, δ_0 satisfying $\delta \geq \delta_0 \geq 1$, and vector $v(l)$, one has*

$$\sum_{l=\delta_0}^{\delta} v^{\mathrm{T}}(l) R \sum_{l=\delta_0}^{\delta} v(l) \leq \widetilde{\delta} \sum_{l=\delta_0}^{\delta} v^{\mathrm{T}}(l) R v(l), \quad (16)$$

where $\widetilde{\delta} = \delta - \delta_0 + 1$.

3. Main Results

Theorem 1. *If there exist matrices K, L and positive-definite matrices $P_{i,r} > 0$, $P_{j,s} > 0$, $S_1 > 0$, $S_2 > 0$, $S_3 > 0$, $S_4 > 0$, $Z_1 > 0$, $Z_2 > 0$ such that*

$$\Phi \triangleq \begin{bmatrix} \Phi_{11} & * & * & * & * \\ \Phi_{21} & \Phi_{22} & * & * & * \\ \Phi_{31} & \Phi_{32} & \Phi_{33} & * & * \\ 0 & Z_1 & 0 & -S_1 - Z_1 & * \\ 0 & 0 & Z_2 & 0 & -S_2 - Z_2 \end{bmatrix} < 0 \quad (17)$$

where

$$\begin{aligned}
\Phi_{11} &= (A + B_1KI_1)^T \widetilde{P}_{j,s} (A + B_1KI_1) \\
&\quad + \mu^2 (A + B_1KI_1 - I)^T Z_1 (A + B_1KI_1 - I) \\
&\quad + d^2 (A + B_1KI_1 - I)^T Z_2 (A + B_1KI_1 - I) \\
&\quad + S_1 + S_2 + (\mu + 1) S_3 + (d + 1) S_4 - Z_1 \\
&\quad - Z_2 - P_{i,r}, \\
\Phi_{21} &= (aI_2LC)^T \widetilde{P}_{j,s} (A + B_1KI_1) \\
&\quad + \mu^2 (aI_2LC)^T Z_1 (A + B_1KI_1 - I) \\
&\quad + d^2 (aI_2LC)^T Z_2 (A + B_1KI_1 - I) + Z_1, \\
\Phi_{22} &= (a^2 + b^2)(I_2LC)^T \widetilde{P}_{j,s} I_2LC) \\
&\quad + \mu^2 (a^2 + b^2)(I_2LC)^T Z_1 I_2LC \\
&\quad + d^2 (a^2 + b^2)(I_2LC)^T Z_2 I_2LC) - S_3 \\
&\quad - 2Z_1, \\
\Phi_{31} &= (cB_2KI_1)^T \widetilde{P}_{j,s} (A + B_1KI_1) \\
&\quad + \mu^2 (cB_2KI_1)^T Z_1 (A + B_1KI_1 - I) \\
&\quad + d^2 (cB_2KI_1)^T Z_2 (A + B_1KI_1 - I) + Z_2, \\
\Phi_{32} &= (cB_2KI_1)^T \widetilde{P}_{j,s} (aI_2LC) \\
&\quad + \mu^2 (cB_2KI_1)^T Z_1 (aI_2LC) \\
&\quad + d^2 (cB_2KI_1)^T Z_2 (aI_2LC), \\
\Phi_{33} &= (c^2 + e^2)(B_2KI_1)^T \widetilde{P}_{j,s} (B_2KI_1) \\
&\quad + \mu^2 (c^2 + e^2)(B_2KI_1)^T Z_1 (B_2KI_1) \\
&\quad + d\mu^2 (c^2 + e^2)(B_2KI_1)^T Z_2 (B_2KI_1) - S_4 \\
&\quad - 2Z_3, \\
\widetilde{P}_{j,s} &= \sum_{j=0}^{\mu} \sum_{r=0}^{d} \lambda_{ij} \pi_{rs} P_{j,s},
\end{aligned} \quad (18)$$

holds for all $i, j \in \Upsilon$, $r, s \in \Theta$, system (9) is stochastically stable.

Proof. Let $\varphi(k) = \phi(k+1) - \phi(k)$, and construct the following Lyapunov function:

$$\begin{aligned}
V(\phi(k), \mu(k), d(k)) &\triangleq \phi^T(k) \Xi_{\mu(k),d(k)} \phi(k) \\
&= \sum_{\rho=1}^{4} V_\rho (\phi(k), \mu(k), d(k)),
\end{aligned} \quad (19)$$

where

$$\begin{aligned}
&V_1(\phi(k), \mu(k), d(k)) = \phi^T(k) P_{\mu(k),d(k)} \phi(k), \\
&V_2(\phi(k), \mu(k), d(k)) \\
&\quad = \sum_{l=k-\mu}^{k-1} \phi^T(l) S_1 \phi(l) + \sum_{l=k-d}^{k-1} \phi^T(l) S_2 \phi(l), \\
&V_3(\phi(k), \mu(k), d(k)) \\
&\quad = \sum_{l=k-\mu(k)}^{k-1} \phi^T(l) S_3 \phi(l) + \sum_{n=-\mu+1}^{0} \sum_{m=k+n}^{k-1} \phi^T(l) S_3 \phi(l) \\
&\qquad + \sum_{l=k-d(k)}^{k-1} \phi^T(l) S_4 \phi(l) \\
&\qquad + \sum_{n=-d+1}^{0} \sum_{m=k+n}^{k-1} \phi^T(l) S_4 \phi(l), \\
&V_4(\phi(k), \mu(k), d(k)) \\
&\quad = \sum_{n=-\mu+1}^{0} \sum_{m=k+n}^{k-1} \mu \varphi^T(m) Z_1 \varphi(m) \\
&\qquad + \sum_{n=-d+1}^{0} \sum_{m=k+n}^{k-1} d \varphi^T(m) Z_2 \varphi(m).
\end{aligned} \quad (20)$$

Apparently, we have $\Xi_{\mu(k),d(k)} > 0$.

$$\begin{aligned}
E\{\Delta V_1\} &= E\{\phi^T(k+1) P_{\mu(k+1),d(k+1)} \phi(k+1) \mid \mu(k) \\
&= i, d(k) = r\} - \phi^T(k) P_{\mu(k),d(k)} \phi(k)
\end{aligned}$$

$$
\begin{aligned}
&= E\Bigg\{((A+B_1KI_1)\phi(k)+aI_2LC\phi(k-\mu(k)) \\
&+(\alpha(k)-a)I_2LC\phi(k-\mu(k)) \\
&+cB_2KI_1\phi(k-d(k)) \\
&+(\beta_k-c)B_2KI_1\phi(k-d(k)))^T\sum_{j=0}^{\mu}\sum_{r=0}^{d}\lambda_{ij}\pi_{rs}P_{j,s} \\
&\cdot((A+B_1KI_1)\phi(k)+aI_2LC\phi(k-\mu(k)) \\
&+(\alpha_k-a)I_2LC\phi(k-\mu(k)) \\
&+cB_2KI_1\phi(k-d(k)) \\
&+(\beta_k-c)B_2KI_1\phi(k-d(k)))\Bigg\}-\phi^T(k)P_{i,r}\phi(k) \\
&= \phi^T(k)(A+B_1KI_1)^T\widetilde{P}_{j,s}(A+B_1KI_1)\phi(k) \\
&+\phi^T(k)(A+B_1KI_1)^T\widetilde{P}_{j,s}(aI_2LC)\phi(k-\mu(k)) \\
&+\phi^T(k)(A+B_1KI_1)^T\widetilde{P}_{j,s}(cB_2KI_1)\phi(k-d(k)) \\
&+\phi^T(k-\mu(k))(aI_2LC)^T\widetilde{P}_{j,s}(A+B_1KI_1)\phi(k) \\
&+\phi^T(k-\mu(k))(aI_2LC)^T\widetilde{P}_{j,s}(aI_2LC)\phi(k-\mu(k)) \\
&+b^2\phi^T(k-\mu(k))(I_2LC)^T\widetilde{P}_{j,s}(I_2LC)\phi(k-\mu(k)) \\
&+\phi^T(k-\mu(k))(aI_2LC)^T\widetilde{P}_{j,s}(cB_2KI_1)\phi(k \\
&-d(k))+\phi^T(k-d(k))(cB_2KI_1)^T\widetilde{P}_{j,s}(A \\
&+B_1KI_1)\phi(k)+\phi^T(k-d(k))(cB_2KI_1)^T \\
&\cdot\widetilde{P}_{j,s}(aI_2LC)\phi(k-\mu(k))+\phi^T(k-d(k)) \\
&\cdot(cB_2KI_1)^T\widetilde{P}_{j,s}(cB_2KI_1)\phi(k-d(k))+e^2\phi^T(k \\
&-d(k))(B_2KI_1)^T\widetilde{P}_{j,s}(B_2KI_1)\phi(k-d(k))-\phi^T(k) \\
&\cdot P_{i,r}\phi(k),
\end{aligned}
\tag{21}
$$

where $\widetilde{P}_{j,s}=\sum_{j=0}^{\mu}\sum_{r=0}^{d}\lambda_{ij}\pi_{rs}P_{j,s}$.

$$
\begin{aligned}
E\{\Delta V_2\} &= \phi^T(k)S_1\phi(k)-\phi^T(k-\mu)S_1\phi(k-\mu) \\
&+\phi^T(k)S_2\phi(k) \\
&-\phi^T(k-d)S_2\phi(k-d). \\
E\{\Delta V_3\} &= \phi^T(k)S_3\phi(k)-\phi^T(k-i)S_3\phi(k-i) \\
&+\sum_{l=k+1-\mu(k+1)}^{k-1}\phi^T(l)S_3\phi(l) \\
&-\sum_{l=k+1-\mu(k)}^{k-1}\phi^T(l)S_3\phi(l) \\
&+\mu\phi^T(k)S_3\phi(k)-\sum_{l=k+1-\mu}^{k}\phi^T(l)S_3\phi(l) \\
&+\phi^T(k)S_4\phi(k) \\
&-\phi^T(k-r)S_4\phi(k-r) \\
&+\sum_{l=k+1-d(k+1)}^{k-1}\phi^T(l)S_4\phi(l) \\
&-\sum_{l=k+1-d(k)}^{k-1}\phi^T(l)S_4\phi(l) \\
&+d\phi^T(k)S_4\phi(k) \\
&-\sum_{l=k+1-d}^{k}\phi^T(l)S_4\phi(l).
\end{aligned}
\tag{22}
$$

It is noticed that

$$
\begin{aligned}
&\sum_{l=k+1-\mu(k+1)}^{k-1}\phi^T(l)S_3\phi(l)+\sum_{l=k+1-d(k+1)}^{k-1}\phi^T(l)S_4\phi(l) \\
&= \sum_{l=k+1-\mu(k+1)}^{k-1}\phi^T(l)S_3\phi(l) \\
&+\sum_{l=k+1-\mu(k+1)}^{k-\mu(k)}\phi^T(l)S_3\phi(l) \\
&+\sum_{l=k+1-d(k)}^{k-1}\phi^T(l)S_4\phi(l) \\
&+\sum_{l=k+1-d(k+1)}^{k-d(k)}\phi^T(l)S_4\phi(l) \\
&\le \sum_{l=k+1-\mu(k)}^{k-1}\phi^T(l)S_3\phi(l)+\sum_{l=k+1-\mu}^{k}\phi^T(l)S_3\phi(l) \\
&+\sum_{l=k+1-d(k)}^{k-1}\phi^T(l)S_4\phi(l)+\sum_{l=k+1-d}^{k}\phi^T(l)S_4\phi(l),
\end{aligned}
\tag{23}
$$

Hence, we can get

$$
\begin{aligned}
E\{\Delta V_3\} &\le \phi^T(k)S_3\phi(k)-\phi^T(k-i)S_3\phi(k-i) \\
&+\mu\phi^T(k)S_3\phi(k)+\phi^T(k)S_4\phi(k)-\phi^T(k-r) \\
&\cdot S_4\phi(k-r)+d\phi^T(k)S_4\phi(k),
\end{aligned}
\tag{24}
$$

$$\begin{aligned}
E\{\Delta V_4\} &= E\left\{\mu^2\varphi^T(k) Z_1\varphi(k)\right\} \\
&- E\left\{\sum_{l=k-\mu}^{k-1}\tau\varphi^T(l) Z_1\varphi(l)\right\} \\
&+ E\left\{d^2\varphi^T(k) Z_2\varphi(k)\right\} \\
&- E\left\{\sum_{l=k-d}^{k-1}d\varphi^T(l) Z_2\varphi(l)\right\} = \mu^2(\phi^T(k) \\
&\cdot (A + B_1KI_1 - I)^T Z_1 (A + B_1KI_1 - I)\phi(k) \\
&+ \phi^T(k)(A + B_1KI_1 - I)^T Z_1 (aI_2LC)\phi(k - \mu(k)) \\
&+ \phi^T(k)(A + B_1KI_1 - I)^T Z_1 (cB_2KI_1) \\
&\cdot \phi(k - d(k)) + \phi^T(k - \mu(k))(aI_2LC)^T \\
&\cdot Z_1 (A + B_1KI_1 - I)\phi(k) + (a^2 + b^2) \\
&\cdot \phi^T(k - \mu(k))(I_2LC)^T Z_1 (I_2LC)\phi(k - \mu(k)) \\
&+ \phi^T(k - \mu(k))(aI_2LC)^T Z_1 (cB_2KI_1) \\
&\cdot \phi(k - d(k)) + \phi^T(k - d(k))(cB_2KI_1)^T \\
&\cdot Z_1 (A + B_1KI_1 - I)\phi(k) + \phi^T(k - d(k)) \\
&\cdot (cB_2KI_1)^T Z_1 (aI_2LC)(k - \mu(k)) + (c^2 + e^2) \\
&\cdot \phi^T(k - d(k))(B_2KI_1)^T Z_1B_2KI_1\phi(k - d(k)) \\
&+ d^2(\phi^T(k)(A + B_1KI_1 - I)^T Z_2 (A + B_1KI_1 - I) \\
&\cdot \phi(k) + \phi^T(k)(A + B_1KI_1 - I)^T Z_2 (aI_2LC) \\
&\cdot \phi(k - \mu(k)) + \phi^T(k)(A + B_1KI_1 - I)^T \\
&\cdot Z_2 (cB_2KI_1)\phi(k - d(k)) + \phi^T(k - \mu(k)) \\
&\cdot (aI_2LC)^T Z_2 (A + B_1KI_1 - I)\phi(k) + (a^2 + b^2) \\
&\cdot \phi^T(k - \mu(k))(I_2LC)^T Z_2 (I_2LC)\phi(k - \mu(k)) \\
&+ \phi^T(k - \mu(k))(aI_2LC)^T Z_2 (cB_2KI_1) \\
&\cdot \phi(k - d(k)) + \phi^T(k - d(k))(cB_2KI_1)^T \\
&\cdot Z_2 (A + B_1KI_1 - I)\phi(k) + \phi^T(k - d(k)) \\
&\cdot (cB_2KI_1)^T Z_2 (aI_2LC)\phi(k - \mu(k)) + (c^2 + e^2) \\
&\cdot \phi^T(k - d(k))(B_2KI_1)^T Z_2B_2KI_1\phi(k - d(k)) \\
&- E\left\{\sum_{l=k-\mu}^{k-1}\mu\varphi^T(l) Z_1\varphi(l)\right\} \\
&- E\left\{\sum_{l=k-d}^{k-1}d\varphi^T(l) Z_2\varphi(l)\right\}.
\end{aligned} \tag{25}$$

Since

$$\begin{aligned}
&- E\left\{\sum_{l=k-\mu}^{k-1}\mu\varphi^T(l) Z_1\varphi(l)\right\} \\
&- E\left\{\sum_{l=k-d}^{k-1}d\varphi^T(l) Z_2\varphi(l)\right\} \\
&\leq -E\left\{\sum_{l=k-i}^{k-1}i\varphi^T(l) Z_1\varphi(l)\right\} \\
&- E\left\{\sum_{l=k-\mu}^{k-i-1}(\mu - i)\varphi^T(l) Z_1\varphi(l)\right\} \\
&- E\left\{\sum_{l=k-r}^{k-1}r\varphi_l^T Z_2\varphi_l\right\} \\
&- E\left\{\sum_{l=k-d}^{k-r-1}(d - r)\varphi_l^T Z_2\varphi_l\right\}.
\end{aligned} \tag{26}$$

From Lemma 2, we can obtain

$$\begin{aligned}
&- E\left\{\sum_{l=k-i}^{k-1}i\varphi^T(l) Z_1\varphi(l)\right\} \\
&- E\left\{\sum_{l=k-\mu}^{k-i-1}(\mu - i)\varphi^T(l) Z_1\varphi(l)\right\} \\
&\leq -[\phi(k) - \phi(k - i)]^T Z_1 [\phi(k) - \phi(k - i)] \\
&- [\phi_{k-i} - \phi_{k-\mu}]^T Z_1 [\phi_{k-i} - \phi_{k-\mu}].
\end{aligned} \tag{27}$$

$$\begin{aligned}
&- \sum_{l=k-r}^{k-1}r\varphi^T(l) Z_2\varphi(l) - \sum_{l=k-d}^{k-r-1}(d - r)\varphi^T(l) Z_2\varphi(l) \\
&\leq -[\phi(k) - \phi(k - r)]^T Z_2 [\phi(k) - \phi(k - r)] \\
&- [\phi(k - r) - \phi(k - d)]^T \\
&\cdot Z_2 [\phi(k - r) - \phi(k - d)].
\end{aligned} \tag{28}$$

From (21)-(28), we can get

$$\begin{aligned}
&E\{\Delta V(\phi(k), \mu(k), d(k)) \mid \mu(k) = i, d(k) = r\} \\
&\leq \xi^T(k)\Phi\xi(k) \leq -\lambda_{\min}(-\Phi)\xi^T(k)\xi(k) \\
&\leq -\delta\|\xi(k)\|^2 \leq -\delta\|\phi(k)\|^2,
\end{aligned} \tag{29}$$

where

$$\begin{aligned}
&\xi(k) \\
&= \left[\phi^T(k)\ \ \phi^T(k - i)\ \ \phi^T(k - r)\ \ \phi^T(k - \mu)\ \ \phi^T(k - d)\right]^T, \\
&\delta = \inf\{\lambda_{\min}(-\Phi)\} > 0.
\end{aligned} \tag{30}$$

From (29), for any $T \geq 1$, we can obtain

$$
\begin{aligned}
& E\left\{\sum_{k=0}^{\infty}\|\phi(k)\|^2\right\} \\
& \quad \leq \frac{1}{\delta} E\{V(\phi(0), \mu(0), d(0))\} \\
& \qquad - \frac{1}{\delta} E\{V(\phi(T+1), \mu(T+1), d(T+1))\} \\
& \quad \leq \frac{1}{\delta} E\{V(\phi(0), \mu(0), d(0))\} \\
& \quad = \frac{1}{\delta} \phi^T(0)\, \Xi_{\mu(0), d(0)} \phi(0).
\end{aligned} \tag{31}
$$

It can be seen from Definition 1 that the closed-loop system (9) is stochastically stable which completes the proof. □

Corollary 2. *When $\omega(k) \neq 0$, if there exist matrices K, L and positive-definite matrices $P_{i,r} > 0$, $P_{j,s} > 0$, $M_{j,s} > 0$, $S_1 > 0$, $S_2 > 0$, $S_3 > 0$,$S_4 > 0$, $Z_1 > 0$, $Z_2 > 0$,$Y_1 > 0$, $Y_2 > 0$ such that*

$$
\begin{bmatrix}
\Gamma_{11} & * & * & * & * \\
\Gamma_{21} & \Gamma_{22} & * & * & * \\
\Gamma_{31} & \Gamma_{32} & \Gamma_{33} & * & * \\
\Gamma_{41} & 0 & 0 & \Gamma_{44} & * \\
\Gamma_{51} & \Gamma_{52} & 0 & 0 & -I
\end{bmatrix} < 0 \tag{32}
$$

$$
P_{j,s} M_{j,s} = I, \quad Z_l Y_l = I, \quad l \in \{1,2\} \tag{33}
$$

where

$$
\begin{aligned}
\Gamma_{11} &= \begin{bmatrix} \Lambda & * & * \\ Z_1 & -S_3 - 2Z_1 & * \\ Z_2 & 0 & -S_4 - 2Z_2 \end{bmatrix}, \\
\Gamma_{21} &= \begin{bmatrix} 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \\ 0 & 0 & 0 \end{bmatrix}, \\
\Gamma_{22} &= \begin{bmatrix} -S_1 - Z_1 & * & * \\ 0 & -S_2 - Z_2 & * \\ 0 & 0 & -\gamma^2 * I \end{bmatrix}, \\
\Gamma_{31} &= \begin{bmatrix} \mu(A + B_1 K I_1 - I) & \mu\sqrt{a^2+b^2} I_2 LC & \mu\sqrt{c^2+e^2} B_2 K I_1 \\ d(A + B_1 K I_1 - I) & d\sqrt{a^2+b^2} I_2 LC & d\sqrt{c^2+e^2} B_2 K I_1 \end{bmatrix}, \\
\Gamma_{32} &= \begin{bmatrix} 0 & 0 & B_\omega \\ 0 & 0 & B_\omega \end{bmatrix}, \\
\Gamma_{33} &= \begin{bmatrix} -Y_1 & * \\ 0 & -Y_2 \end{bmatrix}, \\
\Gamma_{41} &= \Pi \begin{bmatrix} A + B_1 K I_1 & \sqrt{a^2+b^2} I_2 LC & \sqrt{c^2+e^2} B_2 K I_1 \\ \vdots & \vdots & \vdots \\ A + B_1 K I_1 & \sqrt{a^2+b^2} I_2 LC & \sqrt{c^2+e^2} B_2 K I_1 \end{bmatrix}, \\
\Pi &= \operatorname{diag}\left\{\sqrt{\lambda_{00}\pi_{00}}, \ldots, \sqrt{\lambda_{\mu\mu}\pi_{dd}}\right\}, \\
\Gamma_{44} &= \operatorname{diag}\left\{-M_{0,0}, \ldots, -M_{\mu,d}\right\}, \\
\Gamma_{51} &= \begin{bmatrix} 0 & \sqrt{a^2+b^2} VC & 0 \end{bmatrix}, \\
\Gamma_{52} &= \begin{bmatrix} 0 & 0 & -I_3 \end{bmatrix}, \\
\Lambda &= S_1 + S_2 + (1+\mu) S_3 + (1+d) S_4 - Z_1 - Z_2 - P_{i,r},
\end{aligned} \tag{34}
$$

hold for all $i, j \in \Upsilon, r, s \in \Theta$, the closed-loop system (9) satisfies the H_∞ performance indicators shown in (12).

Proof.

$$
\begin{aligned}
& E\{V(\phi(k+1), \mu(k+1), d(k+1))\} \\
& \quad - E\{V(\phi(k), \mu(k), d(k))\} + E\left\{r_e^T(k) r_e(k)\right\} \\
& \quad - \gamma^2 E\left\{\omega^T(k)\omega(k)\right\} < \zeta^T(k) \widetilde{\Phi} \zeta(k).
\end{aligned} \tag{35}
$$

where

$$
\widetilde{\Phi} \triangleq \begin{bmatrix}
\Phi_{11} & * & * & * & * & * \\
\Phi_{21} & \widetilde{\Phi}_{22} & * & * & * & * \\
\Phi_{31} & \Phi_{32} & \Phi_{33} & * & * & * \\
0 & Z_1 & 0 & -S_1 - Z_1 & * & * \\
0 & 0 & Z_2 & 0 & -S_2 - Z_2 & * \\
0 & -I_3^T VC & 0 & 0 & 0 & \Phi_{66}
\end{bmatrix}, \tag{36}
$$

$$
\begin{aligned}
\widetilde{\Phi}_{22} &= \Phi_{22} + (VC)^T VC, \\
\Phi_{66} &= -\gamma^2 I + I_3^T I_3, \\
\varsigma(k) &= \left[\xi^T(k) \ \ \omega^T(k)\right]^T
\end{aligned}
$$

By Schur complement lemma, $\widetilde{\Phi} < 0$ is equivalent to

$$
\begin{bmatrix}
\Gamma_{11} & * & * & * & * \\
\Gamma_{21} & \Gamma_{22} & * & * & * \\
\Gamma_{31} & \Gamma_{32} & \widetilde{\Gamma}_{33} & * & * \\
\Gamma_{41} & 0 & 0 & \widetilde{\Gamma}_{44} & * \\
\Gamma_{51} & \Gamma_{52} & 0 & 0 & -I
\end{bmatrix} < 0 \tag{37}
$$

where

$$
\begin{aligned}
\widetilde{\Gamma}_{33} &= \begin{bmatrix} -Z_1 & * \\ 0 & -Z_2 \end{bmatrix}, \\
\widetilde{\Gamma}_{44} &= \operatorname{diag}\left\{-P_{0,0} \ldots - P_{\mu,d}\right\}.
\end{aligned} \tag{38}
$$

Therefore, if (37) holds, we can obtain

$$\begin{aligned} &E\{V(\phi(k+1),\mu(k+1),d(k+1))\} \\ &\quad - E\{V(\phi(k),\mu(k),d(k))\} + E\{r_e^T(k) r_e(k)\} \\ &\quad - \gamma^2 E\{\omega^T(k)\omega(k)\} < 0. \end{aligned} \tag{39}$$

Further, we can get

$$E\left\{\sum_{k=0}^{\infty} r_e^T(k) r_e(k)\right\} \le \gamma^2 E\left\{\sum_{k=0}^{\infty} \omega^T(k)\omega(k)\right\}, \tag{40}$$

which indicates that system (9) satisfies the performance index (12).

Letting $Z_1^{-1} = Y_1$, $Z_2^{-1} = Y_2$, $P_{j,s}^{-1} = M_{j,s}$, $j \in \Upsilon$, $s \in \Theta$, we can get (32) and (33) from (37).

Due to the fact that there exist nonlinear terms in the constraints of the Corollary 2, it is difficult to use the Matlab LMI toolbox directly. By use of the CCL [19, 20], it can be transformed into the following nonlinear minimization problem:

min tr$(\sum_{l=1}^{2} Z_l Y_l + \sum_{j=0}^{\mu}\sum_{s=0}^{d} P_{j,s} M_{j,s})$, s.t. (32), (41) and (42),

$$\begin{bmatrix} P_{j,s} & I \\ I & M_{j,s} \end{bmatrix} \ge 0, \quad j \in \Upsilon,\ s \in \Theta, \tag{41}$$

$$\begin{bmatrix} Z_l & * \\ I & Y_l \end{bmatrix} \ge 0, \quad l \in \{1,2\}. \tag{42}$$

Further, the algorithm for solving the controller and filter gain matrix is given.

Step 1. Given H_∞ performance index $\gamma = \gamma_0$, set the maximum number of iterations N.

Step 2. Solve equations (32), (41), and (42) and get a feasible solutions $(P_{j,s}^0, M_{j,s}^0, Z_1^0, Z_2^0, Y_1^0, Y_2^0, K^0, L^0)$, and let $k = 0$.

Step 3. Solve the following nonlinear minimization problem: min tr $(\sum_{l=1}^{2}(Z_l^k Y_l + Z_l Y_l^k) + \sum_{j=0}^{\mu}\sum_{s=0}^{d}(P_{j,s}^k M_{j,s} + P_{j,s} M_{j,s}^k))$ s.t. (32), (41), and (42), and let $(Z_1^k = Z_1, Y_1^k = Y_1, Z_2^k = Z_2, Y_2^k = Y_2, P_{j,s}^k = P_{j,s}, M_{j,s}^k = F_{j,s}, K^k = K, L^k = L)$.

Step 4. Check if (32)-(33) is satisfied: if it is satisfied letting $\gamma = \gamma - \sigma$, σ is a proper positive integer, and letting $k = k+1$, go to Step 3; if the iterations exceed N, the iteration terminates.

Step 5. Check the value of γ after the iteration is terminated: if $\gamma = \gamma_0$, then the optimization problem has no solution within the set number of iterations; otherwise $\gamma_{\min} = \gamma + \sigma$. □

Remark 3. In order not to make the conclusion too complicated, this paper assumes that the elements of the transition probability matrix of time-delays are completely known. For partially unknown case, methods of separating known or unknown elements or estimating them with related inequalities can be used (see [21] for details).

Table 1: Relationship between $\gamma_{\min}$ and data packet transmission success probability a, c.

a/c	0.4/0.5	0.5/0.6	0.6/0.7	0.7/0.8
$\gamma_{\min}$	1.0320	1.0296	1.0271	1.0262

4. Numerical Simulation

Consider the controlled plant with the following parameters:

$$\begin{aligned} A_P &= \begin{bmatrix} 0.1 & 0.3 \\ -1 & 0.8 \end{bmatrix}, \\ B_p &= \begin{bmatrix} 0.39 \\ 0.1 \end{bmatrix}, \\ B_d &= \begin{bmatrix} 0.1 \\ 0.1 \end{bmatrix}, \\ B_f &= \begin{bmatrix} 0.1 \\ 0.1 \end{bmatrix}, \\ C_P &= \begin{bmatrix} 1.5 & 0.3 \\ -0.1 & 0.4 \end{bmatrix}. \end{aligned} \tag{43}$$

Assume the S/C time-delay $\mu(k) \in \Upsilon = \{0,1\}$ and the C/A time-delay $d(k) \in \Theta = \{0,1\}$. The transition probability matrices are $G = \left[\begin{smallmatrix} 0.4 & 0.6 \\ 0.5 & 0.5 \end{smallmatrix}\right]$, $H = \left[\begin{smallmatrix} 0.3 & 0.7 \\ 0.6 & 0.4 \end{smallmatrix}\right]$. Packet transmission success probability is $E\{\alpha(k)\} = 0.8$, $E\{\beta(k)\} = 0.9$, respectively. Assume that the initial states are $x(-1) = \begin{bmatrix} 0 & 0 \end{bmatrix}^T$, $x(0) = \begin{bmatrix} 1.8 & -2 \end{bmatrix}^T$, $\hat{x}(-1) = \begin{bmatrix} 0 & 0 \end{bmatrix}^T$ and the network time-delay initial mode $\mu(0) = d(0) = 0$. One run of $\mu(k)$ and $d(k)$ can been seen in Figures 2 and 3, respectively.

Given residual gain $V = \begin{bmatrix} 0.1 & 0.1 \end{bmatrix}$, the external disturbance is a random signal with a mean of 0 and an amplitude of less than 0.01. The fault signal is

$$f(k) = \begin{cases} 5, & k = 15, \ldots, 20 \\ 0, & \end{cases} \tag{44}$$

According to Corollary 2, the filter gain, controller gain, and H_∞ minimum attenuation level are obtained as follows:

$$\begin{aligned} L &= \begin{bmatrix} -0.2500 & 0.3681 \\ -0.4412 & 0.3308 \end{bmatrix}, \\ K &= \begin{bmatrix} -0.0679 & 0.0323 \end{bmatrix}, \\ \gamma_{\min} &= 1.0247. \end{aligned} \tag{45}$$

In addition, the relationship between the probability of successful packet transmission and the minimum H_∞ attenuation level is shown in Table 1. It can be seen from the table that the greater the success probability of data packet transmission, the stronger the system disturbance suppression ability.

Select residual evaluation function as $(k) = E\{\sum_{\rho=0}^{k}\sqrt{r^T(\rho) r(\rho)}\}$, and the FD threshold can be obtained

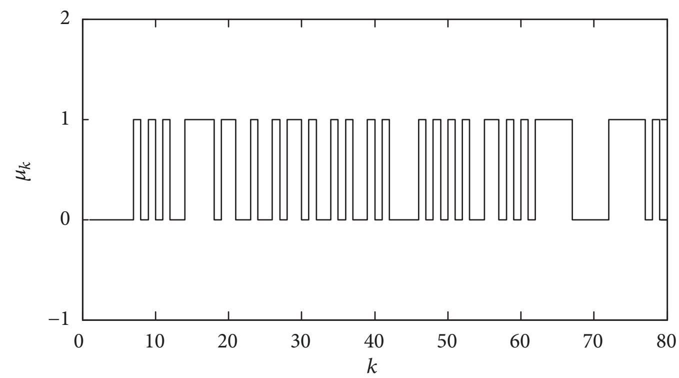

FIGURE 2: S/C time delay $\mu(k)$.

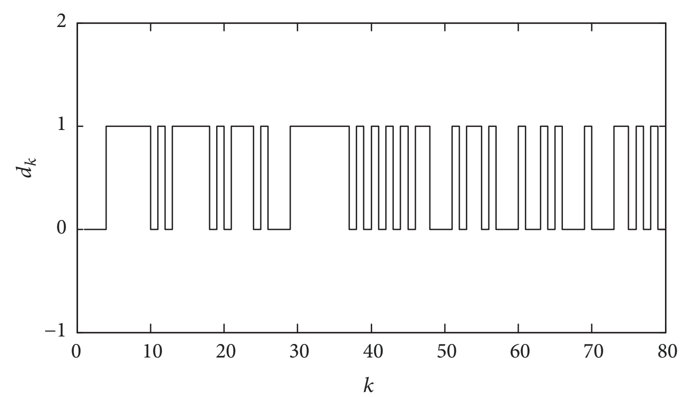

FIGURE 3: C/A time delay $d(k)$.

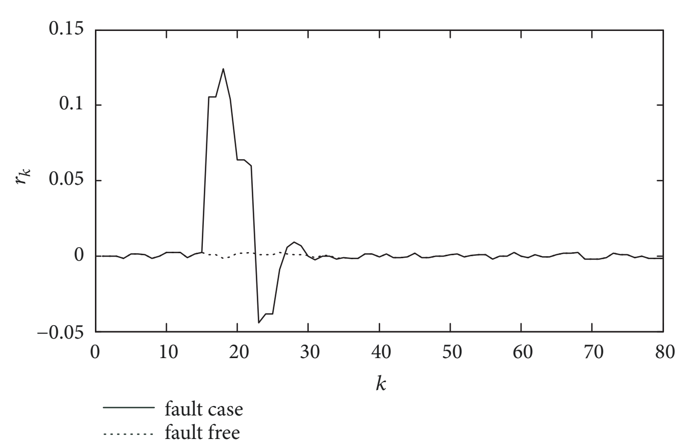

FIGURE 4: Residual signal $r(k)$.

as $J_{th} = \sup_{\omega(k)\in L_2, f(k)=0} E\{\sum_{\rho=0}^{80}\sqrt{r^T(\rho)r(\rho)}\} = 0.0870$. The residual signal $r(k)$ and residual evaluation function $J(k)$ curve are shown in Figures 4 and 5, respectively.

It can be seen from Figure 5 that the residual signal $r(k)$ and the residual evaluation function $J(k)$ change significantly when the fault occurs. Moreover, it can be obtained that $J(16) = 0.0157 < J_{th} = 0.0870 < J(17) = 0.1197$ which means that the fault detect filter detects the fault in the second time period after the fault has occurred.

5. Conclusions

In this paper, the robust H_∞ FD problem has been researched for NCSs with time-delay and data packet loss in both S/C and C/A channels. Two dependent Markov chains are used to describe the S/C time-delay and C/A time-delay, respectively. Two random variables obeying the Bernoulli distribution are exploited to describe the S/C data packet loss and C/A data packet loss, respectively. The closed-loop system model is obtained by the method of state augmentation. The sufficient

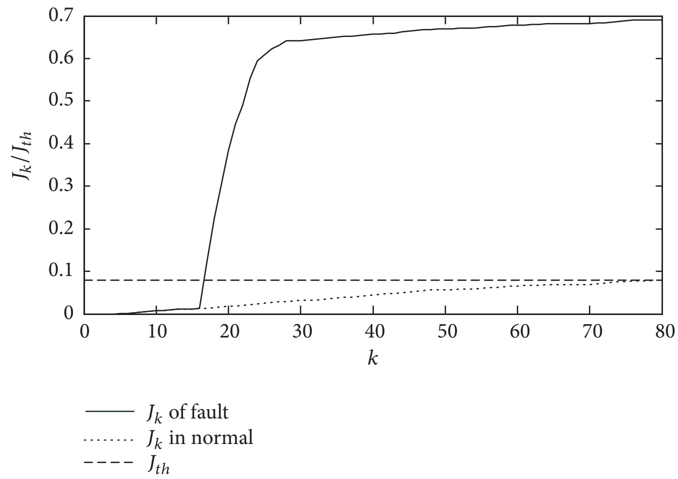

FIGURE 5: Residual evaluation function $J(k)$ and threshold J_{th}.

conditions for the stochastic stability of the closed-loop systems have been obtained by the Lyapunov Stability theory. Furthermore, the solution method of controller, fault filter gain matrix, and the minimum H∞ performance indicator is proposed by the idea of CCL. The relationship between data packet loss probability and system H_∞ performance is also given. From the simulation example we can see that the fault filter proposed in this paper can detect the fault timely and it is not only robust to the external disturbance but also sensitive to the fault.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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