International Journal of Robust and Nonlinear Control

WILEY

RESEARCH ARTICLE

Secure Observer-Assisted Fuzzy Tracking Control for Non-Linear Networked Systems With Event- and Protocol-Based Communication

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Received: 2 October 2024 | **Revised:** 3 December 2024 | **Accepted:** 4 January 2025

Funding: National Natural Science Foundation of China under Grant Nos. 62373196, 62373252, and 62273174, in part by the Natural Science Foundation of Jiangsu Province of China under Grant No. BK20230063, and in part by the Startup Foundation for Introducing Talent of NUIST under Grant No. 2024r063.

Keywords: adaptive event-triggered mechanism | deception attack | round robin protocol | Takagi-Sugeno fuzzy model | tracking control

ABSTRACT

In this paper, the secure observer-assisted Takagi-Sugeno (T-S) fuzzy tracking control issue for non-linear networked control systems (NCSs) with communication constraints is comprehensively investigated. Firstly, to deal with the limited network bandwidth, a novel two-stage data transmission scheme (TS-DTS), which employs an adaptive event-triggered mechanism (AETM) and round robin (RR) protocol, is proposed to effectively reduce bandwidth pressure as well as to avoid potential data collision. Meanwhile, considering the frequent occurrence of cyber attacks in a networked environment, deception attack that seriously threats the data integrity is particularly concerned and elaborately modeled. Then, an augmented T-S fuzzy system is constructed based on designing the framework of the observer-assisted tracking controller in aid of solving the considered problem. Subsequently, the observer and controller gains are devised with the analysis of sufficient conditions for the stability and H_∞ tracking control performance of the established system. A simulation example is finally conducted to verify the availability of the proposed T-S fuzzy tracking control approach.

1 | Introduction

Nowadays, networked control systems (NCSs) have been widely adopted in diverse applications due to their ability to cost-effectively achieve flexible and reliable control by leveraging mature communication network technologies [1]. In view of this, many research efforts have been devoted to the design and analysis of control strategies for NCSs [2]. However, the specific studies are often hindered by the non-linear characteristics presented by NCSs. Unfortunately, given the difficulties in accurately modeling system features and the complexities of the external environment, it is hard to ignore the non-linearity in practice [3]. To establish feasible control methods for non-linear NCSs, the Takagi-Sugeno (T-S) fuzzy model has attracted great research concerns as it can represent the dynamics of non-linear systems via a group of linear sub-models based on “IF-THEN” rules [4]. Actually, by further introducing membership functions (MFs), the sub-models can be properly integrated to achieve efficient linear approximation for non-linear systems [5].

Given the mentioned powerful capability of the T-S fuzzy model, lots of works with different focuses have been conducted on T-S fuzzy systems. For instance, the authors in [6] discussed the design of fuzzy security filter based on a multi-domain event-triggering strategy; quantitative sliding mode control for fuzzy systems with communication protocols was studied in [7]; taking the external disturbances into consideration, tracking control for fuzzy systems was explored in [8]. It is worth noting that tracking control is now getting significant attention due to its widespread use in practical applications, such as autonomous driving, trajectory prediction, and path positioning [9–11]. In fact, compared with traditional control problems, tracking control is more complicated since both the system stability and tracking performance should be effectively guaranteed. Therefore, it is critical and challenging to investigate tracking control issues based on the T-S fuzzy model. Although some interesting related results have been presented [12, 13], but they assume that system states can be acquired precisely which is hard to be realized. In consideration of this, designing observer-based T-S fuzzy tracking controllers is more desirable [14, 15], and which will be the primary focus of our study.

Despite that the difficulty in obtaining accurate system states can be eased by introducing an observer, the research on fuzzy tracking control for non-linear NCSs is still encumbered by network-induced imperfections, and a major one being limited network bandwidth. For mitigating the impact of bandwidth-constrained communication, event-triggered mechanism (ETM) is proposed to reduce network load by filtrating unnecessary system signals, that is, if the error between the current sampled data and latest transmitted data is less than a predefined threshold, the current signal will be viewed as unnecessary and then be discarded [16, 17]. Given the advantage of ETM, it has been widely employed in many practical scenarios, e.g., distributed computing systems [18], smart grids [19] and autonomous vehicle systems [20], to enhance system performance. We would like to note that the event-triggering threshold will significantly affect the performance of ETM. In conventional ETMs, the thresholds are set to be constant and then lack of adaptability. So, adaptive ETM (AETM), in which the event-triggering threshold is dynamically adjusted to adapt to the variation of system states, is becoming popular recently [21]. Based on AETM, some observer-assisted T-S fuzzy tracking control strategies have been proposed for bandwidth-limited NCSs. For example, the observer-based fuzzy adaptive event-triggered collaborative control issue over single-input and single-output uncertain non-linear systems was investigated in [22]; by using distributed observers, adaptive event-triggered tracking control for fuzzy multi-agent systems with input saturation was studied in [23]; an observer-based fuzzy command filtered tracking controller was developed in [24] for first-order uncertain non-linear systems with sensor faults and AETM.

As aforementioned AETM can effectively alleviate the constraint of communication resources, however, the data collision among multiple data generators at each event-triggering instant is still unavoidable under bandwidth-limited scenario [25], which will degrade system performance substantially. Towards this end, many network communication protocols, such as random access (RA) protocol [26], weighted try-once-discard (WTOD) protocol [27] and round robin (RR) protocol [28], have been introduced. In particular, the RR protocol in which competitors will be scheduled one by one in a cyclic manner is gaining prevalence owing to that it can guarantee conflict-free and fair data transmission with low implementation complexity. The practical applications of RR protocol can be found in many areas, such as resource allocation in cloud computing [29], task arrangement over multitasking systems [30] and signal scheduling for power supply systems [31]. In the literature, some RR-based control methods have also been offered for T-S fuzzy systems with limited bandwidth [32, 33]. Nevertheless, to the best of our knowledge, none of the existed works investigates fuzzy tracking control issue over RR-enabled non-linear NCSs, not to mention integrated using AETM and RR protocol to support the solving of the discussed problem. Therefore, this paper will tackle the observer-assisted tracking control problem over T-S fuzzy systems with event- and protocol-based communication.

In addition to limited communication bandwidth, stochastic cyber attack is another challenge in designing an efficient fuzzy tracking control approach. In practice, various types of cyber attacks, e.g., replay attack [34], denial-of-service (DoS) attack [35] and deception attack [36], are launched by attackers with different focuses. Among these, deception attack poses significant risks to data integrity given that they always try to replace the original signal with malicious data; moreover, the attack is difficult to be a timely detected since it can mimic the normal data pattern. Hence, the influence of deception attack will be seriously taken into account in this study. Secure fuzzy control for non-linear NCSs subject to deception attack has already attracted many interests of scholars. The authors in [37]. discussed the observer-based consistency control problem over fuzzy multi-agent systems threatened by deception attack; the adaptive security control problem for a class of non-linear multi-agent systems under deception attack was studied in [38]. However, neither of the researches shares the same objective with our work. In [39], the event-based tracking control issue over networked switched fuzzy systems was addressed under a deception attack scenario, but the proposed method can not be applied to our studied problem since that data collision and observer are not considered.

Based on the above discussion, in this paper, we will dedicate to devising a secure observer-based fuzzy tracking controller for non-linear NCSs constrained by limited network bandwidth and deception attack. The main contributions and novelties of the work are listed below.

- A novel two-stage data transmission scheme (referred to as TS-DTS), in which an AETM is employed to actively reduce network traffic load at the first stage and RR protocol is used to avoid potential data collision at the second stage, is proposed to comprehensively mitigate the influence of the limited bandwidth on tracking performance. Compared with [23, 24, 40] which adopt either AETM or communication protocol to deal with the bandwidth constraint in fuzzy tracking control, the proposed TS-DTS can not only reduce communication traffic but also enable fair and conflict-free data scheduling, so as to effectively respond to the communication limitation.
- On the basis of TS-DTS and formally describing the action of deception attack, an observer-assisted fuzzy tracking control system model is constructed to support the solving of the

studied problem. Compared to [8, 12, 13] without using an observer, the established framework can well handle the practical circumstance that the accurate system state is difficult to obtain. Moreover, differing from the existing observer-based fuzzy tracking models reported in [14, 15, 41], both communication constraint and deception attack are considered in the constructed model, which will enhance the applicability of the proposed method.

- Based on analyzing the sufficient conditions for the stochastic stability and H_∞ tracking control performance of the established system, a new fuzzy tracking control method is designed to achieve desired tracking effectiveness under the envisioned complicated scenario. Although some similar analysis frameworks have been employed in the literature [14, 42, 43], the devised method focuses on a unique analysis target, and thus different analyzing processes and outcomes are presented in this work.

The rest of the paper is organized as follows. In Section 2, the system model, proposed TS-DTS and considered deception attack are first introduced, and then the problem formulation is presented accordingly. In Section 3, sufficient conditions ensuring the stochastic stability and H_∞ tracking control performance of the envisioned T-S fuzzy system are analyzed, which is followed by the devise of the observer-assisted fuzzy tracking controller. The performance of the proposed tracking control method is verified via simulations in Section 4. Section 5 makes the conclusion of the paper.

2 | Problem Statement

In this paper, we consider a non-linear NCS described by T-S fuzzy model with s rules, and the i-th ($i = 1, 2, \dots, s$) rule is depicted as follows.

Plant Rule i: IF $\mu_1(h)$ is $\mathcal{Y}_{i1}$ and $\mu_2(h)$ is $\mathcal{Y}_{i2}$ ... and $\mu_q(h)$ is $\mathcal{Y}_{iq}$, THEN

$$\begin{aligned} x(h+1) &= A_i x(h) + B_i u(h) + E_i w(h) \\ y(h) &= C_i x(h) \end{aligned} \tag{1}$$

where $\mu_g(h)$ ($g = 1, 2, \dots, q$) are the premise variables and $\mathcal{Y}_{ig}$ are the fuzzy sets; $x(h) \in \mathbb{R}^{n_x}$, $y(h) \in \mathbb{R}^{n_y}$ and $u(h) \in \mathbb{R}^{n_u}$ denote the system state, measured output and control input, respectively; $w(h) \in \mathbb{R}^{n_\omega}$ represents the external disturbance that lies in $\mathbb{L}_2[0, \infty)$; A_i, B_i, C_i and E_i are known system matrices with compatible dimensions. Actually, given the merits of the model (1), e.g., preferable robustness, flexibility and scalability, it has been widely used to depict various non-linear psychical systems, such as transportation systems and power systems.

Denoting $\mu(h) = [\mu_1(h), \mu_2(h), \dots, \mu_q(h)]^T$ and following the weighted defuzzification process, the above introduced T-S fuzzy system can be formulated as below.

$$\begin{aligned} x(h+1) &= \sum_{i=1}^{s} v_i(\mu(h))\left[A_i x(h) + B_i u(h) + E_i w(h)\right] \\ y(h) &= \sum_{i=1}^{s} v_i(\mu(h)) C_i x(h) \end{aligned} \tag{2}$$

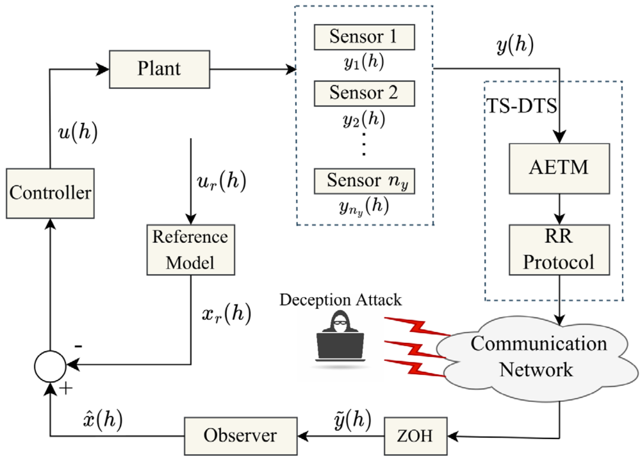

FIGURE 1 | The framework of the considered observer-assisted fuzzy tracking control system.

In (2), $v_i(\mu(h))$ refers to the standard MF which is defined as:

$$v_i(\mu(h)) = \frac{\prod_{g=1}^{q} Z_{ig}\left(\mu_g(h)\right)}{\sum_{i=1}^{s}\prod_{g=1}^{q} Z_{ig}\left(\mu_g(h)\right)} \geq 0 \tag{3}$$

where $Z_{ig}\left(\mu_g(h)\right)$ indicates the grade of membership of $\mu_g(h)$ in $\mathcal{Y}_{ig}$. Based on the definition, it is apparent that $\sum_{i=1}^{s} v_i(\mu(h)) = 1$.

On the basis of the above-described T-S fuzzy model, the framework of the considered observer-assisted fuzzy tracking control system with TS-DTS and deception attack is presented by Figure 1. As shown, the system state is assumed to be sensed by n_y sensors and then the measurement output can be specifically denoted as $y(h) = \left[y_1(h), y_2(h), \dots, y_{n_y}(h)\right]^T$, where $y_j(h)$ represents the measured signal generated by sensor j ($j = 1, 2, \dots, n_y$). The transmission of $y(h)$ will be arranged by TS-DTS, moreover, by considering the influence of deception attack and introducing a zero-order-holder (ZOH), the real input and output signals of the employed observer are denoted as $\tilde{y}(h)$ and $\hat{x}(h)$, respectively. In the tracking control system, the following reference model is adopted:

$$x_r(h+1) = A_r x_r(h) + B_r u_r(h) \tag{4}$$

where $x_r(h) \in \mathbb{R}^{n_{x_r}}$ is the reference state with a desired trajectory for $x(h)$ to follow, $u_r(h) \in \mathbb{R}^{n_{u_r}}$ is the bounded reference input; A_r and B_r are the constant matrices with appropriate dimensions. Then, the tracking controller will be devised based on $\hat{x}(h)$ and $x_r(h)$. The specific implementation of TS-DTS, constitution of $\tilde{y}(h)$ and design of the observer and controller will be introduced shortly.

2.1 | The Implementation of TS-DTS

In the proposed TS-DTS, an AETM with the following event-triggering condition is employed at the first stage.

$$\eta^T(h)\eta(h) - \sigma y^T(h)y(h) \geq \frac{1}{\theta}\epsilon(h) \tag{5}$$

where $\eta(h) = y(h) - y(t_m)$ represents the gap between the current measurement signal, that is, $y(h)$, and the latest signal that is handled to release to the network, that is, $y(t_m)$, (where $0 = t_0 < t_1 < \cdots < t_m < \cdots$ be the sequence of event-triggering instants); $\sigma \in (0, 1)$ and $\theta > 0$ are the given parameters; the positive time-varying threshold function $\epsilon(h)$ is defined as:

$$\epsilon(h+1) = \lambda\epsilon(h) + \sigma y^T(h)y(h) - \eta^T(h)\eta(h) \tag{6}$$

with the initial condition $\epsilon(0) \geq 0$ and the assumption $\lambda\theta \geq 1$ ($\lambda \in (0, 1)$ is a constant scalar). According to the AETM, it can be derived that:

$$t_{m+1} = \min_{h \in \mathbb{N}^+}\{h | h > t_m \text{ \&\& (5) is satisfied with } h\} \tag{7}$$

Remark 1. For the described AETM, if the condition presented by (5) is satisfied, then the current measurement signal $y(h)$ will be arranged to be released into the communication network, otherwise, the signal will be directly discarded. Actually, as stated by (6), the larger the value of $\eta(h)$, the smaller the value of $\epsilon(h)$ which means that the more likely the condition (5) can be triggered. It is also worth noting that the introduced AETM will reduce to a conventional static ETM while $\theta \to +\infty$.

Despite the advantage of the AETM in reducing the network traffic load, at each event-triggering instant, the measurement output composed by the information generated from n_y sensors still can not be successfully delivered due to the data collision incurred by limited communication bandwidth. In view of this, RR protocol is employed at the second stage to realize collision-free data transmission of sensors. Following the RR protocol, at event-triggering instant t_m $(m = 1, 2, \ldots)$, only one sensor is allowed to access the network so as to avoid data collision, and the index of the authorized sensor is set as:

$$f(t_m) = \ mod\ (m-1, n_y) + 1 \tag{8}$$

where *mod* denotes modulus operation. Based on the RR protocol and the introduction of ZOH, $y_j(t_m)$ can be updated as below.

$$\tilde{y}_j(t_m) = \begin{cases} y_j(t_m), & \text{if } j = f(t_m), \\ \tilde{y}_j(t_{m-1}), & \text{otherwise} \end{cases} \tag{9}$$

For simplicity, it is assumed that the measurement data generated by n_y sensors at t_0, that is, $y_j(t_0)$ $(j = 1, 2, \ldots, n_y)$, can be successfully transmitted, and then it has $\tilde{y}_j(t_0) = y_j(t_0)$.

Remark 2. As revealed by (9), the ZOH strategy is employed in the updating of the measurement signals, and then the stored most recent signals for the unscheduled sensors are used to compensate for the untransmitted data. Compared with another commonly used updating law, that is, the zero-input strategy, where the signals of the sensors that can not access the network are set to zero, the ZOH strategy can enhance the stability and robustness of the considered system by ensuring the continuity of the signal transmission [16, 25]. Certainly, additional difficulties in the subsequent design and analysis of the observer-assisted T-S fuzzy tracking controller will be induced inevitably by the ZOH strategy.

Remark 3. For the proposed TS-DTS, the AETM is first initiated, and thus only the measurement signals satisfying the condition (5) can be released. As a result, the bandwidth pressure can be effectively alleviated. Given that n_y sensors will simultaneously try to send their data to the communication network at each event-triggering instant, which will lead to data conflict due to the communication constraint, then the RR protocol depicted by (8) is activated to guarantee that only one sensor can be authorized to access the network at each event-triggering instant to avoid data collision. By seamlessly integrating the AETM and RR protocol, TS-DTS can significantly mitigate the limitation of communication bandwidth.

2.2 | Attack-Affected Measurement Signal

The presented TS-DTS can significantly reduce the negative impact of limited communication bandwidth, but it can not be neglected that the released signal $y_{f(t_m)}(t_m)$ is still affected by the deception attack. To obtain the real measurement signal that arrived at the observer, the formulation of the considered deception attack is then specifically introduced. Given the stochastic property of the deception attack, a Bernoulli variable $\alpha(h)$ with the following probability is first used to describe the occurrence of the envisioned attack.

$$\text{Prob}\{\alpha(h) = 1\} = \overline{\alpha} \quad (\text{Prob}\{\alpha(h) = 0\} = 1 - \overline{\alpha}) \tag{10}$$

Specifically, $\alpha(h) = 1$ indicates that the attack is successfully launched at time instant h, while $\alpha(h) = 0$ denotes that the released signal can be transmitted without the influence of the deception attack.

For the considered deception attack, an energy-bounded function $\phi(h) = \left[\phi_1(h), \phi_2(h), \ldots, \phi_{n_y}(h)\right]^T$ is further adopted to model the attack signal, that is, $\phi(h)$ satisfies the following condition:

$$\phi^T(h)\phi(h) \leq y^T(h)G^T G y(h) \tag{11}$$

where G is a constant matrix with a suitable dimension. Taking the above-formulated deception attack into account, the measurement signal presented in (9) can be renewed as:

$$\tilde{y}_j(t_m) = \begin{cases} y_j(t_m) + \alpha(t_m)(-y_j(t_m) + \phi_j(t_m)), & \text{if } j = f(t_m), \\ \tilde{y}_j(t_{m-1}), & \text{otherwise} \end{cases} \tag{12}$$

By introducing Kronecker delta function $\delta(\cdot) \in \{0, 1\}$, and denoting $\tilde{y}(t_m) = \left[\tilde{y}_1(t_m), \tilde{y}_2(t_m), \ldots, \tilde{y}_{n_y}(t_m)\right]^T$, it can be obtained that:

$$\begin{aligned} \tilde{y}(t_m) = {} & (1 - \alpha(t_m))\Phi_{f(t_m)} y(t_m) + (I - \Phi_{f(t_m)})\tilde{y}(t_{m-1}) \\ & + \alpha(t_m)\Phi_{f(t_m)}\phi(t_m) \end{aligned} \tag{13}$$

where $\Phi_{f(t_m)} = diag\{\delta(f(t_m) - 1), \delta(f(t_m) - 2), \ldots, \delta(f(t_m) - n_y)\}$.

Remark 4. In practice, cyber attacks often present stochasticity because of the enabling of defense mechanisms and the influence of real-time network status [44]. So the considered deception attack is assumed to be governed by a Bernoulli process. In the

Bernoulli process, the probability $\overline{\alpha}$ can be assigned based on conducting monitoring and evaluation continuously [45]. Moreover, $\phi(h)$ satisfying (11) is used to depict the behavior of the deception attack due to that the energy-bounded signal can not be detected easily, thereby enhancing the stealthiness of the attack [37].

2.3 | Design of the Observer-Assisted Fuzzy Tracking Controller

Considering the employment of ZOH, it can be achieved that $\tilde{y}(h) = \tilde{y}(t_m)$ for $h \in [t_m, t_{m+1})$ $(m = 0, 1, 2, \dots)$. Therefore, without loss of generality, the following derivation and analysis will focus on the interval $[t_m, t_{m+1})$. Then, the observer for the T-S fuzzy system is constructed as below.

Observer Rule i: IF $\mu_1(h)$ is $\mathcal{Y}_{i1}$ and $\mu_2(h)$ is $\mathcal{Y}_{i2}$ … and $\mu_q(h)$ is $\mathcal{Y}_{iq}$, THEN

$$\hat{x}(h+1) = A_i\hat{x}(h) + L_{i,f(h)}\tilde{y}(h) \tag{14}$$

where $\hat{x}(h) \in \mathbb{R}^{n_x}$ is the estimation for $x(h)$ and $f(h) = f(t_m)$; $L_{i,f(h)}$ are the observer gains which will be devised shortly. By using the standard MF $v_i(\mu(h))$, it can be derived that:

$$\hat{x}(h+1) = \sum_{i=1}^{s} v_i(\mu(h))\left[A_i\hat{x}(h) + L_{i,f(h)}\tilde{y}(h)\right] \tag{15}$$

With the assistance of the developed observer, the fuzzy tracking controller is thereby designed as:

Controller Rule p: IF $\mu_1(h)$ is $\mathcal{Y}_{p1}$ and $\mu_2(h)$ is $\mathcal{Y}_{p2}$ … and $\mu_q(h)$ is $\mathcal{Y}_{pq}$, THEN

$$u(h) = K_{p,f(h)}(\hat{x}(h) - x_r(h)) \tag{16}$$

where $K_{p,f(h)}$ are the controller gains waiting to be decided. Similarly, it can be gotten that:

$$u(h) = \sum_{p=1}^{s} v_p(\mu(h))K_{p,f(h)}(\hat{x}(h) - x_r(h)) \tag{17}$$

Based on the observer and controller, we define the observer error and tracking error as $e(h) = x(h) - \hat{x}(h)$ and $\hat{e}(h) = x(h) - x_r(h)$, respectively. Then, by substituting (17) into (2), it can be derived that:

$$\begin{aligned}
x(h+1) &= \sum_{i=1}^{s} v_i(\mu(h))[A_ix(h) + B_iu(h) + E_iw(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))\\
&\quad [A_ix(h) + B_iK_{p,f(h)}(\hat{x}(h) - x_r(h)) + E_iw(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))\\
&\quad [A_ix(h) + B_iK_{p,f(h)}\hat{e}(h) - B_iK_{p,f(h)}e(h) + E_iw(h)]
\end{aligned} \tag{18}$$

According to (15) and (18), it has:

$$\begin{aligned}
e(h+1) &= x(h+1) - \hat{x}(h+1)\\
&= \sum_{i=1}^{s} v_i(\mu(h))\left[A_ix(h) + B_iu(h) + E_iw(h)\right]\\
&\quad - \sum_{i=1}^{s} v_i(\mu(h))[A_i\hat{x}(h) + L_{i,f(h)}\tilde{y}(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))[A_i(x(h) - \hat{x}(h))\\
&\quad + B_iK_{p,f(h)}(\hat{x}(h) - x_r(h)) - L_{i,f(h)}\tilde{y}(h) + E_iw(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))\\
&\quad [A_ie(h) + B_iK_{p,f(h)}(\hat{e}(h) - e(h))\\
&\quad - L_{i,f(h)}((1 - \alpha(t_m))\Phi_{f(h)}(y(h) - \eta(h))\\
&\quad + (I - \Phi_{f(h)})\tilde{y}(t_{m-1}) + \alpha(t_m)\Phi_{f(h)}\phi(t_m)) + E_iw(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))[(A_i - B_iK_{p,f(h)})e(h)\\
&\quad + B_iK_{p,f(h)}\hat{e}(h) - (1 - \alpha(t_m))L_{i,f(h)}\Phi_{f(h)}C_ix(h)\\
&\quad - \alpha(t_m)L_{i,f(h)}\Phi_{f(h)}\phi(t_m) + (1 - \alpha(t_m))L_{i,f(h)}\\
&\quad \Phi_{f(h)}\eta(h) - L_{i,f(h)}(I - \Phi_{f(h)})\tilde{y}(t_{m-1}) + E_iw(h)]
\end{aligned} \tag{19}$$

Furthermore, based on (4) and (18), it can be obtained that:

$$\begin{aligned}
\hat{e}(h+1) &= x(h+1) - x_r(h+1)\\
&= \sum_{i=1}^{s} v_i(\mu(h))[A_ix(h) + B_iu(h) + E_iw(h)\\
&\quad - A_rx_r(h) - B_ru_r(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))\\
&\quad [A_ix(h) + B_iK_{p,f(h)}(\hat{x}(h) - x_r(h))\\
&\quad + E_iw(h) - A_rx_r(h) - B_ru_r(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))[A_i\hat{e}(h) + B_iK_{p,f(h)}(\hat{e}(h)\\
&\quad - e(h)) + (A_i - A_r)x_r(h) - B_ru_r(h) + E_iw(h)]\\
&= \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))[(A_i + B_iK_{p,f(h)})\hat{e}(h)\\
&\quad - B_iK_{p,f(h)}e(h) + (A_i - A_r)x_r(h) + E_iw(h) - B_ru_r(h)]
\end{aligned} \tag{20}$$

By summarizing up (18)–(20), the following augmented T-S fuzzy system can be constructed.

$$\begin{aligned}
\chi(h+1) = \sum_{i=1}^{s}\sum_{p=1}^{s} v_i(\mu(h))v_p(\mu(h))[(F_{1ip} + F_{2ip})\chi(h)\\
+ (\Pi_{1ip} + \Pi_{2ip})U(h)]
\end{aligned} \tag{21}$$

where

$$\chi(h) = \left[e^T(h)\ \hat{e}^T(h)\ x^T(h)\ x_r^T(h)\ \tilde{y}^T(t_{m-1})\right]^T,$$

$$U(h) = \left[w^T(h)\ u_r^T(h)\ \phi^T(t_m)\ \eta^T(h)\right]^T,$$

$$F_{1ip} = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} & -\vec{\alpha}\Gamma_{13} & 0 & -\Gamma_{14} \\ -\Gamma_{12} & \Gamma_{15} & 0 & \Gamma_{16} & 0 \\ -\Gamma_{12} & \Gamma_{12} & A_i & 0 & 0 \\ 0 & 0 & 0 & A_r & 0 \\ 0 & 0 & \vec{\alpha}\Gamma_{17} & 0 & \Gamma_{18} \end{bmatrix},$$

$$\Pi_{1ip} = \begin{bmatrix} E_i & 0 & -\vec{\alpha}L_{i,f(h)}\Phi_{f(h)} & \vec{\alpha}L_{i,f(h)}\Phi_{f(h)} \\ E_i & -B_r & 0 & 0 \\ E_i & 0 & 0 & 0 \\ 0 & B_r & 0 & 0 \\ 0 & 0 & \vec{\alpha}\Phi_{f(h)} & -\vec{\alpha}\Phi_{f(h)} \end{bmatrix}$$

$$F_{2ip} = \left[0\ 0\ R_1\ 0\ 0\right], \Pi_{2ip} = \left[0\ 0\ R_2\ R_2\right],$$

$$R_1 = \left[R_{11}^T\ 0\ 0\ 0\ R_{12}^T\right]^T, R_2 = \left[R_{21}^T\ 0\ 0\ 0\ R_{22}^T\right]^T,$$

$$\Gamma_{11} = A_i - \Gamma_{12}, \Gamma_{12} = B_i K_{p,f(h)},$$

$$\Gamma_{13} = L_{i,f(h)}\Phi_{f(h)}C_i, \Gamma_{14} = L_{i,f(h)}(I - \Phi_{f(h)}),$$

$$\Gamma_{15} = A_i + \Gamma_{12}, \Gamma_{16} = A_i - A_r,$$

$$\Gamma_{17} = \Phi_{f(h)}C_i, \Gamma_{18} = I - \Phi_{f(h)},$$

$$R_{11} = \tilde{\alpha}(t_m)L_{i,f(h)}\Phi_{f(h)}C_i, R_{12} = -\tilde{\alpha}(t_m)\Phi_{f(h)}C_i,$$

$$R_{21} = -\tilde{\alpha}(t_m)L_{i,f(h)}\Phi_{f(h)}, R_{22} = \tilde{\alpha}(t_m)\Phi_{f(h)},$$

$$\vec{\alpha} = 1 - \overline{\alpha}, \tilde{\alpha}(t_m) = \alpha(t_m) - \overline{\alpha}, f(h) = 1, 2, \ldots, n_y$$

Definition 1. ([46]) For the augmented T-S fuzzy system (21) with an initial value $\chi(0)$, under $w(h) \equiv 0$, if there exists a matrix $S > 0$ which can assure that:

$$E\left\{\sum_{h=0}^{\infty} ||\chi(h)||^2|_{\chi(0)}\right\} \leq \chi^T(0)S\chi(0)$$

then the system is stochastic stable.

Definition 2. Tseng ([47]) Given a weighting matrix Q and a predefined attenuation level γ, if the following inequality:

$$E\left\{\sum_{h=0}^{\infty} \hat{e}^T(h)Q\hat{e}(h)\right\} \leq \gamma^2 \sum_{h=0}^{\infty} \tilde{\omega}^T(h)\tilde{\omega}(h)$$

holds for all $w(h) \neq 0$, where $\tilde{\omega}(h) = \begin{bmatrix} w(h) \\ u_r(h) \end{bmatrix}$, then the H_∞ tracking control performance with the index γ of the augmented T-S fuzzy system (21) is said to be guaranteed under zero-initial condition.

In light of the above derivation and definition, the studied tracking control problem can be transformed into devising observer-assisted T-S fuzzy controller with the form (17) to achieve the stochastic stability and H_∞ tracking control performance of the augmented T-S fuzzy system (21). At the end of this section, the following lemma is further described to aid the subsequent derivation.

Lemma 1. ([42]) *The singular value decomposition for a given full rank matrix $\mathcal{X} \in \mathbb{R}^{n_x \times n_y}$ can be expressed as $\mathcal{X} = \mathcal{O}\begin{bmatrix} \mathcal{S} \\ 0 \end{bmatrix}\mathcal{V}^T$, where $\mathcal{O}^T\mathcal{O} = I$ and $\mathcal{V}^T\mathcal{V} = I$. For matrices $\mathcal{H} > 0$, $\mathcal{D} \in \mathbb{R}^{n_x \times n_x}$ and $\mathcal{E} \in \mathbb{R}^{n_y \times n_x}$, there exists a matrix $\overline{\mathcal{H}}$ such that $\mathcal{H}\mathcal{X} = \mathcal{X}\overline{\mathcal{H}}$ if and only if:*

$$\mathcal{H} = \mathcal{O}\begin{bmatrix} \mathcal{D} & 0 \\ 0 & \mathcal{E} \end{bmatrix}\mathcal{O}^T$$

3 | Main Results

In this section, the sufficient conditions that the system (21) is stochastic stable with guaranteed H_∞ tracking control performance are analyzed in Theorems 1 and 2 firstly. Then, the desired observer-assisted T-S fuzzy controller is designed by calculating the observer and controller gains in Theorem 3. Considering the introduction of the AETM, the following derivation also focuses on $h \in [t_m, t_{m+1})$.

Theorem 1. *Given scalars $\theta > 0$, $\lambda \in (0,1)$, $\sigma \in (0,1)$, $\overline{\alpha} \in (0,1)$, observer gains $L_{i,k}$ and controller gains $K_{p,k}$ $(i, p = 1, 2, \ldots, s; k = 1, 2, \ldots, n_y)$, the stochastic stability of the augmented T-S fuzzy system (21) can be obtained if there exist positive-define matrices $P_k > 0$ with compatible dimensions so that the following matrix inequalities hold:*

$$\Omega_{ipk} = \begin{bmatrix} \Xi_{1,1} + \Theta_1 & * \\ \Xi_{2,1} + \Theta_3 & \Xi_{2,2} + \Theta_2 \end{bmatrix} < 0 \tag{22}$$

where

$$\Xi_{1,1} = F_{1ip}^T P_l F_{1ip} + \overline{F}_{2ip}^T P_l \overline{F}_{2ip} - P_k,$$

$$\Xi_{2,1} = \mathcal{H}_{1ip}^T P_l F_{1ip} + \overline{\mathcal{H}}_{2ip}^T P_l \overline{F}_{2ip},$$

$$\Xi_{2,2} = \mathcal{H}_{1ip}^T P_l \mathcal{H}_{1ip} + \overline{\mathcal{H}}_{2ip}^T P_l \overline{\mathcal{H}}_{2ip},$$

$$\mathcal{H}_{1ip} = \begin{bmatrix} 0 & -\vec{\alpha}L_{i,k}\Phi_k & \vec{\alpha}L_{i,k}\Phi_k \\ -B_r & 0 & 0 \\ 0 & 0 & 0 \\ B_r & 0 & 0 \\ 0 & \vec{\alpha}\Phi_k & -\vec{\alpha}\Phi_k \end{bmatrix},$$

$$\overline{F}_{2ip} = \left[0\ 0\ W\ 0\ 0\right], \overline{\mathcal{H}}_{2ip} = \left[0\ M\ M\right],$$

$$W = \left[W_1^T\ 0\ 0\ 0\ W_2^T\right]^T, M = \left[M_1^T\ 0\ 0\ 0\ M_2^T\right]^T,$$

$$M_1 = -\sqrt{\overline{\alpha}\vec{\alpha}}L_{i,k}\Phi_k, M_2 = \sqrt{\overline{\alpha}\vec{\alpha}}\Phi_k, W_1 = -M_1C_i,$$

$$W_2 = -M_2C_i,$$

$$\Theta_1 = diag\left\{0, 0, C_i^T G^T G C_i^T - \sigma\left(\lambda - 1 - \frac{1}{\theta}\right)C_i^T C_i, 0, 0\right\},$$

$$\Theta_2 = diag\left\{0, -I, \left(\lambda - 1 - \frac{1}{\theta}\right)I + G^T G\right\},$$

$$\Theta_3 = \left[0\ 0\ C\ 0\ 0\right], C = \left[0\ 0\ -C_i^T G^T G\right]^T$$

Proof. Constructing a mode-dependent Lyapunov function as:

$$V(h) = \chi^T(h)P_k\chi(h) + \frac{1}{\theta}\epsilon(h) \tag{23}$$

and defining the forward difference of $V(h)$ as $\Delta V(h) \triangleq V(h+1) - V(h)$. Then, under $w(k) \equiv 0$ and taking into account the upper-bound of the generated deception signal (that is, the condition presented by (11)), it can be inferred that:

$$
\begin{aligned}
&E\{\Delta V(h)\} \\
&= E\Big\{\chi^T(h+1)P_l\chi(h+1) \\
&\quad +\frac{1}{\theta}\epsilon(h+1) - \chi^T(h)P_k\chi(h) - \frac{1}{\theta}\epsilon(h)\Big\} \\
&\leq E\{\chi^T(h+1)P_l\chi(h+1) - \chi^T(h)P_k\chi(h)\} \\
&\quad + \frac{1}{\theta}\epsilon(h+1) - \frac{1}{\theta}\epsilon(h) \\
&\quad + y^T(t_m)G^TGy(t_m) - \phi^T(t_m)\phi(t_m) \\
&= E\Bigg\{\sum_{i=1}^{s}\sum_{p=1}^{s}\upsilon_i(\mu(h))\upsilon_p(\mu(h)) \\
&\quad \big[(F_{1ip}+F_{2ip})\chi(h) + (\mathcal{H}_{1ip}+\mathcal{H}_{2ip}) \\
&\quad \times\mathcal{M}(h)]^T P_l[(F_{1ip}+F_{2ip})\chi(h) + (\mathcal{H}_{1ip}+\mathcal{H}_{2ip})\mathcal{M}(h)] - \chi^T(h) \\
&\quad \times P_k\chi^T(h) + \frac{1}{\theta}\epsilon(h+1) - \frac{1}{\theta}\epsilon(h) \\
&\quad + y^T(t_m)G^TGy(t_m) - \phi^T(t_m)\phi(t_m)\Big\}
\end{aligned} \tag{24}
$$

where

$$
\mathcal{M}(h) = \begin{bmatrix} u_r^T(h) & \phi^T(t_m) & \eta^T(h) \end{bmatrix}^T, \mathcal{H}_{2ip} = \begin{bmatrix} 0 & R_2 & R_2 \end{bmatrix}
$$

According to the event-triggering condition (5), it has:

$$
\begin{aligned}
&\frac{1}{\theta}\epsilon(h+1) - \frac{1}{\theta}\epsilon(h) \\
&= \frac{1}{\theta}\big[(\lambda-1)\epsilon(h) + \sigma y^T(h)y(h) - \eta^T(h)\eta(h)\big] \\
&\leqslant \Big(\lambda - 1 - \frac{1}{\theta}\Big)\eta^T(h)\eta(h) - \sigma\Big(\lambda - 1 - \frac{1}{\theta}\Big)y^T(h)y(h) \\
&= \Big(\lambda - 1 - \frac{1}{\theta}\Big)\eta^T(h)\eta(h) - \sigma\Big(\lambda - 1 - \frac{1}{\theta}\Big)[x^T(h)C_i^TC_ix(h)]
\end{aligned} \tag{25}
$$

Then, based on (10), (24) and (25), it can be obtained that:

$$
\begin{aligned}
&E\{\Delta V(h)\} \\
&\leq E\Bigg\{\sum_{i=1}^{s}\sum_{p=1}^{s}\upsilon_i(\mu(h))\upsilon_p(\mu(h)) \\
&\quad [(F_{1ip}+F_{2ip})\chi(h) + (\mathcal{H}_{1ip}+\mathcal{H}_{2ip}) \times \mathcal{M}(h)]^T \\
&\quad P_l[(F_{1ip}+F_{2ip})\chi(h) + (\mathcal{H}_{1ip}+\mathcal{H}_{2ip})\mathcal{M}(h)] - \chi^T(h)P_k \\
&\times \chi^T(h) + \Big(\lambda - 1 - \frac{1}{\theta}\Big)\eta^T(h)\eta(h) \\
&\quad - \sigma\Big(\lambda - 1 - \frac{1}{\theta}\Big)x^T(h)C_i^TC_ix(h) \\
&\quad + y^T(t_m)G^TGy(t_m) - \phi^T(t_m)\phi(t_m)\Big\} \\
&= \sum_{i=1}^{s}\sum_{p=1}^{s}\upsilon_i(\mu(h))\upsilon_p(\mu(h))\big[\zeta_1^T(h)\Omega_{ipk}\zeta_1(h)\big]
\end{aligned} \tag{26}
$$

where $\zeta_1(h) = \big[\chi^T(h) \;\; \mathcal{M}^T(h)\big]^T$.

Letting $\mathcal{W} \triangleq \sum_{i=1}^{s}\sum_{p=1}^{s}\upsilon_i(\mu(h))\upsilon_p(\mu(h))\zeta_1^T(h)\Omega_{ipk}\zeta_1(h)$, then it can be inferred from (22) that $\mathcal{W} < 0$, and thereby we have:

$$
\begin{aligned}
&E\{\chi^T(h+1)P_l\chi(h+1) - \chi^T(h)P_i\chi(h)\} \\
&\quad \leq -\lambda_{min}(-\mathcal{W})\chi^T(h)\chi(h)
\end{aligned} \tag{27}
$$

By summing both sides of (27) from $h = 0$ to ∞, then one has:

$$
\begin{aligned}
&E\left\{\sum_{h=0}^{\infty}||\chi(h)||^2\right\} \\
&\leq (\lambda_{min}(-\mathcal{W}))^{-1}\{\chi^T(0)P_k\chi(0) - E\{\chi^T(h+1)P_l\chi(h+1)\} \\
&\leq (\lambda_{min}(-\mathcal{W}))^{-1}\chi^T(0)P_k\chi(0) \\
&= \chi^T(0)\mathcal{N}\chi(0)
\end{aligned} \tag{28}
$$

Given that $\mathcal{N} = (\lambda_{min}(-\mathcal{W}))^{-1}P_k > 0$, so according to Definition 1, the stochastic stability of the augmented T-S fuzzy system (21) is achieved. □

Remark 5. In the constructed Lyapunov function (23), the first term $\chi^T(h)P_k\chi(h)$ in $V(h)$ depends on $f(h)$ and thus reflects the influence of the adopted RR protocol on data transmission. Moreover, the second term $\frac{1}{\theta}\epsilon(h)$ is introduced in $V(h)$ to characterize the dynamic adjustment of $\epsilon(h)$ in the employed AETM. By comprehensively taking the impact of the proposed TS-DTS into account, the stability of the augmented T-S fuzzy system (21) is then analyzed based on the established positive definite function $V(h)$.

Based on Theorem 1, we then analyze the H_∞ tracking control performance of the system (21) in Theorem 2.

Theorem 2. *Given scalars $\theta > 0$, $\lambda \in (0,1)$, $\sigma \in (0,1)$, $\overline{\alpha} \in (0,1)$, a weighting matrix $Q > 0$, a predefined attenuation level γ, observer gains $L_{i,k}$ and controller gains $K_{p,k}$ $(i,p = 1,2,\dots,s; k = 1,2,\dots,n_y)$, the stochastic stability with guaranteed H_∞ tracking control performance of the augmented T-S fuzzy system (21) can be achieved if there exist positive-define matrices $P_k > 0$ with compatible dimensions so that the following matrix inequalities hold*:

$$
\mathcal{Z}_{ipk} = \begin{bmatrix} \Xi_{1,1}+\Lambda_1 & * \\ \Xi_{2,1}+\overline{\Theta}_3 & \Xi_{2,2}+\Lambda_2 \end{bmatrix} < 0 \tag{29}
$$

where

$$
\begin{aligned}
&\Xi_{2,1} = \Pi_{1ip}^TP_lF_{1ip} + \overline{\Pi}_{2ip}^TP_l\overline{F}_{2ip}, \Xi_{2,2} = \Pi_{1ip}^TP_l\Pi_{1ip} + \overline{\Pi}_{2ip}^TP_l\overline{\Pi}_{2ip}, \\
&\Lambda_1 = diag\Big\{0, Q, C_i^TG^TGC_i - \sigma\Big(\lambda - 1 - \frac{1}{\theta}\Big)C_i^TC_i, 0, 0\Big\}, \\
&\Lambda_2 = diag\Big\{-\gamma^2I, -\gamma^2I, -I, \Big(\lambda - 1 - \frac{1}{\theta}\Big)I + G^TG\Big\}, \\
&\overline{\Pi}_{2ip} = \begin{bmatrix} 0 & 0 & M & M \end{bmatrix}, \overline{\Theta}_3 = \begin{bmatrix} 0 & 0 & \overline{C} & 0 & 0 \end{bmatrix}, \\
&\overline{C} = \begin{bmatrix} 0 & 0 & 0 & -C_i^TG^TG \end{bmatrix}^T
\end{aligned}
$$

Proof. Under $w(h) \neq 0$, we employ the same Lyapunov function (23) and follow the similar derivation process as presented in Theorem 1, then if $\mathcal{Z}_{ipk} < 0$, we can obtain that:

$$
\begin{aligned}
&E\{\Delta V(h)\} + E\{\hat{e}^T(h)Q\hat{e}(h)\} - \gamma^2\tilde{\omega}^T(h)\tilde{\omega}(h) \\
&= \sum_{i=1}^{s}\sum_{p=1}^{s}\upsilon_i(\mu(h))\upsilon_p(\mu(h))\left[\zeta^T(h)\mathcal{Z}_{ipk}\zeta(h)\right] \leq 0
\end{aligned} \tag{30}
$$

where

$$
\zeta(h) = \left[\chi^T(h)\ \ U^T(h)\right]^T, \tilde{\omega}(h) = \left[w^T(h)\ \ u_r^T(h)\right]^T
$$

By means of (30) and zero-initial condition, it can be deduced that:

$$
\begin{aligned}
&E\left\{\sum_{h=0}^{\infty}\hat{e}^T(h)Q\hat{e}(h)\right\} \\
&< \gamma^2\sum_{h=0}^{\infty}\tilde{\omega}^T(h)\tilde{\omega}(h) - \sum_{h=0}^{\infty}E\{\Delta V(h)\} \\
&= \gamma^2\sum_{h=0}^{\infty}\tilde{\omega}^T(h)\tilde{\omega}(h) - \{E\{V(\infty)\} - E\{V(0)\}\} \\
&= \gamma^2\sum_{h=0}^{\infty}\tilde{\omega}^T(h)\tilde{\omega}(h) - E\{V(\infty)\} \\
&< \gamma^2\sum_{h=0}^{\infty}\tilde{\omega}^T(h)\tilde{\omega}(h)
\end{aligned} \tag{31}
$$

which implies that the H_∞ tracking control performance of the system (21) for the predefined attenuation level γ is assured according to Definition 2. □

We would like to note that the above analyses on the stochastic stability and H_∞ tracking control performance of the system (21) are conducted based on the given observer and controller parameters, and the inequalities presented by (29) are difficult to be solved due to the existence of some non-linear terms. Therefore, we then recur to linear matrix inequality (LMI) technology to deal with the non-linear terms, and thereby obtain appropriate observer and controller gains in the following theorem.

Theorem 3. *Given scalars $\theta > 0$, $\lambda \in (0,1)$, $\sigma \in (0,1)$, $\overline{\alpha} \in (0,1)$, a weighting matrix $Q > 0$ and a predefined attenuation level γ, the stochastic stability with guaranteed H_∞ tracking control performance of the augmented T-S fuzzy system (21) can be achieved if there exist positive-definite matrices $P_k = diag\{P_{1,k}, P_{2,k}, P_{3,k}, P_{4,k}, P_{5,k}\} > 0$, $S = diag\{S_k, S_k, \ldots, S_k, S_k\} > 0$ $(k = 1, 2, \ldots, n_y)$, matrices $H_{i,k}$ and $Z_{i,p,k}$ $(i, p = 1, 2, \ldots, s)$ with compatible dimensions so that the following LMIs hold:*

$$
\begin{bmatrix} \overline{P}_k & * \\ \tilde{\Xi} & \hat{P}_l \end{bmatrix} < 0 \tag{32}
$$

where

$$
\tilde{\Xi} = \begin{bmatrix} \tilde{\Xi}_{1,1} & \tilde{\Xi}_{1,2} \\ \tilde{\Xi}_{2,1} & \tilde{\Xi}_{2,2} \end{bmatrix},
$$

$$
\tilde{\Xi}_{1,1} = \begin{bmatrix}
\tilde{\Gamma}_{11} & \tilde{\Gamma}_{12} & \tilde{\Gamma}_{13} & 0 & \tilde{\Gamma}_{14} \\
-\tilde{\Gamma}_{12} & \tilde{\Gamma}_{15} & 0 & \tilde{\Gamma}_{16} & 0 \\
-\tilde{\Gamma}_{12} & \tilde{\Gamma}_{12} & S_kA_i & 0 & 0 \\
0 & 0 & 0 & S_kA_r & 0 \\
0 & 0 & \vec{\alpha}S_k\Phi_kC_i & 0 & S_k(I - \Phi_k)
\end{bmatrix},
$$

$$
\tilde{\Xi}_{1,2} = \begin{bmatrix}
S_kE_i & 0 & -\overline{\alpha}H_{i,k}\Phi_k & \vec{\alpha}H_{i,k}\Phi_k \\
S_kE_i & -S_kB_r & 0 & 0 \\
S_kE_i & 0 & 0 & 0 \\
0 & S_kB_r & 0 & 0 \\
0 & 0 & \overline{\alpha}S_k\Phi_k & -\vec{\alpha}S_k\Phi_k
\end{bmatrix}
$$

$$
\tilde{\Xi}_{2,1} = \begin{bmatrix} 0 & 0 & \tilde{W} & 0 & 0 \end{bmatrix}, \tilde{\Xi}_{2,2} = \begin{bmatrix} 0 & 0 & \tilde{M} & \tilde{M} \end{bmatrix},
$$

$$
\tilde{W} = \begin{bmatrix} W_1^T & 0 & 0 & 0 & W_2^T \end{bmatrix}^T, \tilde{M} = \begin{bmatrix} M_1^T & 0 & 0 & 0 & M_2^T \end{bmatrix}^T,
$$

$$
\tilde{\Gamma}_{11} = S_kA_i - \tilde{\Gamma}_{12}, \tilde{\Gamma}_{12} = B_iZ_{i,p,k},
$$

$$
\tilde{\Gamma}_{13} = -\vec{\alpha}H_{i,k}\Phi_kC_i, \tilde{\Gamma}_{14} = -H_{i,k}(I - \Phi_k), \tilde{\Gamma}_{15} = S_kA_i + \tilde{\Gamma}_{12},
$$

$$
\tilde{\Gamma}_{16} = S_k(A_i - A_r), \tilde{M}_1 = -\sqrt{\overline{\alpha}\vec{\alpha}}H_{i,k}\Phi_k,
$$

$$
\tilde{M}_2 = \sqrt{\overline{\alpha}\vec{\alpha}}S_k\Phi_k, \tilde{W}_1 = -\tilde{M}_1C_i, \tilde{W}_2 = -\tilde{M}_2C_i,
$$

$$
\begin{aligned}
\hat{P}_l = diag\{&P_{1,l} - \mathcal{H}_e\{S_k\}, P_{2,l} - \mathcal{H}_e\{S_k\}, \\
&P_{3,l} - \mathcal{H}_e\{S_k\}, P_{4,l} - \mathcal{H}_e\{S_k\}, P_{5,l} - \mathcal{H}_e\{S_k\}\},
\end{aligned}
$$

$$
P_l = diag\{P_{1,l}, P_{2,l}, P_{3,l}, P_{4,l}, P_{5,l}\}, \mathcal{H}_e\{S_k\} = S_k + S_k^T
$$

Proof. Firstly, according to Schur complement, it is apparently that $\mathcal{Z}_{ipk} < 0$ hold if and only if the following matrices:

$$
\begin{bmatrix} \overline{P}_k & * \\ \Xi & \overline{P}_l \end{bmatrix} < 0 \tag{33}
$$

are satisfied, where

$$
\Xi = \begin{bmatrix} \overline{F}_{1ip} & \overline{\Pi}_{1ip} \\ \overline{F}_{2ip} & \overline{\Pi}_{2ip} \end{bmatrix}, \overline{P}_k = \begin{bmatrix} -P_k + \Lambda_1 & * \\ \Theta_3 & \Lambda_2 \end{bmatrix},
$$

$$
\overline{P}_l = diag\{-P_l^{-1}, -P_l^{-1}\}
$$

Then, by pre-multiplying and post-multiplying the left side of (33) with $diag\{I, S\}$ and $diag\{I, S^T\}$, respectively, it can be derived that:

$$
\begin{bmatrix} \overline{P}_k & * \\ \hat{\Xi} & \tilde{P}_l \end{bmatrix} < 0 \tag{34}
$$

where

$$
\hat{\Xi} = \begin{bmatrix} \hat{\Xi}_{1,1} & \hat{\Xi}_{1,2} \\ \hat{\Xi}_{2,1} & \hat{\Xi}_{2,2} \end{bmatrix},
$$

$$
\hat{\Xi}_{1,1} = \begin{bmatrix}
\hat{\Gamma}_{11} & \hat{\Gamma}_{12} & \hat{\Gamma}_{13} & 0 & \hat{\Gamma}_{14} \\
-\hat{\Gamma}_{12} & \hat{\Gamma}_{15} & 0 & \hat{\Gamma}_{16} & 0 \\
-\hat{\Gamma}_{12} & \hat{\Gamma}_{12} & S_kA_i & 0 & 0 \\
0 & 0 & 0 & S_kA_r & 0 \\
0 & 0 & \vec{\alpha}S_k\Phi_kC_i & 0 & S_k(I - \Phi_k)
\end{bmatrix},
$$

$$\hat{\Xi}_{1,2} = \begin{bmatrix} S_k E_i & 0 & -\bar{\alpha} S_k L_{i,k} \Phi_k & \vec{\alpha} S_k L_{i,k} \Phi_k \\ S_k E_i & -S_k B_r & 0 & 0 \\ S_k E_i & 0 & 0 & 0 \\ 0 & S_k B_r & 0 & 0 \\ 0 & 0 & \overline{\alpha} S_k \Phi_k & -\vec{\alpha} S_k \Phi_k \end{bmatrix},$$

$$\hat{\Xi}_{2,1} = \begin{bmatrix} 0 & 0 & \overline{W} & 0 & 0 \end{bmatrix}, \hat{\Xi}_{2,2} = \begin{bmatrix} 0 & 0 & \overline{M} & \overline{M} \end{bmatrix},$$

$$W = \begin{bmatrix} \overline{W}_1^T & 0 & 0 & \overline{W}_2^T \end{bmatrix}^T, M = \begin{bmatrix} \overline{M}_1^T & 0 & 0 & \overline{M}_2^T \end{bmatrix}^T,$$

$$\overline{M}_1 = -\sqrt{\overline{\alpha}\vec{\alpha}} S_k L_{i,k} \Phi_k, \overline{M}_2 = \sqrt{\overline{\alpha}\vec{\alpha}} S_k \Phi_k,$$

$$\overline{W}_1 = -\overline{M}_1 C_i, \overline{W}_2 = -\overline{M}_2 C_i, \hat{\Gamma}_{11} = S_k A_i - \hat{\Gamma}_{12},$$

$$\hat{\Gamma}_{12} = S_k B_i K_{p,k}, \hat{\Gamma}_{13} = -\vec{\alpha} S_k L_{i,k} \Phi_k C_i,$$

$$\hat{\Gamma}_{14} = -S_k L_{i,k}(I - \Phi_k), \hat{\Gamma}_{15} = S_k A_i + \hat{\Gamma}_{12}, \hat{\Gamma}_{16} = S_k(A_i - A_r),$$

$$\tilde{P}_l = \mathrm{diag}\Big\{ -S_k P_{1,l}^{-1} S_k^T, -S_k P_{2,l}^{-1} S_k^T, -S_k P_{3,l}^{-1} S_k^T, -S_k P_{4,l}^{-1} S_k^T, -S_k P_{5,l}^{-1} S_k^T \Big\}$$

Given that P_l are positive-definite matrices, it can be known that $P_{b,l} > 0$ $(b = 1, \dots, 5)$ which is followed by $P_{b,l}^{-1} > 0$, then it has $(P_{b,l} - S_k) P_{b,l}^{-1} (P_{b,l} - S_k)^T = P_{b,l} - S_k - S_k^T + S_k P_{b,l}^{-1} S_k^T \geq 0$ which further deduces that $-S_k P_{b,l}^{-1} S_k^T \leq P_{b,l} - \mathcal{H}_e\{S_k\}$. Moreover, based on Lemma 1, for $S_k = O_i \begin{bmatrix} D_{ik} & 0 \\ 0 & E_{ik} \end{bmatrix} O_i^T$ and $B_i = O_i \begin{bmatrix} N_i \\ 0 \end{bmatrix} V_i^T$, in which $O_i^T O_i = I$ and $V_i^T V_i = I$, it can be gotten that $S_k B_i = B_i \overline{S}_{ki}$ with $\overline{S}_{ki} = V_i N_i^{-1} D_{ik} N_i V_i^T$. By defining $H_{i,k} = S_k L_{i,k}$, $Z_{i,p,k} = \overline{S}_{ki} K_{p,k}$, and substituting $-S_k P_{b,l}^{-1} S_k^T$ and $S_k B_i$ in (34) with $P_{b,l} - \mathcal{H}_e\{S_k\}$ and $B_i \overline{S}_{ki}$, respectively, (32) can be finally obtained. Meanwhile, we can get that $L_{i,k} = S_k^{-1} H_{i,k}$ and $K_{p,k} = \overline{S}_{ki}^{-1} Z_{i,p,k}$. □

Remark 6. To overcome the difficulties caused by the non-linear terms in solving for the observer and controller gains, the Schur complement lemma is used in Theorem 3 to derive (33). Then, (34) is obtained by pre-multiplying and post-multiplying the left side of (33) with $diag\{I, S\}$ and $diag\{I, S^T\}$, respectively. It is worth noting that (34) still contains non-linear terms involving the controller gains $K_{p,k}$, such as $S_k B_i K_{p,k}$. Therefore, based on (34), Lemma 1 is further applied to eliminate the related non-linear terms in the solution. e.g., $S_k B_i K_{p,k}$ is transformed into $B_i Z_{i,p,k}$.

Remark 7. Tracking control problem for T-S fuzzy systems has been exploited in some existing research such as [12, 15, 48, 49], but the limited network bandwidth and stochastic cyber attacks are not considered in these works. To alleviate the bandwidth pressure, AETM-based fuzzy tracking controllers are designed in [23, 24, 50], however, the data collision at each event-triggering instant caused by limited communication resource is still being neglected, which will inevitably degrade the performance of the fuzzy controllers. Some recent studies have tried to use both AETM and RR protocol to mitigate the impact of bandwidth limitation [25, 51], nevertheless [25], focuses on designing output feedback controller over Markov switching systems while [51] devotes to achieve sliding mode control for Markov jumping systems, so neither of them shares the same objective with our study that to design secure observer-assisted T-S fuzzy tracking controller. Concerning on the influence of cyber attacks, fuzzy tracking control issue has been addressed in [39, 52, 53], but the bandwidth limitation is not considered in [52, 53]; although ETM is adopted in [39], but the work is conducted under conflict-free data transmission scenario, and thus differs from our study that uses RR protocol to void data collision in the case of insufficient bandwidth so as to enhance the effectiveness of the designed secure tracking controller.

4 | Numerical Results

In this section, a simulation example is conducted to demonstrate the feasibility of the proposed observer-assisted T-S fuzzy control method. We first introduce the simulation settings, and then present the simulation results and the corresponding illustration. Considering a two-rule-based T-S fuzzy system with the following parameters:

$$A_1 = \begin{bmatrix} -0.2506 & -0.1093 \\ -0.2039 & -0.2167 \end{bmatrix}, B_1 = \begin{bmatrix} -0.4587 \\ 0 \end{bmatrix},$$

$$A_2 = \begin{bmatrix} -0.2632 & -0.1583 \\ -0.1909 & -0.1537 \end{bmatrix}, B_2 = \begin{bmatrix} 0 \\ -0.2569 \end{bmatrix},$$

$$C_1 = \begin{bmatrix} 0.45 & 0 \\ 0 & 0.2 \end{bmatrix}, \quad E_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, C_2 = \begin{bmatrix} 0.32 & 0 \\ 0 & 0.1 \end{bmatrix},$$

$$E_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

the fuzzy MFs of the system are set as:

$$v_1(\mu(h)) = \frac{1 - \sin^2(\|x_1(h)\|_2)}{2}, v_2(\mu(h)) = 1 - v_1(\mu(h))$$

and the system state is denoted as $x(h) = \begin{bmatrix} x_1^T(h) & x_2^T(h) \end{bmatrix}^T$, furthermore, two sensors are deployed to acquire the system state, that is, $n_y = 2$.

The parameters for the reference model are given below.

$$A_r = \begin{bmatrix} 0.1257 & 0.2248 \\ 0.2458 & 0.1659 \end{bmatrix}, B_r = \begin{bmatrix} -0.2512 & 0.9548 \\ 0.8254 & -0.2587 \end{bmatrix}$$

The scalars relevant to the AETM employed in the proposed TS-DTS are set to be $\sigma = 0.7, \lambda = 0.9$ and $\theta = 10$. For the considered deception attack, we define $\overline{\alpha} = 0.5$ and $\phi(h) = 0.1 \sin(h - 1) y(h)$ with $G = \mathrm{diag}\{0.1, 0.1\}$. We further set the H_∞ performance index as $\gamma = 0.8$, then the following observer and controller gains are obtained by solving the LMIs listed in Theorem 3.

$$L_{11} = \begin{bmatrix} -0.1623 & 0.0047 \\ -0.1757 & 0.0034 \end{bmatrix}, L_{12} = \begin{bmatrix} 0.0006 & -0.0559 \\ 0.0011 & -0.1140 \end{bmatrix},$$

$$L_{21} = \begin{bmatrix} -0.1690 & 0.0019 \\ -0.0814 & 0.0014 \end{bmatrix}, L_{22} = \begin{bmatrix} 0.0004 & -0.0459 \\ 0.0004 & -0.0280 \end{bmatrix},$$

$$K_{11} = \begin{bmatrix} -0.1439 & -0.1005 \end{bmatrix}, K_{12} = \begin{bmatrix} -0.2724 & -0.1962 \end{bmatrix},$$

$$K_{21} = \begin{bmatrix} -0.1397 & -0.0897 \end{bmatrix}, K_{22} = \begin{bmatrix} -0.2378 & -0.1700 \end{bmatrix}$$

On the basis of the devised observer and controller, and setting the initial conditions as $x(0) = \begin{bmatrix} 0 & 0.25 \end{bmatrix}^T$, $x_r(0) = \begin{bmatrix} 0 & 0.2 \end{bmatrix}^T$ and $\hat{x}(0) = \begin{bmatrix} 0 & -0.5 \end{bmatrix}^T$, the simulation results are then displayed by Figures 2–9. To be specific, the trajectories of the system state and its estimation are shown in Figure 2, it can be seen that the estimated state is very close to the real system state after about $h = 15$, which confirms the efficiency of the designed observer. The observer errors and the considered deception attack are presented in Figure 3. As shown, the observer errors converge to zero even under the influence of the deception attack, and thus the validity of the observer is further corroborated. The state responses of the T-S fuzzy system and the reference system are shown in Figure 4, it can be found that with the assistance of the effective observer, desirable tracking control performance of the devised controller can be achieved. The tracking errors approaching to zero under

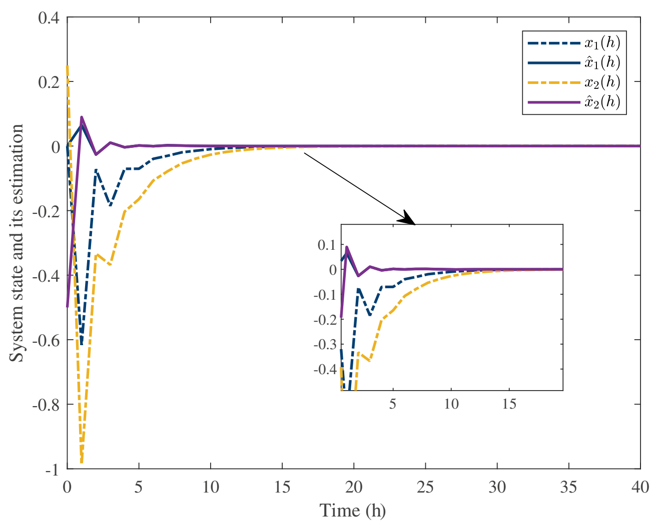

FIGURE 2 | Trajectories of $x(h)$ and $\hat{x}(h)$.

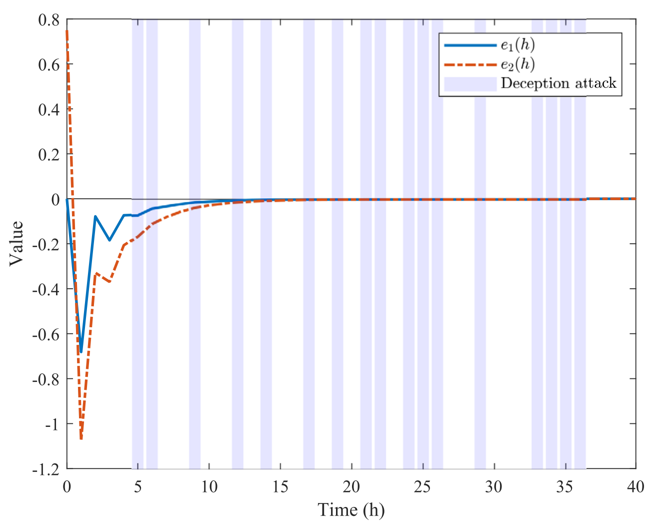

FIGURE 3 | Observer errors and the deception attack.

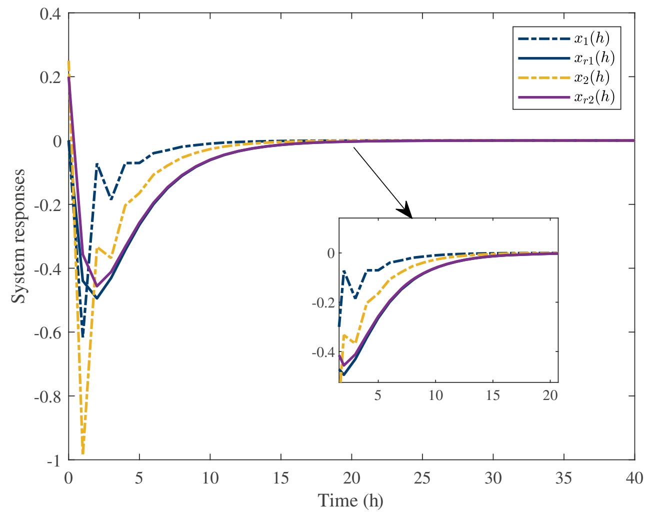

FIGURE 4 | Trajectories of $x(h)$ and $x_r(h)$.

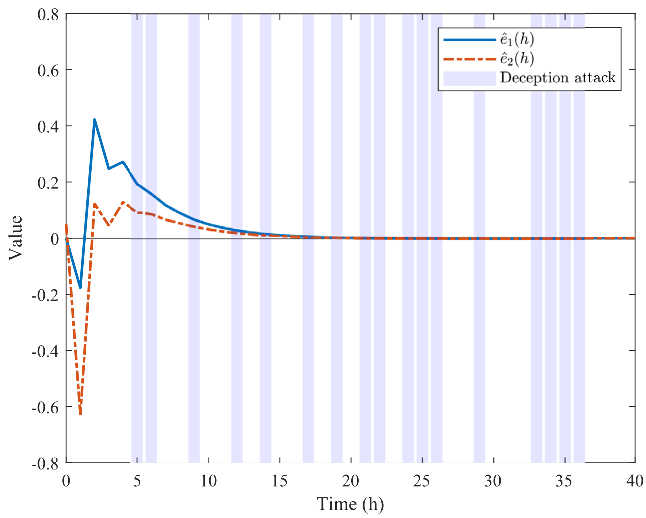

FIGURE 5 | Tracking errors and the deception attack.

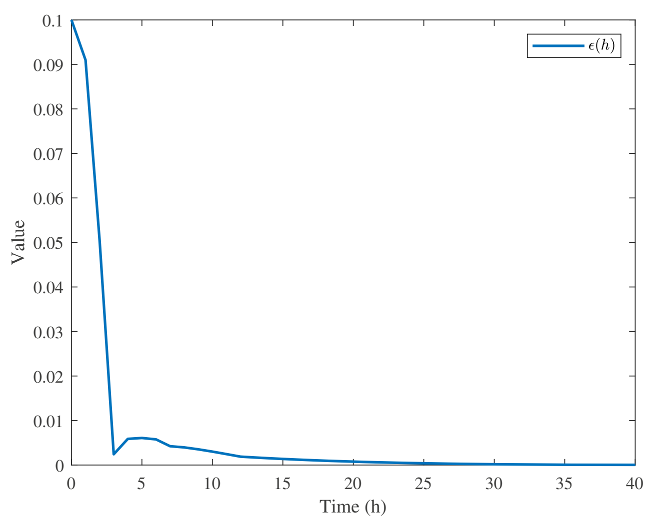

FIGURE 6 | The trajectory of $\epsilon(h)$.

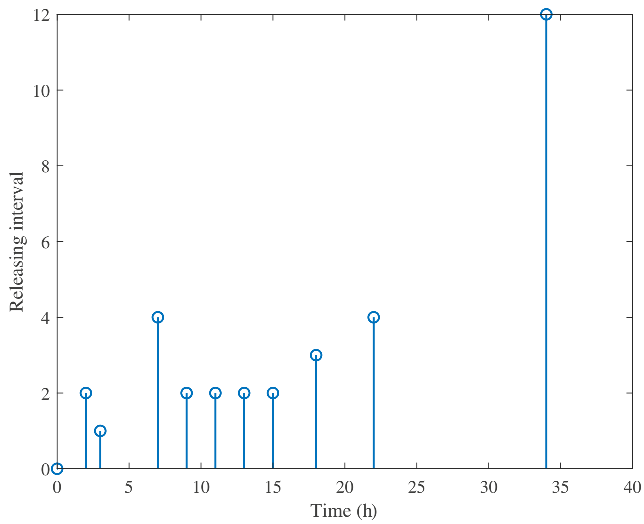

FIGURE 7 | The releasing instants and releasing intervals under TS-DTS.

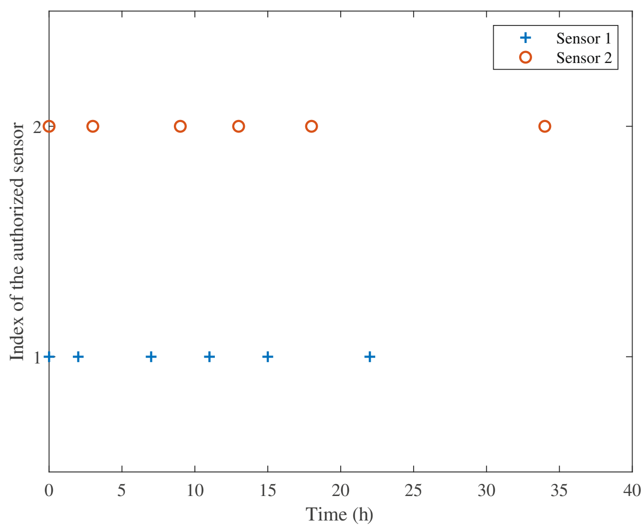

FIGURE 8 | The index of the authorized sensor at each releasing instant under TS-DTS.

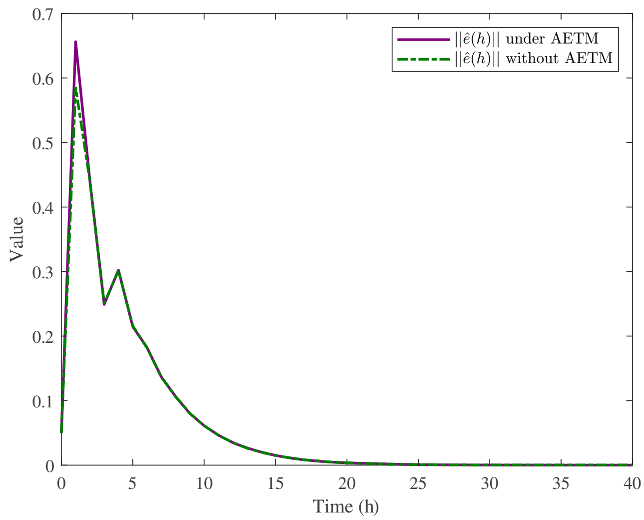

FIGURE 9 | $||\hat{e}(h)||$ obtained with and without the AETM.

the deception attack are also exhibited in Figure 5 to consolidate the result revealed by Figure 4.

In addition, the trajectory of the time-varying threshold function $\epsilon(h)$ is depicted by Figure 6, following which the specific signal-releasing instants and intervals under TS-DTS are shown in Figure 7, it validates that the redundant data dissatisfying the condition (5) will not be released into the communication network and thus the limited network bandwidth can be effectively saved. Furthermore, the index of the authorized sensor at each event-triggering instant under TS-DTS is presented in Figure 8. It can be found that one of the two sensors is allowed to access the communication network at each event-triggering instant (except for t_0) and thus the data collision can be avoided, moreover, the two sensors scheduled periodically which guarantees the fair transmission of measurement signals.

We would like to note that the delay of information updating within the system will arise because the use of the AETM results in only signals satisfying the defined event-triggering condition being released. However, according to this condition, it is obvious that the discarded signals exhibit a small variation from the most recently released data. Therefore, the delay is expected to have a minor impact on the tracking performance. To verify this, the tracking errors under the AETM and without it are presented in Figure 9, then it can be observed that $||\hat{e}(h)||$ derived under the AETM is only slightly larger than that obtained without the AETM.

5 | Conclusion

In this paper, the observer-assisted T-S fuzzy tracking control problem for non-linear NCSs has been comprehensively studied under the limitation of network bandwidth and the risk of deception attack. A data transmission scheme, named as TS-DTS, has been proposed to tackle the issues induced by bandwidth-constrained environment, that is, the AETM employed in the first stage of TS-DTS reduces the transmission of redundant measurement signals while the RR protocol adopted in the second stage of TS-DTS resolves the data collision at each event-triggering instant. The considered deception attack has been modeled by a Bernoulli process to capture its stochastic feature. Based on these, an augmented T-S fuzzy system has been constructed with the desired observer and controller. Then, sufficient conditions assuring the stochastic stability with predefined H_∞ performance index of the system have been derived, following which the method for calculating the observer and controller gains has been reported. Finally, the simulation results have been presented and illustrated to show the effectiveness of the study. Future research could involve designing new DTSs with different characteristics and extending the current results to T-S fuzzy systems with other uncertain influence factors. It should be noted that the proposed methodology is based on accurately modeled system dynamics. However, considering the complexities and uncertainties frequently encountered in practice, future efforts will focus on exploring a data-driven tracking approach for T-S fuzzy systems. Furthermore, given that the RR protocol may lead to increased delays in critical data transmission, our future work will also be dedicated to developing a novel communication protocol that can achieve a tradeoff between fairness and efficiency, thereby enhancing the tracking performance of the system.

Conflicts of Interest

The authors declare no conflicts of interest.

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