Opportunistic Wireless Control Over State-Dependent Fading Channels*

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Abstract— The heterogeneous system consisting of the wireless control system (WCS) and mobile agent system (MAS) is ubiquitous in Industrial Internet of Things (IIoT) systems. Within this system, the positions of mobile agents may lead to shadow fading on the wireless channel that the WCS is controlled over and can significantly compromise the WCS's performance. This paper focuses on the controller design for the MAS to ensure the performance of WCS in the presence of WCS and MAS coupling. Firstly, the constrained finite field network (FFN) with profile-dependent switching topology is adopted to proceed the operational control for the MAS. By virtue of the algebraic state space representation (ASSR) method, an equivalent form is obtained for the WCS and MAS coupling. A necessary and sufficient condition in terms of constrained set stabilization is then established to ensure the Lyapunov-like performance with expected decay rate. Finally, a graphical method and together with the breath-first searching is provided to design state feedback controllers for the MAS. With this method, it is easy to check the constrained set stabilization of MAS and to ensure the performance requirements of WCS in the presence of WCS and MAS coupling. The study of an illustrative example shows the effectiveness of the proposed method.

I. INTRODUCTION

Internet of Things (IoT) is an emerging domain in which all things are interconnected to realize dynamic information interaction [1]. Restricting the things in IoT to the industrial scenario, Industrial Internet of Things (IIoT) enables flexible, efficient and sustainable production in many fields including smart manufacturing through numerous plants that can be reconfigured based on process requirements [2], [3]. These plants consist of heterogeneous physical systems with sensing, computation, communication and actuation capabilities, which interact autonomously with each other by exchanging information over wireless networks [4].

In typical IIoT applications, e.g., smart manufacturing, heterogeneous physical systems which may have different objectives coordinate with each other to jointly perform overall task [2], [5]. The typical characteristic of the IIoT system lies in that numerous wireless sensors are deployed to monitor and control industrial plants forming wireless control networks (WCSs). An integral aspect of IIoT in smart manufacturing are mobile agents systems (MASs), which coordinate with the WCS in various ways, and can flexibly execute diverse tasks contributing to the overall manufacturing process [6]-[11]. However, the joint coordination of MASs and WCSs brings heterogeneity to IIoT systems. Moreover, the positions of mobile agents may lead to shadow fading on the wireless channel that the WCS is controlled over and can significantly compromise the WCS's performance. The fading channel measurements acquired at a rolling mill at Sandvik in Sweden [9] show that mobile machinery and cranes in the ceiling leads to substantial variations in the measured channel gains. Therefore, it is necessary to explicitly examine the state-dependency of wireless channels due to such WCS and MAS coupling to ensure the performance of WCSs.

The channel gains used to characterize shadow fading are traditionally modeled as independent identical distributed random processes [12] or Markov chains [13], where the network state is assumed to be independent from physical states. Under this assumption, research on scheduling wireless network parameters has been conducted to satisfy given control performance requirements such as stability [14], [15], controllability and observability [16] and minimizing linear quadratic objectives [17]. A survey on design and optimization for WCSs is presented in [18]. It is obvious that these methods on performance analysis of WCS fail in the scenario where the WCS and MAS coupling exists. Few works addressing the dependence of network state on physical states have been conducted. Reference [19] considers the power control in vehicular WCS, where the influence of vehicles’s physical states on the network state has been established to ensure the performance of the WCS. In [10], the authors study a state-dependent channel model, based on which a novel co-design paradigm addressing the coupling between a WCS and a single mobile agent has been proposed to achieve safety and efficiency of overall IIoT system. A Markov decision process is adopted to characterize the dynamics of a mobile agent, which is, however, limited to the single agent case.

In this paper, we consider a heterogeneous IIoT system where a WCS and an MAS coordinate with each other to jointly perform overall task over state-dependent fading channels. We focus on the opportunistic wireless control to ensure the Lyapunov-like performance with expected decay rate of the WCS in the presence of WCS and MAS coupling. How to convert the performance requirements of the WCS to a specific control objective of MAS is the key to this...
The contributions of this paper are two-fold. Firstly, by discretizing the workshop of the MAS into finite two-dimensional regions, the constrained finite field network (FFN) with profile-dependent switching topology is adopted to proceed the operational control for the MAS, which requires finite communication, memory and computation resources, and can achieve finite-time convergence. Secondly, based on the algebraic state space representation (ASSR) method, the performance requirements of the WCS is converted into the constrained set stabilization of the FFN. A graphical method together with the breath-first searching is proposed for the controller design for the MAS to ensure the performance requirements of WCS in the presence of WCS and MAS coupling. Compared with the existing results on set stabilization of finite-value systems obtained via algebraic approaches [20], [21], [22], the results proposed in this paper is more computationally economical.

This paper is organized as follows. Section II characterizes the heterogeneous IIoT system and problem formulation. Lyapunov-like performance analysis of the WCS is presented in Section III. In Section IV, main results are demonstrated by an illustrative example, which is followed by the conclusion in Section V.

Notations: The cone of $m \times m$ real positive definite (semi-definite) matrices is denoted by $S^m_+$. $S^m_+$ denotes the $s$-th column and the $s$-th row of a matrix by $F$ by $Col_s(F)$ and $Row_s(F)$, respectively. For $s \in \mathbb{Z}_+$, define $\mathcal{D}_s := \{0, 1, \ldots, s-1\}$ and $\Delta_s := \{d^s_i : i = 1, \ldots, s\}$, where $\mathcal{D}_s := \text{Col}_s(I_s)$ and $I_s$ is the $s$-dimensional identity matrix. $L_{s \times t}$ consists of all $s \times t$ logical matrices in the form of $M = [\delta^{1}_{s} \delta^{2}_{s} \cdots \delta^{n}_{s}]$, which is briefly expressed as $M = \delta^{s}_{s}[i_1 i_2 \cdots i_s]$. Throughout this paper, the semi-tensor product (⊗) is the basic matrix product [23]. In most places of this paper, the symbol “⊗” is omitted. $W_{s \times s} := [I_s \otimes \delta^1 \cdots I_s \otimes \delta^s]$ and $P_{s,s} := \text{diag}[\delta^1 \cdots \delta^s]$ represent the swap matrix and power-reducing matrix, respectively [23], where ⊗ is the Kronecker product.

II. PROBLEM FORMULATION

In this paper, we consider a heterogeneous IIoT system where a WCS and an MAS coordinate with each other to jointly perform overall task. ‘S’ and ‘A’ respectively represent sensing and actuation capabilities. The local channel state of each system $i$ ($\gamma_i(k) \in \mathcal{D}$) is a discrete variable with $\gamma_i(k) \in \{0, 1, \ldots, n\}$ and $\nu_i(k) \in \{0, 1, \ldots, m\}$, respectively, where ‘c’ and ‘o’ respectively represent the closed-loop (measurement is received) and open-loop (no measurement is received). The additive terms $\delta_i(k)$ represent an independent identically distributed noise process with mean zero and covariance $\Sigma_i \in S^m_+$. The above WCS description (1) can model a variety of control operations [14]. In this model, the closed-loop dynamics for all $q$ systems are fixed, that is, adequate controllers have been pre-designed.

At every slot $k$ each sensor $i$ chooses whether transmitting over the shared channel or not adapting to its local channel state. Discretize the wireless channel state of the WCS into $s$ values with each value representing a channel state interval, denoted by $0, 1, \cdots, s-1$, and denote the local channel state of system $i$ at slot $k$ by $\gamma_i(k) \in \mathcal{D}$. Assume that the wireless communication policy is pre-designed, and suppose that it holds

$$\alpha_i(k) = h_i(\gamma_i(k)), \quad \text{(2)}$$

where $h_i : \mathcal{D} \rightarrow \mathcal{D}_2$, $\alpha_i(k) = 1$ (or 0) means that sensor $i$ transmits (or does not transmit) over the shared channel at slot $k$.

At slot $k$, if sensor $i$ chooses to transmit over the shared channel, assume that it selects a transmit power level $\mu_i(k) \in \{\mu_{i,1}, \ldots, \mu_{i,p_i}\}$ according to the following rule:

$$P\{\mu_i(k) = \mu_{i,a} | \alpha_i(k) = 1, \gamma_i(k) = b\} = \mu_{i,a,b}. \quad \text{(3)}$$
where $a \in \{1, \cdots, p_1\}$, $b \in D_s$, $\mu_{a,b}^i \in [0,1]$ and $P$ is the probability.

The sensor’s transmission might fail due to packet decoding errors and packet collisions. Use $\eta_i(k) \in \mathcal{D}_2$ to indicate the successful or fail packet decoding at the access point of system $i$ at time $k$. If sensor $i$ transmits at slot $k$, and no other sensor transmits, then the relationship among the packet decoding success, local channel state and transmission power is

$$P\{\eta_i(k) = 1|z(k) = z\} = \gamma_{a,z},$$

where $a \in \mathcal{D}_s$ and $\eta_{a,b}^i \in [0,1]$. Where $a \in \mathcal{D}_s$ and $\eta_{a,b}^i \in [0,1]$.

**B. Description of the MAS**

We adopt the FFN architecture [24] to model the operational control for MASs with limited communication, memory and computation capabilities. For the state agents, the state is updated as a weighted combination of its own value and those of its in-neighbors including state agents and control agents. More specifically, it holds that

$$\beta_0(k+1) = \left\{ \sum_{i=1}^{n} a_i \sigma_{i,j}^k \right\} \times \beta_0(k)$$

where $\kappa$ is a prime number, $a_i \in \mathcal{D}_s \times \mathcal{D}_s \times \mathcal{D}_s$, $\delta_{i,j} \in \mathcal{D}_s$, $i = 1, \cdots, n$, $l = 1, \cdots, m$, $\sigma : \mathcal{N} \rightarrow \{1, \cdots, m\}$ is the profile-dependent switching signal, and operations “$+$” and “$\times$” are modular addition and modular multiplication over $\mathcal{D}_s$, respectively [25].

Consider the state feedback controller of FFN (5) in the following form:

$$u(k) = \pi(\beta_0(k)),$$

where $\pi : \mathcal{D}_s^m \rightarrow \mathcal{D}_s^m$. Define the profile of FFN (5) by $z(k) := (u(k), \beta(0)) \in \mathcal{D}_s^m$. Given an initial state profile $\beta_0(k) = \beta_0 \in \mathcal{C}_\beta$ and a state feedback law $\pi$. If for any initial state profile $\beta_0 \in \mathcal{C}_\beta$, $z(k;0,\pi)$, holds for any $k \in \mathcal{N}$, we call $\pi$ an admissible state feedback law. Denote the set of all admissible state feedback laws $\Pi$. If $\beta_0 \in \mathcal{C}_\beta$, $z(k;0,\pi)$ holds for any $k \in \mathcal{N}$, we call $\pi$ an admissible state feedback law.

**C. WCS and MAS Coupling**

When the WCS and the MAS coordinate with each other to jointly perform overall task, the positions of mobile agents may lead to shadow fading on the wireless channel that the WCS is controlled over. We model such state-dependent fading channel as follows:

$$P\{z(k) = a|z(k) = z\} = \gamma'_{a,z},$$

where $a \in \mathcal{D}_s^{m+n}$ and $\gamma'_{a,z} \in [0,1]$. According to (2)-(4), the positions of the mobile agents influence the probability of successful wireless transmission for the WCS. The WCS and MAS coupling can be expressed as

$$P\{\eta_i(k) = 1|z(k) = z\} = P\{\eta_i(k) = 1|z(k) = z\} \times P\{\eta_i(k) = 1|z(k) = z\}$$

where $a \in \mathcal{D}_s^{m+n}$ and $\gamma'_{a,z} \in [0,1]$. In addition, the state feedback law $\pi$ has the form

$$\pi \in \mathcal{D}_s \rightarrow \mathcal{D}_s \times \mathcal{D}_s.$$
Define $A_{i,j} = [a_{1,j} \cdots a_{w,j}]$, $B_{i,j} = [b_{1,j} \cdots b_{w,j}]$, $i,j = 1, \cdots, n$, $l = 1, \cdots, m$. Then, using the vector form of elements in $\mathcal{D}_K \{1, \cdots, w\}$ and skipping tedious derivations, for the dynamics of the $i$-th agent in (5), it holds

$$\beta(k+1) = F_{x,i}^k F_{x,i}[MN \otimes (F_{x,i}^{n-1} F_{x,i})]W_{[w,M,N]} P_{x,w} \times \sigma(k) z(k) = F_{x,i} \sigma(k) z(k),$$

where $F_{x,i} := [A_{x,i} \otimes (F_{x,i} A_{x,i+1})]W_{[w,M,N]} P_{x,w}$ and $F_{x,i} := [B_{x,i} \otimes (F_{x,i} B_{x,i+1})]W_{[w,M,N]} P_{x,w}$, $F_{x,i}$ and $F_{x,i}$ represent the structural matrices for $x_\pi$ and $x_\Omega$, respectively [26].

In this paper, we consider the profile-dependent switching signal with the form $\sigma(k) \in \Theta(z(k))$, which together with (10) shows $\beta(k+1) = F_{x,i} \sigma(k) z(k)$, where $\Theta \in \mathcal{L}_\ast \otimes MN$ and $F_{x,i} \in \mathcal{L}_\ast \otimes MN$. Multiplying the dynamics of $n$ state agents in FFN (5), one can obtain the following equivalent algebraic form of FFN (5):

$$\beta(k+1) = F z(k),$$

where $F \in \mathcal{L}_\ast \otimes MN$ satisfying $Col(F) = \kappa_{\pi}^n Col(F_i)$, $i = 1, \cdots, MN$. Split matrix $F$ into $M$ equal blocks as $F = [B k_{1}(F) B k_{2}(F) \cdots B k_{M}(F)]$.

Similarly, we can obtain the equivalent algebraic form for state feedback controller (6) as $u(k) = L F z(k)$, where $L \in \mathcal{L}_x \otimes N$ is the state feedback gain matrix.

In addition, using the vector form of $z(k)$, the WCS and MAS coupling (8) can be converted into an equivalent form

$$P \{\lambda_i(k) = 1|z(k)\} = \Lambda_i z(k),$$

where $\lambda_i = [\lambda_{i1} \lambda_{i2} \cdots \lambda_{iMN}]$ with $\lambda_{ij}$ given in (8), and $z$ has vector form $\kappa_{MN} \in \{1, \cdots, MN\}$.

**B. Lyapunov-like Performance Analysis of the WCS**

In this part, in order to facilitate the controller design for the MAS, we convert Lyapunov-like performance requirements (9) of WCS (1) to a specific control objective of FFN (11).

Consider Lyapunov-like performance requirements (9). According to (5), (6) and (8), $\lambda_i(k)$ is independent of $x_i(k)$, which together with $\mathbb{E}[\xi_i(k)] = 0$ shows

$$\mathbb{E}[V_i(x_i(k+1)|x_i(k), z(k)|\beta_0, \pi)] = P \{\lambda_i(k) = 1|z(k)| x_i(k)|A_{x,i} Q A_{x,i} x_i(k)\}
+ P \{\lambda_i(k) = 0|z(k)| x_i(k)|A_{x,i} Q A_{x,i} x_i(k) + T_i(Q, \xi_i).$$

Then, condition (9) is equivalent to the condition that for all $x_i(k) \neq 0$, $\mathbb{E}[\xi_i(k)] = 0$

$$P \{\lambda_i(k) = 1|z(k)| x_i(k)|A_{x,i} Q A_{x,i} x_i(k) - \rho_i Q_i x_i(k)\}
+ P \{\lambda_i(k) = 0|z(k)| x_i(k)|A_{x,i} Q A_{x,i} x_i(k) - A_{x,i} Q A_{x,i} x_i(k)\},$$

which is equivalent to

$$P \{\lambda_i(k) = 1|z(k)| x_i(k)|A_{x,i} Q A_{x,i} x_i(k) - \rho_i Q_i x_i(k)\} \geq s_i,$$

where

$$s_i = \sup_{y \in \mathbb{R}^n, y 
eq 0} \frac{y^\top (A_{x,i} Q A_{x,i} - \rho_i Q_i) y}{y^\top (A_{x,i} Q A_{x,i} - A_{x,i} Q A_{x,i}) y}.$$

It is noted that $s_i$ represents the lower bound of the probability of successful transmission for system $i$ that ensures the desired Lyapunov decay rate $\rho_i$ under the WCS and MAS coupling.

Based on the above representation, we can then define $\Omega(s)$ consisting of all profiles of FFN (11) in $C_i$, under the influence of which the probability of successful transmission for each system $i$ is no less than $s_i$, that is,

$$\Omega(s) := \bigcap_{z_1, \cdots, z_n} \{C_{\mathcal{B}, 0}^0: \text{Col}(\Lambda_i) \geq s_i \} \subset C_i, \quad (15)$$

where $z = [z_1, \cdots, z_n]$. $C_i := \{z = \mu \in \mathcal{D}_\ast \otimes \mathcal{M}: \beta \in C_i \}$ and $\Lambda_i$ is defined in (12). From (12) and (13), $\Omega(s)$ consists of all profiles of FFN (11) ensuring the desired Lyapunov decay rates for all systems in WCS (1).

**Definition 2:** Given $\mathcal{M} \subset \mathcal{D}_\ast \otimes \mathcal{M}$, FFN (11) is called constrained control-state $\mathcal{M}$-stabilizable, if there exist a state feedback law $\pi \in \Pi$ and a positive integer $T$ such that $z(k; \beta_0, \pi) \in \mathcal{M}$ holds for any integer $k \geq T$ and any initial state profile $\beta_0 \in C_\beta$.

We have the following result on the $(Q, \rho)$-asymptotically stability of WCS (1).

**Lemma 1:** WCS (1) is $(Q, \rho)$-asymptotically stable with respect to FFN (11), if and only if FFN (11) is constrained control-state $\Omega(s)$-stabilizable, where $\Omega(s)$ is defined in (15).

**Proof:** The result can be directly obtained from (12), (13) and the construction of $\Omega(s)$. $\Box$

For $\mathcal{M} \subset \mathcal{D}_\ast \otimes \mathcal{M}$, define $\Phi(\mathcal{M}) := \{\beta \in C_\beta: \text{such that } u(\beta) \in \mathcal{M}\}$. Correspondingly, for any $\beta \in \Phi(\mathcal{M})$, define $C_{\mathcal{M}}(\beta) = \{u \in C_u(\beta): u(\beta) \in \mathcal{M}\}$.

**Definition 3:** Given $\mathcal{M} \subset \mathcal{D}_\ast \otimes \mathcal{M}$, a subset $\mathcal{G} \subset \Phi(\mathcal{M})$ is called a constrained control invariant set (CCIS) of FFN (11) with respect to $\mathcal{M}$, if for any $\beta_0 \in \mathcal{G}$, there exists a control sequence $u = \{u(k) \in C_{\mathcal{M}}(\beta(k)): k \in \mathbb{N}\}$ such that $\beta(k; \beta_0, u) \in \mathcal{G}$ holds for any $k \in \mathbb{N}$.

The union of all CCISs with respect to $\mathcal{M}$ is called its largest constrained control invariant set (LCCIS) with respect to $\mathcal{M}$, denoted by $I(\mathcal{M})$.

By virtue of LCCIS, the following result establishes the equivalence between constrained control-state set stabilization and constrained set stabilization, the proof of which is reported in [27].

**Lemma 2:** FFN (11) is constrained control-state $\mathcal{M}$-stabilizable, if and only if it is constrained $I(\mathcal{M})$-stabilizable.

Based on Lemmas 1 and 2, the following result deduces the $(Q, \rho)$-asymptotically stability of WCS (1) to the constrained set stabilization of FFN (11).

**Theorem 1:** WCS (1) is $(Q, \rho)$-asymptotically stable with respect to FFN (11) if and only if FFN (11) is constrained $I(\Omega(s))$-stabilizable, where $\Omega(s)$ is defined in (15).

**Proof:** The result can be directly obtained from Lemmas 1 and 2, so we omit the proof here. $\Box$

**C. A Graphical Method for Feasible Controller Design**

In this part, we present a graph-based criterion on $(Q, \rho)$-asymptotically stability of WCS (1), which is much easier to verify. To this end, we introduce the constrained state transition graph (STG) $G[C_{\beta, \beta}^0, C_{u, u}^0] = (V(G[C_{\beta, \beta}^0]), E(G[C_{\beta, \beta}^0, C_u^0]))$.
with respect to state constraints $C^0_β$ and control constraints $C^u_β (β) , β ∈ C^0_β$.

Represent each state profile $δ^0_β ∈ C^0_β$ by a vertex $v_a$ and collect all vertices to form the vertex set $V(G(C^0_β \cup C^u_β))$. In addition, represent each constrained one-step state profile transition from $δ^0_β ∈ C^0_β$ to $δ^0_u ∈ C^0_u$ by a directed edge, denoted by $(v_a, v_b)$, and collect all directed edges to form a edge set $E(G(C^0_β \cup C^u_β))$, then $E(G(C^0_β \cup C^u_β)) = \{(v_a, v_b) ∈ C^0_β × C^0_u : δ^0_u ∈ D_1 (δ^0_β , C^0_u)\}$, where $D_1 (δ^0_β , C^0_u)$ denotes the one-step reachable set of state profile $δ^0_β$ with respect to control constraint $C^0_u (δ^0_β)$. Then, it holds that $D_1 (δ^0_β , C^0_u) = \{Col_a(Blk_k(F)) : δ^0_u ∈ C^0_u (δ^0_β)\}$.

By Definition 3, LCCIS $I(Ω(s))$ is essentially an LCIS contained in $Φ(Ω(s))$ with control constraints $C^u(β) , β ∈ Φ(Ω(s))$. Thus, by virtue of Algorithm 2 in [28] with replacing $G[Φ(Ω(s))] by G[Φ(Ω(s)), C^u(Ω(s))]$, one can obtain $I(Ω(s))$.

Assume that $I(Ω(s)) = \emptyset$. We construct a STG $Gc$ to check the constrained $I(Ω(s))$-stabilizability by contracting $I(Ω(s))$ to a single vertex and verifying all edges in $G[Col_β (I(Ω(s))) \cup \{v_o, C_μ\}$. More specifically, the STG $Gc$ is defined as $V(Gc) = (C^0_β \cup I(Ω(s))) \cup \{v_o\}$ and

$$E(Gc) := E^T (G) \cup \{(v_o, v_a) : \text{there exists } δ^0_β \in I(Ω(s)) \text{ such that } δ^0_β ∈ D_1 (δ^0_u ; C_μ) , v_a ∈ V(G)\},$$

where $v_0$ is a new node representing $I(Ω(s))$, $E^T (G) := \{(v_o, v_a) \in E(G)\}$ and $G := G[Col_β \setminus I(Ω(s))]$. Then, we can adopt the breadth-first search algorithm to check the constrained $I(Ω(s))$-stabilization of FFN (11).

We have the following criterion on $(Q, p)$-asymptotically stability of WCS (1), the proof of which is reported in [27].

**Theorem 2:** WCS (1) is $(Q, p)$-asymptotically stable with respect to FFN (11), if and only if $V(T_{n_0}) = V(Gc)$, where $T_{n_0}$ is the breadth-first spanning tree of $Gc$ rooted at $v_0$. Moreover, feasible state feedback laws $w^∗$ with state feedback gain matrices $L^∗ = [l_1 l_2 \cdots l_n]$ can be constructed as follows:

$$I^∗_a \subseteq \{U_a, \delta^0_β \in I(Ω(s))\},$$

$$\overline{U}_a, \delta^0_β \in C^0_β \setminus I(Ω(s)),$$

$$\Delta_M, \delta^0_β \in Δ_N \setminus C^0_β,$$

where

$$U_a = \{ δ^l_M ∈ C^u_β (δ^0_β) : \sum \text{Row}_h (Col_a (Blk_k(F))) = 1\},$$

$$\overline{U}_a = \{ δ^l_M ∈ C_μ (δ^0_β) : Col_a (Blk_k(F)) = p[t(v_o, v_a)]\},$$

$p[v_o, v_a]$ denotes the set of all paths from $v_0$ to $v_a$ with the number of vertices in each path $p$ being $t(v_o, v_a)$, and $p[j]$ denotes the $j$-th element of path $p$.

**IV. ILLUSTRATIVE EXAMPLE**

Consider a heterogeneous IIoT system consisting of two autonomous assembly arms and an automated guided vehicle system (AGVS) of three AGVs. When the raw materials of the production line are about to run out, the AGVS enter the workshop of autonomous assembly arms. Then, two autonomous assembly arms load raw materials into the AGVS by exchanging information between AGVs and remote controllers via wireless networks. Finally, the AGVS transport raw materials to the corresponding production line.

In the AGVS, assume that only two state agents are responsible for transporting raw materials, and the control agent does not have the transport ability. Discretize the workshop of AGVS into three two dimensional regions. Assume that the AGVS has three modes as $A_{11} = [1 \ 0 \ 0]$, $A_{12} = [1 \ 0 \ 0]$, $A_{21} = [1 \ 0 \ 0]$, $A_{22} = [1 \ 0 \ 0]$; $B_{11} = [1 \ 0 \ 0]$, $B_{21} = [0 \ 1 \ 0]$. Then, the AGVS is modeled as the following FFN with profile-dependent switching topology:

$$\overline{β} (k+1) = \overline{a} (k) + \overline{b} (k) + \overline{c} (k) \times 3 \overline{β} (k)$$

where $u(k), \overline{β}(k) ∈ β_3, i = 1, 2$.

Assume that the two autonomous assembly arms are located in region 0 and region 2, respectively. The dynamics of the WCS of the two autonomous assembly arms is in the form of (1) with states $x_1(k) ∈ ℜ$ and $x_2(k) = [x_{s1}(k) x_{s2}(k)] ∈ ℜ^2$ denoting the differences between current and desired states, where $A_{s1} = 0.4$, $A_{s2} = 1.1$, $A_{s3} = [-0.4 \ -0.1 \ 0.0 \ 0.6]$, and $A_{s4} = [-1 \ -0.4 \ -0.5 \ 0.3]$. They are perturbed by zero-mean univariate Gaussian noises. Let $p_1 = 0.75$, $p_2 = 0.95$, $Q_1 = 1$ and suppose that $Q_2$ solve $A_{s2} Q_2 A_{s2}^T = 0.7Q_2 + I$. Then, by (14), we can obtain $s_1 = 0.4$ and $s_2 = 0.42$.

The algebraic equivalent form of profile-dependent switching signal is $σ (k) = Z (k)$, where $Z = δ_1 [1 \ 3 \ 1 \ 1 \ 2 \ 3 \ 2 \ 3 \ 1 \ 1 \ 2 \ 1 \ 1 \ 2 \ 1 \ 1 \ 3 \ 2 \ 2 \ 1 \ 3 \ 1 \ 1 \ 3 \ 1]$. Then, we can obtain the equivalent algebraic form of FFN (17) as $β (k+1) = Fz(k)$, where $F = δ_1 [7 \ 3 \ 5 \ 2 \ 8 \ 6 \ 1 \ 3 \ 9 \ 8 \ 4 \ 1 \ 7 \ 5 \ 2 \ 6 \ 5 \ 1 \ 3 \ 9 \ 4 \ 4 \ 1]$. Let $C_β = Δ_β$ and

$$C_μ (β) = \{ δ^l_1, δ^l_2, δ^l_3, δ^l_4, δ^l_5 : β ∈ δ^l_i, i = 1, \cdots, 4\},$$

$$\{ δ^l_6, δ^l_7, δ^l_8, δ^l_9, \ β ∈ δ^l_i, i = 5, \cdots, 9\}.$$
feasible state feedback laws of AGVS can be designed as
$L^* = \delta_3[2 1 1 3 j 2 2 3]$, $i = 1; 2$, $j = 2; 3$.
By resorting to the Monte Carlo method and averaging over 100 simulation results, we plot in Fig. 2 the evolution of the states for the WCS with two state agents of the AGVS all starting from position 2 under the obtained feasible state feedback law $\pi^*_1$ with $L_{1}^* = \delta_3[2 1 1 3 2 2 3]$, and a random state feedback law $\pi$ with $L = \delta_3[2 1 1 2 2 3 2 2]$. Simulation results show that state feedback laws $\pi^*_1$ and $\pi$ all ensure the Lyapunov-like performance of the WCS and the transient period $T$ under $\pi^*_1$ is shorter than that under $\pi$, and that is because under $\pi^*_1$, each state profile of the AGVS enters $I(\Omega(s))$ along with a corresponding path in $T_{\nu^*_1}$.

Fig. 2. The evolution of the empirical averages of the states for the WCS under state feedback law $\pi^*_1$ and $\pi$, respectively.

V. CONCLUSIONS

In this paper, we have focused on the controller design for the MAS to ensure the performance of WCS in the presence of WCS and MAS coupling. Using the ASSR approach, we have obtained an equivalent form for the WCS and MAS coupling. Then, we have proposed a criterion in terms of constrained set stabilization to guarantee the Lyapunov-like performance with expected decay rate. In addition, based on graph theory and the breath-first searching, we have designed state feedback controllers for the MAS to ensure the performance requirements of WCS in the presence of WCS and MAS coupling. Future works will devote to converting the set stabilization of large-scale MASs into the set stabilization of subsystems via aggregation method.

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