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DYNAMIC CHARACTERISTICS OF MESH–BASED NETWORK CONTROL SYSTEM UNDER OPTIMAL RESOURCE CIRCUMSTANCES

Dong Huang — Bigui He *

Network control system (NCS) has been presenting significance in industry and automation by supporting usability and convenience. However, for insufficiency for diversity of infrastructure and scalability, it has limitations in the field of flexibility for network architecture compared to the wireless mobile network. Hence, there shows the pressing need for tackling the existing network control system with control flow by wireless mesh network (WMN) with strong flexibility effectively. Consequently, for each control system, its stability is one of the prerequisites and criteria. In this paper, a novel optimization model was developed for planning the optimal resource utilization of wireless mesh network (WMN), and then the dynamic characteristics of mesh-based network control system are analyzed and discussed.

K e y w o r d s: wireless mesh network (WMN), network control system (NCS), dynamic characteristic, optimal resource

1 INTRODUCTION

The Internet of things and cloud computing are one of the main orientations to the next IT technologies of our country, and also should the global information grid be for the military use at the time of today. The Internet of things shows high requirements for the flexibility of the network structure, the adaptability and the manageability to the various traffic flows. On the other hand, as the objective of the cloud computing is the fast and reliable transition of computing flows, and it demands high flexibility and reliability of network structure. The global information grid calls for the scalability and survivability of the network satisfying the goal of information sharing and integrated processing in the battlefield condition. On the other hand, with the development of communication technology, Wireless Mesh Network (WMN) being a kind of distributed, high-capacity and high-rate wireless network, plays an important role in industry and daily life. It was widely used in many areas such as family broadband network, neighborhood network, emergency rescue, provisional meeting and so on. So it is a suitable transmission platform for the Internet of things and cloud computing.

For wireless mesh network (WMN), it shows a cost-effective solution for ubiquitous high-speed services [1]. For its dynamically self-organized and self-configured infrastructure, its nodes can automatically establish and maintain mesh connectivity among themselves. On the basis of demand of industrial control for WMN, up-to-date regulating methods, and the characteristics of WMN in industry control network, the characteristics of industrial network control for WMN application is under study. The research on effect of communication delay of network control system on industrial control is underway. Further, the adjustment and control abilities of WMN for new industry supporting as well as network optimization technique needed be studied. Finally, on the basis of Smart Grid control system requirement, the key techniques of WMN in electrical information transmission corridor should be considered.

Each node in WMN, called mesh router, operates not only as a host but also as a router for the traffic flow. Mesh routers are interconnected mutually so as to form a fixed infrastructure offering connectivity ability to mesh clients and gateway functionality for connections to the Internet of the mobile network users [2]. This infrastructure, forming a wireless backhaul network, is integrated with the network backbone by special routers called mesh gateways, as depicted in Fig.1. Mesh clients access the network backbone by multi-hop communications through the backhaul network [3].

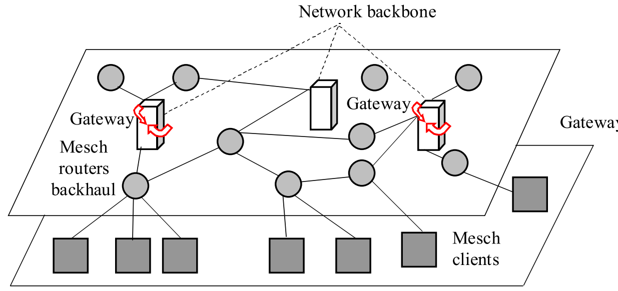

Fig. 1. Model of wireless mesh network

Network Control System (NCS) is the state-of-the-art controlling measure, and presents the promising applications in a variety of areas. It is a spatially distributed system in which the communication among plants, sensors, actuators, and controllers occurs through a shared

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band-limited digital communication network. So it shows its application values significantly in many areas, ranging from industry for good delivery to remote medical treatment.

In view of the many advantages of wireless mesh network in application areas, it can be extended into NCS plants. So on the one hand, the delay time in the control loop of the network control system needs to be considered. In such network control system, information is transmitted from sensors to controllers via wireless routers and gateways, and the process from controllers to actuators may not be instantaneous and may suffer transmission delays. According to [4], the network delay has strong influence on the NCS's quality of control that can be ameliorated as the delay time decreasing. Such network delay can be highly variable due to their strong dependence on variable network conditions.

Furthermore, stability becomes a key factor of criterion for the network control system. Recently, significant efforts have been devoted to developing stability illuminations by handling the network delay in NCS, but there transmission scenarios are restrained within the scope of the wired medium and the simplified sensor network. [5]addresses the problems of how uncertain delays smaller than one sampling period affect the stability of the NCS. [6] states feedback stability of NCS with varying sampling period in using results from hybrid systems theory. In the case of random delays, queuing frameworks[7], timestamps and stochastic control theory[8] have been proposed for the stability problem of NCS, and [9]addresses the problems of how uncertain delays smaller than one sampling period affect the stability of the NCS.

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In spite of stability showing its significance in mesh-based network control system and traffic planning, researchers and designers seldom take account of this factor in some particular scenarios. Moreover, the character of this dynamic factor can be used to decide and testify the inner quality that is essential to the flexibility and scalability of the wireless mesh network system. So our novelty and contribution is to combine the network control system with wireless mesh network, and determine the performance and characteristics of stability for the whole system.

2 PROBLEM STATEMENT

In this paper, our focus is on the stability-one of the important dynamic characteristics of mesh-based network control system on condition that we maximize network resource. A very important requirement for the network performance evaluation is to minimize its delay time and maximize the network resource utilization. This performance measure is however affected by many factors such as link reliability, multi-path state, the number of nodes and link capacity. So in the next section, we develop the mathematical framework to model a maximum network resource utilization problem subject to some specific constraints under statement and formulations of it. In section 4, in the documentation of optimum quality of control for the network control system, we derive the condition for stability of the mesh-based network control system for the scenario where there is only the control flow in the network. In section 5, we analyze the theory for simplicity but without loss of generality.

So our objective of this work is to illustrate and determine whether the mesh-based network control system is stable in finite regions under the optimal transmission condition. Prior to the dynamic characteristics of the mesh-based network control system being analyzed, it is necessary to take the optimal decomposition model of the wireless mesh network into consideration with the aid of optimization decomposition.

To the best of our knowledge, this work presents the first formulation and study of the dynamic characteristics related to mesh-based network control system.

3 MODEL DESCRIPTION

3.1 Modelling the system

The multiple data flow transmission problem can be modeled as follows.

Generally the normal transmission delay time of wireless mesh network can be depicted by Little formula $T = \frac{N}{\lambda}$ where N is the average amount of message in the system, T is the average delay time for the message in the system, and λ is the average arriving rate for the message in the system. The basic description for this model can be depicted as Fig.2.

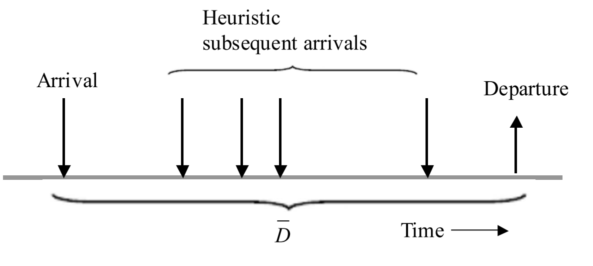

Fig. 2. Diagram of Little formula

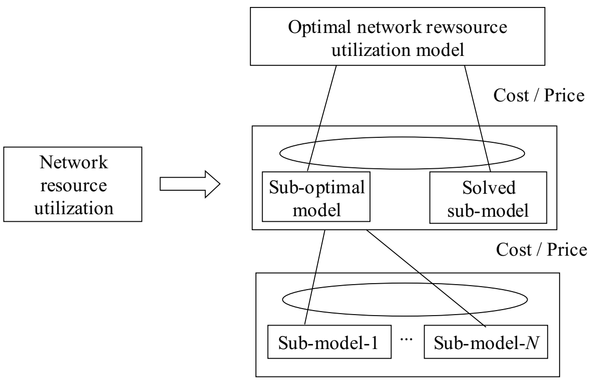

Fig. 3. Block diagram of solving process for resource optimum utilization of communication network

3.2 Solving process of resource optimum-utilization for communication network

Although the transmission delay time is important for the mesh network resource utilization, but it is not enough. Therefore, it is necessary to establish the solving process of network resource as depicted in Fig.3, and we could analyze the optimal network performance by dividing the whole model into several models and sub-models.

So for sufficiently describing the network resource utilization, the joint optimization between transmission link rate and link reliability should be considered [10]. The general utilization model for this optimization can be illustrated as follows

$$\begin{aligned} &\text{maximize}\,\{U_s(x_s,\rho_s)\} = \\ &= \theta_s \frac{x_s^{1-\alpha} - x_x^{\min(1-\alpha)}}{x_s^{\max(1-\alpha)} - x_s^{\min(1-\alpha)}} \\ &+(1-\theta_s)\frac{\rho_s^{(1-\alpha)} - \rho_s^{\min(1-\alpha)}}{\rho_s^{\max(1-\alpha)} - \rho_s^{\min(1-\alpha)}}, \\ &\text{subject to} \quad \rho_s^{\min} \leqslant \rho \leqslant 1 \end{aligned} \tag{1}$$

where for the oddeven number of sending nodes for the traffic flow the weight parameter is

$$\theta_s = \begin{cases} 0.5 - \nu & \text{odd} \\ 0.5 + \nu & \text{even} \end{cases}$$

and where ν beint is the bias parameter, ρ_s is the link reliability when using the link $L(s)$ for the message transmission, α is the cost coefficient, x_s is the amount of traffic flow for source S.

4 STABILITY ANALYSIS

In this section we demonstrate the dynamic characteristics of mesh-based network control system, as shown in Fig.4. We will now consider stability under file arrivals and departures. To adopt a simple Markov chain description, we assume that packet sizes are exponentially distributed with mean 1.

As depicted in Fig 5, two separate phenomena in a network. Flows in progress compete with each other for bandwidth and keep the link filled. If their transfer rates converge, we say that the system is stable at a small time scale. Flows arrive bringing a file of fixed size to be transferred and leave when the transfer is complete. We say that the system is stable at a large time scale if the number of flows in progress is finite at all times.

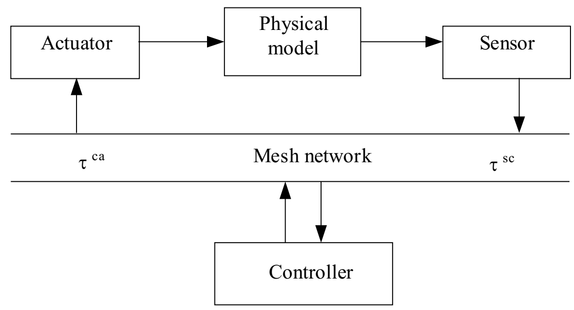

Fig. 4. Architecture of mesh-based network control system

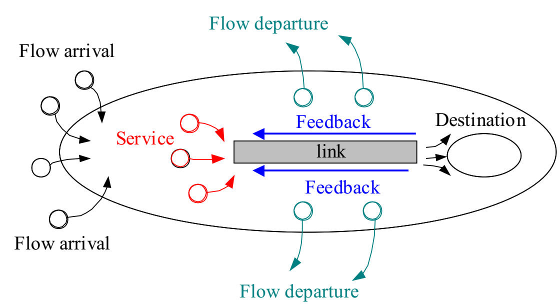

Fig. 5. Two separate phenomena (arrival and departure) in a network

From the point of view for the traffic flows in the communication network, there exists the network congestion when the traffic load is large. Hence, the stability-one of the dynamic characteristics can not be guaranteed. The reasons for this phenomenon could be classified into two sections. On one hand, from the point of view for the single traffic flow transmission link, the traffic flow transmission may become stable when the amount of traffic flow for sending exceeds the link capacity during the process of message receiving and forwarding; on the other hand, when there exists several transmission links in communication network, and each traffic flow has different link sets in its own transmission path, the relativity between different link sets for its corresponding traffic flow exists. In this situation, although the traffic flow load in every link is less than the link capacity, the stable transmission for traffic flow in communication network can not be guaranteed. So the large dimension transmission for flows and indefinite multi-path transmission have bad effect on the internal state of communication network. Therefore, it is necessary to adopt appropriate resource management method for guaranteeing the stable state under the indefinite traffic flow transmission transition and transmission path.

In this subsection, for simplicity we consider there is only the control flow transmitted in the mesh-based network. The subscript i will be dropped for short. For clarity purpose, we use $[0 \quad \delta)$ to denote the time interval $[0 \quad \delta h_i)$, where h_i is the sampling period of the i-th plant. Throughout this subsection, the subscripts "c and "o present the abbreviations for closed-loop and open-loop network systems, respectively.

This subsection focuses on the stability of a single plant with closed/open feedback control loops. We assume that this single control network system is open-loop at times because the outside extended link of the network may be occupied by other network control flow [10]. The single control system can be described by a switched system [11], which is composed of the open-loop subsystem and the closed-loop one.

Suppose $\gamma(\delta)$ is the state vector of open-loop subsystem, and A_0 is its corresponding state matrix. The open-loop network system can be set as

$$\gamma(\delta+1) = A_c\gamma(\delta)\,. \tag{2}$$

And suppose $\gamma(\delta)$ and $\gamma(\delta-1)$ are the state vectors of closed-loop subsystem, and A_c, B_c are their corresponding state matrices respectively, and the close-loop one can be set as [12]

$$\gamma(\delta+1) = B_c\gamma(\delta-T)\,,\ (\delta>0) \tag{3}$$

where

$$A_0 = \Phi = e^{A_c h}, \quad A_{ci} = \sum_{j=1}^{r}\theta_{ij}(\delta)A_{cij}\,,$$
$$B_{ci} = \sum_{j=1}^{r}\theta_{ij}(\delta)B_{cij}\,,\ \sum_{j=1}^{r}\theta_{ij} = 1\,,\ \theta_{ij}(\delta)\ge 0\,,$$
$$A_{cij} = \Phi_i + G_{ij}K_i \text{ and } B_{cij} = \Gamma_i K_i - G_{ij}K_i\,.$$

DEFINITION 1. For any $\delta>0$, assume $\tau_{ci}(\delta)$ is the total number of sampling periods of the i-th plant being closed-loop (attended by the controller) during $[0 \ \ \delta)$, and the ratio $\frac{\tau_{ci}(\delta)}{\delta}$ is the attention rate of the i-th plant [13]. Let $N_i(\delta)$ denote the total number of switching for the i-th plant between open-loop and closed-loop status, and therefore, $N_i(\delta)$ is considered to be the attention frequency.

The system $\gamma(\delta+1) = f\big(\gamma(\delta)\big)$ with $f(0)=0$, is considered to be exponentially stable with decay rate [14] $0<\rho<1$, if $\big\|\gamma(\delta)\big\| \le c\rho^{\delta-\delta_0}\big\|\gamma(0)\big\|$, $\forall\delta\ge\delta_0$.

For the single control system including subsystem (2) and subsystem (3), choose the following appropriate Lyapunov-like function [15]

$$V(\delta) = \begin{cases} V_c(\delta)\,, & \text{if closed-loop,}\\ V_o(\delta)\,, & \text{if open-loop.}\end{cases} \tag{4}$$

The following result gives exponential stability of a single control network system.

Based on the assumption and observation of [16] we propose a deduction of a new Lyapunov stability condition on the mesh-based network control system by the following content.

The mesh-based network control system including the unstable open-loop subsystem see (5) and the stable closed-loop subsystem see (6) is exponentially stable with decay rate ρ $(0<\rho<1)$, provided that there exist φ, ρ, κ^* and κ_c satisfying the following prerequisites:

- The positive functions $V_c(\delta)$ and $V_o(\delta)$ in (7) satisfy

$$V_c(\delta+1)\le\kappa_c V_c(\delta) \text{ and } V_o(\delta+1)\le\kappa_o V_o(\delta) \tag{5}$$

where $0<\kappa_c<1$ and $\kappa_0>1$;

- There exists a constant scalar $\mu>1$, such that

$$V_c(\delta)\le\varphi V_o(\delta)\,,\ V_o(\delta)\le\varphi V_c(\delta) \tag{6}$$

for any $\gamma(\delta)$;

- The attention rate and the attention frequency satisfy

$$\frac{\tau_c(\delta)}{\delta} \ge \frac{\ln\kappa_o - \ln\kappa^*}{\ln\kappa_o - \ln\kappa_c}\,,\ N(\delta)\le N_0 + \frac{\delta}{T} \tag{7}$$

$$\text{and}\quad N_0 = \frac{\ln c}{\ln\varphi}\,,\ T > T_\alpha = \frac{\ln\varphi}{2\ln\rho - \ln\kappa^*} \tag{8}$$

where T_α and N_0 are called the dwell time and the chatter bound respectively, and

$$\kappa_c<\kappa^*<1\,,\quad 0<\rho<1\,.$$

The WMN-based network control system is exponentially stable with decay rate ρ $(0<\rho<1)$, and T denotes the minimum transmission delay of mesh-based network.

5 COMPUTATIONAL SIMULATION

In this section, we provide examples to verify the algorithm and the theory deduced above.

EXAMPLE 1. We consider the related parameter values of the network control system

$$s=30,\quad T=0.191,\mathrm{s}\quad T_c=1.73\,\mathrm{s}\quad \eta=6.3,$$
$$nu=0.91,\quad \rho_s-0.79\quad \alpha=0.6,\quad x_s=3$$

where s is the number of mesh nodes.

According to the equivalent optimization algorithm, the minimum delay T_1 of the network system is 0.805 ms. Assume $\kappa^*=0.63$, $\kappa_0=1.96$, $\kappa_c=0.21$, $\varphi=3.69$,

$$A_{c1} = \begin{bmatrix}1.2 & 0.035\\ 0 & 0.056\end{bmatrix},\qquad B_{c1} = \begin{bmatrix}0.136\\ 0.162\end{bmatrix},$$

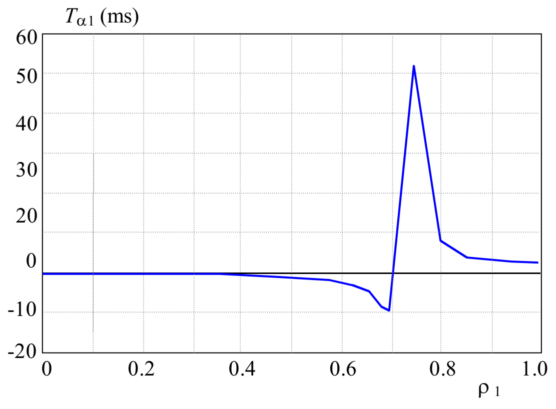

Fig. 6. The relationship between decay rate ρ_1 and $T\alpha_1$

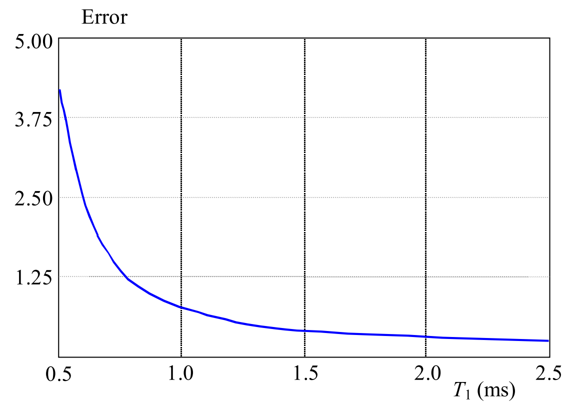

Fig. 7. Response state of control system with delay T_1

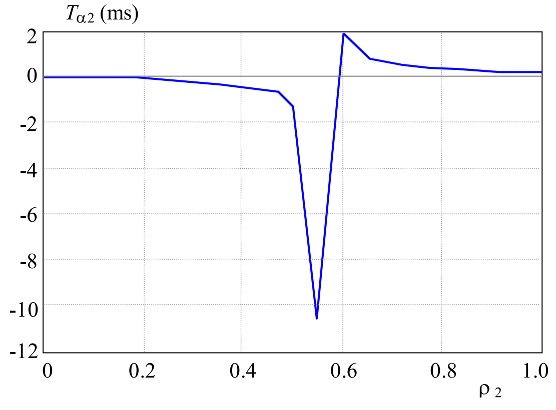

Fig. 8. The relationship between decay rate ρ_2 and $T\alpha_2$

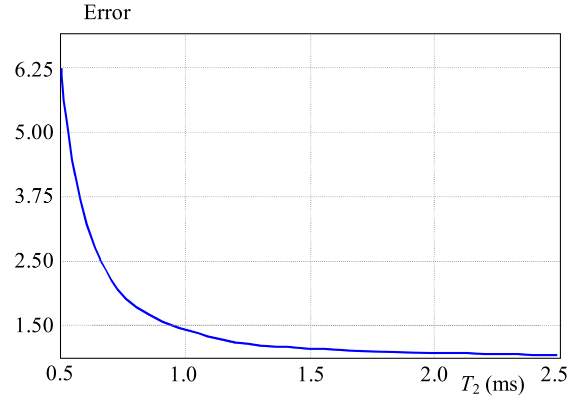

Fig. 9. Response state of control system with delay T_2

we can get the relationship between decay rate ρ_1 and $T_{\alpha 1}$ in Fig. 6. We conclude that the inequality $\rho_1 \leq 0.718$ results in the network control system being exponentially stable, whatever the delay time T_1 $(T_1 \geq 0)$ is. We set $\rho_1 = 0.73$ and use inequality (7) as the criterion. So from Section 4, we can get that $T_{\alpha 1} = 21.3$ ms, and the minimum delay of the network T_1 $(T_1 < T_{\alpha 1})$ does not satisfy the requirements of stability condition of the single network control loop. Therefore, the WMN-based network control system is unstable under this condition. In Fig. 7, we can get the response curve of network control system in Example 1.

EXAMPLE 2. We consider the related parameter values of the network control system are:

$$s = 29, \quad T = 0.998\,0s, \quad \nu = 0.83, \quad \rho_s = 0.72,$$
$$\alpha = 0.33, \quad x_s = 8, \quad \eta = 20.$$

where s denotes the number of mesh nodes, and

$$A_{c1} = \begin{bmatrix} 0.889 & 0.062 \\ 0 & 0.036 \end{bmatrix}, \qquad B_{c2} = \begin{bmatrix} 0.092 \\ 0.366. \end{bmatrix}$$

According to the equivalent optimization algorithm, the minimum delay T_2 of the network system is 0.86 ms. Assume $\kappa^* = 0.21$, $\kappa_0 = 1.6$, $\kappa_c = 0.21, \varphi = 1.6$, and we can get the relationship between decay rate ρ_2 and $T_{\alpha 2}$ in Fig. 8. We conclude that the inequality $\rho_2 | \rho_2 \leq 0.55 \bigcup \rho_2 \geq 0.621$ results in the network control system being exponentially stable, whatever the delay time T_2 $(T_2 \geq 0)$ is. We set $\rho_2 = 0.609$ and use inequality (7) as the criterion. So from Section 4, we can get that $T_{\alpha 2} = 1.62$ ms, and the minimum delay of the network T_2 $(T_2 > T_{\alpha 2})$ satisfies the requirements of stability condition of the single network control loop. Therefore, the mesh-based network control system is unstable under this condition. In Fig. 9, we can get the response curve of network control system in Example 2.

According to the equivalent optimization algorithm, the minimum delay T_3 of the network system is 0.98 ms. Assume $\kappa^* = 0.31$, $\kappa_0 = 1.9$, $\kappa_c = 0.29$, $\varphi = 1.3$, and we can get the relationship between decay rate ρ_3 and $T_{\alpha 3}$ in Fig. 11. We conclude that the inequality $\rho_3 \leq 0.58$ results in the network control system being exponentially stable, whatever the delay time T_3 is. We set $\rho_3 = 0.6$ and use inequality (8) as the criterion. So, from Section 4, we can get that $T_{\alpha 3} = 1.76$ ms, and the minimum delay of the network T_3 $(T_3 < T_{\alpha 3})$ does not satisfy the requirements of stability condition of the single network control loop. Therefore, the WMN-based network control system is unstable under this condition.

According to the examples and discussion above, we can summarize the following issues:

- The flow and delay time shows significant in the effects on the dynamic characteristics of mesh-based network control system.
- In spite of the different conditions or parameters, such as κ^*, κ_0, $\kappa_c$andφ the stability extent of Mesh-based network control system under the circumstance of optimum quality of control may be confined in limited region of [0,1].

6 CONCLUSIONS

In this paper, we propose a flexible scheme for network control system of which the control information can be transmitted by wireless mesh network. First, we analyze the network delay and the optimal resource utilization of Mesh-based network such that the quality of optimum transmission for the network control system can be guaranteed. Then in the following section, we enumerate the criterion of stability condition of Mesh-based network control system. In the final section, we present the numerical examples and simulations for the theory and draw the conclusion that if the optimal solution satisfies the exponential stability condition of mesh-based network control system, the system is stable or otherwise. And our results show that, when we have the minimum delay time of the network ensuring the quality of optimum transmission, the stability extent of the whole network control system become restrictive. Considering only the signal flow for the system in work and also implementing hybrid flows including control flows and various traffic flows will be pursued in the next research.

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