Robust Congestion Control in NFVs and WSDNs with Propagation Delay and External Interference

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Abstract. In today's networks, two new concepts have emerged aiming at cost reduction and control network congestion, namely Network Functions Virtualization (NFV) and Software Defined Networking (SDN). NFV proposes to run the network functions as software instances on datacenters (DC), while SDN presents a new network architecture where the control plane is shifted to a centralized controller. Wireless Software Defined Networking (WSDN) is considered based on the wireless environments, such as propagation delay and external interference. It is critical to keep the network stable at the ideal stable state during congestion control. However, stability control is insufficient to achieve these aims in the presence of propagation delay and external interference.

In this paper, we propose robust congestion control to tackle these problems. Firstly, the traditional WNCS model is introduced to present a basic control model with delay. Then, a robust congestion control model in NFVs and WSDNs is presented, which is extended the traditional WNCS model by utilizing Lyapunov-Krasovskii functionals. Next, Lyapunov-Krasovskii functionals and linear matrix inequalities (LMIs) are adopted to analyze system stabilization with external disturbance. The sufficient conditions are formulated by Linear Matrix Inequalities (LMIs). Finally, a numerical simulation is conducted to indicate the effectiveness of the proposed scheme.

Keywords: Linear Matrix Inequality (LMI) · Lyapunov-Krasovskii functionals · Network Functions Virtualization (NFV) · Robust congestion control · Wireless Software Defined Networking (WSDN)

1 Introduction

With the rapid growth of user data, network services, and the persistent necessity of reducing costs and control network congestion, today's wireless network is facing various challenges [1]. As a key challenge, virtualization of all aspects of our daily life has been resulted in wireless network environments. It turns out that wireless network itself has to be virtualized. New standards and technologies have been developed for network virtualization.

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We have seen growing interest in the operation of the network functions as software - a trend known as Network Functions Virtualization (NFV) [2]. NFV has arisen as an operator-promoted initiative with the objective of increasing the flexibility of network services control and management within the operators' networks [3]. The network functions through software that run on several hardware can be achieved to allocate the network resources. The concept of NFV involves implementing network functions in software which could be located in kinds of infrastructures, including data centres, network nodes and so on. The NFV group of the European Telecommunications Standards Institute (ETSI) is working on developing standards to promote the NFV approach [3].

In parallel, Software Defined Networking (SDN) is being used to steer flows through proper network functions to enforce control policies and jointly manage network [2,4]. Wireless SDN (WSDN) presents a new architecture where the control plane is shifted to a centralized controller [5].

"NFV and WSDN" is able to achieve three important goals: (i) satisfying Quality of Service (QoS) requirement on VNF performance or availability; (ii) accurately monitoring and manipulating network traffic, and controlling network congestion; (iii) minimizing VNF network costs and maximizing global throughput. However, simultaneously achieving all three goals is not possible today, and fundamentally requires more control than NFV and WSDN can offer [2].

It is essential to effectively control network congestion and manage sorts of QoS in current WSDNs to keep network stability in these VNFs [7–9]. Moreover, the stabilized WSDN adopted the stability control may become unstable again due to propagation delay and external interference. Propagation delays increase network cost and reduce network reliability [10]. The external interference in WSDNs leads to network instability [11]. Thus the paper re-stabilizes the network parameters at the ideal states, and a novel concept of robust congestion control is proposed in the network of "NFV and WSDN" architecture. Robust congestion control means that the network parameters are convergent for congestion control in the presence of external interference.

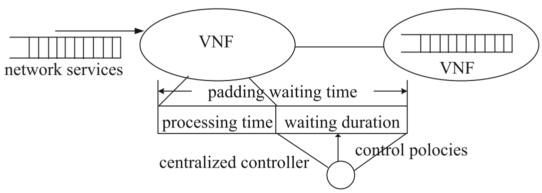

Fig. 1. The padding waiting time for robust control in NFVs and WSDNs.

The padding waiting time is considered as a key parameter for robust congestion control in NFVs and WSDNs. As shown in Fig. 1, the processing time is the duration consumed to process a VNF. A waiting duration may also be introduced by a ideal state to slow down the data plane, and further processing of VNFs is postponed for this waiting duration. The padding waiting time is defined as the sum of the processing time and the waiting duration. When all VNFs have the same processing speeds and the sum of the padding waiting time is minimized, the total service time of all VNFs may be shortened and the WSDN throughput may be maximized.

Excessively limited padding waiting time at source-side may reduce the network throughput and link utilization, and prevent the network from working at the ideal state. Meanwhile, the padding waiting time at source-side may fluctuate unstably around the ideal state under the influence of the external interferences. The instability of all VNFs may cause the instability of the whole network. All VNFs unify their states to achieve the robust congestion control from the centralized controller, so as to minimize the overload of each VNF and keep maximizing the throughput of global WSDN.

Robust control have attracted particular interest in the literature for the traditional network control system [10,12], however, these studies have three crucial limitations. The control policies are firstly not implemented in VNFs. Then, propagation delay is seldom considered in the path of VNF-to-controller during congestion control. And the last limitation is that the traditional theories of the Wireless Network Control Systems (WNCSs) model for robust congestion control do not work well in WSDNs.

Therefore, we focus on modeling the robust congestion control problem and designing the control policies through sufficient conditions of robust congestion control by means of Lyapunov-Krasovskii functionals. A new robust congestion control model is proposed by using Lyapunov-Krasovskii functionals [13,14]. The centralized controller generates control polices and feeds control instructions to the VNFs. Thus, the VNFs could follow these instructions as software to make proper adjustments of the padding waiting time.

2 Model and Analysis

Figure 2 shows a typical scenario of VNFs in WSDNs with propagation delay. The centralized controller is able to collect information from all VNFs to deal with network congestion. There exists an ideal stable state in each VNF for stability control of network congestion. The control policies in the centralized controller are provided to process the VNFs based on the ideal stable state. Our goal is to keep the global network parameters stable at the ideal stable state by robust congestion control with propagation delay and external interference.

The controller designs the control policies and then sends control instructions to adjust the padding waiting time in each VNF. There exists a set of network services, where each network service is composed of a set of VNFs. Each VNF must be processed by means of QoS requirement, satisfying the QoS constraints between the difficult VNFs that compose the corresponding network services.

With propagation delay and external interference, the current state $\bar{S}_i(k)$ in each VNF is considered to constantly approach to the ideal state $\bar{S}_1(k) \rightarrow S_1(k), \cdots, \bar{S}_i(k) \rightarrow S_i(k), \cdots, \bar{S}_N(k) \rightarrow S_N(k)$ by robust congestion control,

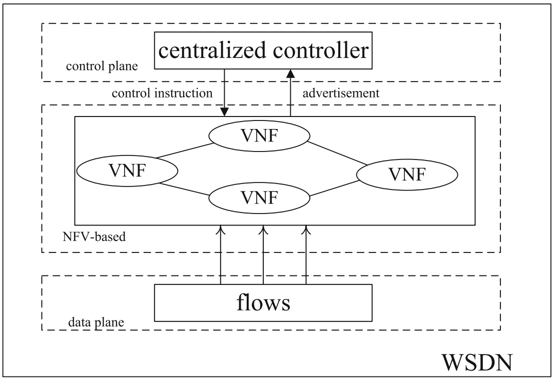

Fig. 2. A typical scenario of NFV with propagation delay in WSDNs.

where k is the discrete count number. $x_i(k) = \bar{S}_i(k) - S_i(k)$ is defined as the error state of the padding waiting time and $\lim_{k\to\infty} ||\bar{S}_i(k) - S_i(k)|| = 0$ for $i = 1, \ldots, N$.

According to analyzing the propagation delay in the closed-loop WSDN, the propagation delay from the VNF to the centralized controller (VC) and from the centralized controller to the VNF (CV) are defined as d_{vc} and d_{cv}, respectively. Suppose that the VC delay d_{vc} and CV delay d_{cv} are constants in WSDNs. The VNF receives the feedback message from the controller with the CV delay d_{cv} in Fig. 2. Denote the constant $d = d_{vc} + d_{cv}$.

The VNFs constantly adjust their padding waiting times following the control instructions. Initially, each VNF advertises the error state of the padding waiting time $x(k) = (x_i(k))$ to the controller. With the packet-in message, the controller calculates $x(k)$, and the controller classifies the global information of the error state and generates a control policy $u(k)$ to keep the padding waiting time stable. The control policy needs to stabilize the padding waiting time in the presence of propagation delay and external interference. The controller makes proper adjustments of the weighted matrix $B_u \in \mathbb{R}^{n\times n}$. Finally, the controller sends a packet-out message, which indicates that the flow originated the packet-in message has been implemented. The closed-loop WSDN is accomplished and modeled with propagation delay as $x(k+1) = Ax(k) + B_u u(k)$, where A is the parameters represented the network features that are non-negative constant matrices with appropriate dimensions.

The control instruction $u(k) = Kx(k),\ K \in \mathbb{R}^{n\times n}$ denotes robust congestion control strength, and the control policies are considered as

$$x(k+1) = Ax(k) + B_u Kx(k-d) \tag{1}$$

Considering external interference, the closed-loop network model can be formulated into a robust $H\infty$ control model. Simultaneously, the closed-loop WSDN (1) with the external interference part add as in (2)

$$x(k+1) = Ax(k) + B_u Kx(k-d) + B_w w(k), \tag{2}$$

where B_w is the weight of external interference that is non-negative constant matrices with appropriate dimensions. For convenience, we assume that the external interference is limited energy and duration.

Thus, the robust congestion control model is converted into a robust $H\infty$ control model. The robust $H\infty$ control model of the error state of the padding waiting time in the presence of propagation delay and external interference is formulated in the closed-loop WSDN.

Consider the following $H\infty$ performance index $J = \sum_{k=0}^{\infty}\{z^T(k)z(k) - \gamma^2 w^T(k)w(k)\}$, where J denotes the relation of the energy of the controlled output $z(k)$ and the external interference $w(k)$, and γ denotes $H\infty$ performance index that is a prescribed positive scalar. This inequality denotes robust $H\infty$ control in traditional WNCS robust congestion control model.

3 Problem Formulations of Robust $H\infty$ Control

According to (1), the robust $H\infty$ control model of the error state of the padding waiting time in the presence of propagation delay and external interference in the closed-loop WSDN is described by

$$\begin{cases} x(k+1) = Ax(k) + B_u u(k) + B_w w(k) \\ \quad u(k) = Kx(k-d) \\ \quad z(k) = Ix(k), \end{cases} \tag{3}$$

where $x(k) = [x_1(k), \ldots, x_n(k)]^T \in \mathbb{R}^n$ is the error state which denotes the varying value of the padding waiting time between the current state and the ideal state, $u(k) = [u_1(k), \ldots, u_n(k)]^T \in \mathbb{R}^n$ is the control instruction, $w(k) = [w_1(k), \ldots, w_n(k)]^T \in \mathbb{R}^n$ is the external interference of limited energy and duration with convariance matrix w and has expectation zero, $z(k) = [z_1(k), \ldots, z_n(k)]^T$ as a measurement is the output of the robust congestion control, k is the discrete count number. Define $A = (a_{ij})_{n\times n} = \begin{cases} a_{ij} = 0, \ if \ i < j \\ 0 \le a_{ij} \le 1, \ if \ i \ge j \end{cases}$, $B_u = (b_{ij})_{n\times n}, \ B_w = diag\{\widehat{b}_1, \widehat{b}_2, \ldots, \widehat{b}_n\}$, and the constant matrix $I \in \mathbb{R}^{n\times n}$.

Definition 1. *For the sake of the simplicity, the closed-loop WSDN (3) is stable with constant propagation delay $d = d_{vc} + d_{cv}$ in NFVs and WSDNs.*

Definition 2. *The closed-loop WSDN (3) is said to be stable, if there exists a state feedback control instruction $u(k) = Kx(k-d), \ K \in \mathbb{R}^{n\times n}$. Thus, $u(k)$ is said to the robust congestion control policies.*

Lemma 1 *(Schur Complement). Given constant matrices P, Q, R, where $P^T = P$, $Q^T = Q$, then the LMI $\begin{bmatrix} P & R \\ R^T & -Q \end{bmatrix} < 0$ is equivalent to the following condition: $Q > 0, \ P + RQ^{-1}R^T < 0$.*

4 Criteria of Robust $H\infty$ Control

In the following, let $\bar{A} = A - I,\ \bar{B} = B_u K$. Rewrite closed-loop WSDN of the error state (3) into a more compact form as

$$\begin{cases} y(k) = \bar{A}x(k) + \bar{B}x(k-d) + B_w w(k) \\ z(k) = Ix(k), \end{cases} \tag{4}$$

where $y(k) = x(k+1) - x(k)$ is the difference state, and $y(k) = [x_1(k+1) - x_1(k),\, x_2(k+1) - x_2(k), \ldots, x_n(k+1) - x_n(k)]^T$.

Theorem 1. *Consider the robust $H\infty$ control model of the error state with propagation delay and external interference in the closed-loop WSDN (4). Given the external interference attenuation level γ and positive integers d. If there exist appropriate dimension symmetric positive definite matrices $P > 0,\ Q > 0$ and $R > 0,\ X = \begin{bmatrix} X_{11} & X_{12} \\ * & X_{22} \end{bmatrix} \geq 0$, and appropriate dimension matrices $N_1,\ N_2$, so that the following conditions (5) and (6) hold:*

$$\varXi = \begin{bmatrix} X_{11} & X_{12} & N_1 \\ * & X_{22} & N_2 \\ * & * & R \end{bmatrix} \geq 0, \tag{5}$$

$$\varOmega = \begin{bmatrix} \omega_{11} & \omega_{12} & PB_w & \bar{A}^T & d\bar{A}^T & I \\ * & \omega_{22} & 0 & \bar{B}^T & d\bar{B}^T & 0 \\ * & * & -\gamma^2 I & B_w^T & dB_w^T & 0 \\ * & * & * & -P^{-1} & 0 & 0 \\ * & * & * & * & -dR^{-1} & 0 \\ * & * & * & * & * & -I \end{bmatrix} < 0, \tag{6}$$

where $\omega_{11} = P\bar{A} + \bar{A}^T P + Q + N_1 + N_1^T + dX_{11}, \omega_{12} = P\bar{B} - N_1 + N_2^T + dX_{12}$, $\omega_{22} = -Q - N_2 - N_2^T + dX_{22}$. Thus, the WSDN achieve robust $H\infty$ control.

Proof. We firstly define $y(l) = x(l+1) - x(l)$. Then, we obtain $x(k+1) = x(k) + y(k)$, and $x(k) - x(k-d) - \sum_{l=k-d}^{k-1} y(l) = 0$.

In the closed-loop WSDN, the Lyapunov-Krasovskii functionals can be expressed by

$$V(k) = x^T(k)Px(k) + \sum\nolimits_{j=k-d}^{k-1} x^T(j)Qx(j) + \sum\nolimits_{\theta=-d+1}^{0} \sum\nolimits_{j=k-1+\theta}^{k-1} y^T(j)Ry(j).$$

where $P = P^T > 0,\ Q = Q^T > 0$ and $R = R^T > 0$ are positive definite symmetric matrices. Define $\triangle V(k) = V(k+1) - V(k)$, thus

$$\begin{aligned} \triangle V(k) \leq{}& 2x^T(k)Py(k) + y^T(k)Py(k) + x^T(k)Qx(k) \\ &- x^T(k-d)Qx(k-d) + dy^T(k)Ry(k) - \sum\nolimits_{l=k-d}^{k-1} y^T(l)Ry(l). \end{aligned} \tag{7}$$

For any appropriate dimension matrix $N_i (i = 1, 2)$, we have

$$0 = 2[x^T(k)N_1 + x^T(k-d)N_2] \times [x(k) - x(k-d) - \sum\nolimits_{l=k-d}^{k-1} y(l)]. \quad (8)$$

And for an appropriate dimension matrix $X = \begin{bmatrix} X_{11} & X_{12} \\ * & X_{22} \end{bmatrix} \geq 0$, we get

$$0 \leq \sum_{l=k-d}^{k-1} \zeta_1^T(k)X\zeta_1(k) - \sum_{l=k-d}^{k-1} \zeta_1^T(k)X\zeta_1(k) = d\zeta_1^T(k)X\zeta_1(k) - \sum_{l=k-d}^{k-1} \zeta_1^T(k)X\zeta_1(k). \quad (9)$$

Thus, from (7) to (9), we have

$$\triangle V(k) \leq \zeta_2^T(k)\{\varLambda + \varPi_1^T(P+dR)\varPi_1\}\zeta_2(k) - \sum_{l=k-d}^{k-1} \zeta_3^T(k,l)\varXi\zeta_3(k,l) + \gamma^2 w^T(k)w(k). \quad (10)$$

with $\zeta_1(k) = [x^T(k)\ x^T(k-d)]^T, \zeta_2(k) = [x^T(k)\ x^T(k-d)\ w^T(k)]^T, \zeta_3(k,l) = [x^T(k)\ x^T(k-d)\ y^T(l)]^T, \varLambda = \begin{bmatrix} \varphi_{11} & \varphi_{12} & PB_w \\ * & \varphi_{22} & 0 \\ * & * & -\gamma^2 I \end{bmatrix}, \varPi_1 = [\bar{A}\ \bar{B}\ B_w]^T, \varPi_2 = [I\ 0\ 0]$.

Defining $\varTheta = \varLambda + \varPi^T P\varPi + d\varPi^T R\varPi$ and using Schur Complement Lemma (Lemma 1), the LMIs in (10) can make inequalities $\varTheta < 0$ true. Then there exists a positive scalar $\varepsilon > 0$ such that $\varTheta < \varepsilon I < 0$. Therefore, it follows that $\varDelta V(k) \leq -\varepsilon||x(k)||^2 < 0\ \forall x(k) \neq 0$.

Considering $w(k) \neq 0$ and Schur Complement Lemma, following the inequalities (5) and (6), we have

$$\triangle V(k) + z^T(k)z(k) - \gamma^2 w^T(k)w(k) \leq \xi^T(k)\varOmega\xi(k) < 0.$$

Sum k from 0 to ∞ with the initionalization of $V(0) = 0$, we can obtain

$$\sum\nolimits_{k=0}^{\infty} \{z^T(k)z(k) - \gamma^2 w^T(k)w(k)\} < 0.$$

Based on the Lyapunov-Krasovskii theory, the robust $H\infty$ control model of the error state of the padding waiting time with propagation delay and external interference in the closed-loop WSDN can achieve robust $H\infty$ control $J < 0$ with desired $H\infty$ performance index $||T_{wz}(z)||_\infty < \gamma$ following (5) and (6).

The proof is completed.

5 Simulation Results

In this section, a numerical example is designed to verify the effectiveness of our stabilization criteria given in Theorem 1. Following (5) and (6), in real WSDN with QoS requirement (shown in Fig. 2), there are eight priority levels, denoted from 0 to 7 with 0 being the highest, which are assigned to differentiated flows with different characteristics. Consider the closed-loop WSDN (3) with different parameters in order to clearly demonstrate control policies with different QoS priorities in the centralized controller:

$B_w = diag\{0.2, 0.1, 0.31, 0.51, 0.11, 0.21, 0.31, 0.41\}$ and

$$A = \begin{bmatrix} 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.76 & 0.15 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.65 & 0 & 0.3 & 0 & 0 & 0 & 0 & 0 \\ 0.31 & 0 & 0.51 & 0.22 & 0 & 0 & 0 & 0 \\ 0.63 & 0.14 & 0 & 0.25 & 0.33 & 0 & 0 & 0 \\ 0.36 & 0 & 0.25 & 0 & 0 & 0.47 & 0 & 0 \\ 0.36 & 0.94 & 0.74 & 0.51 & 0 & 0.65 & 0.45 & 0 \\ 0.31 & 0.26 & 0 & 0.59 & 0 & 0.3 & 0.1 & 0.14 \end{bmatrix}.$$

where A denotes the relationship between $x(k+1)$ and $x(k)$, and we define $A = (a_{ij}) = \begin{cases} a_{ij} = 0, & if\ i < j \\ 0 \le a_{ij} \le 1, & if\ i \ge j \end{cases}$, that means the QoS requirement. The QoS requirement is applied in VNFs to guarantee flows with different priorities controlled. Before starting its execution, the flow with lower priority needs to wait for the completions of all flow queues with non-lower priorities in the VNF k. Additionally, the waiting time consists of the probability weight of every non-lower priority.

5.1 Effectiveness Verification of the Proposed Scheme

According to Theorem 1, there exists a feasible solution to LMIs (5) and (6). We use the zero initial state $x(0) = [0\ 0\ 0\ 0\ 0\ 0\ 0\ 0]$ to reflect the stability of error state at the initial moment. Suppose the control strength $K = -0.1I$, the control policy $B_u = A$. The scenario of the error state $x_i(k), i = 0, 1, \ldots, 7$ with the different priorities are considered to make a comparison. Suppose that a function with constant value and limited count number represents the external interference with limited energy and duration to make the simulation tractable.

Notably, the error states $x(k)$ may increase and then make convergence in the presence of propagation delay and external inferences, as shown in Fig. 3. The result represents that all error states $x(k)$ reach an agreement by the centralized controlling. Thus, this simulation can be conducted to indicate the effectiveness of the proposed scheme in NFVs and WSDNs.

5.2 Design of Control Policy on Robust $H\infty$ Control

This section introduces the design of the control policy based on the proposed scheme in NFVs and WSDNs. We select the intermediate priority $i = 4$ in the simulation. Figure 4 shows the variations of the error state under the different control strength K. The initial state is $y_4(0) = 0$. Compared with the control strength K, it is notable that a tighter control results in the smaller width.

Therefore, the appropriate adjustments of QoS control policy can easily be designed in the controller. The control policy can be designed to control the width measurement.

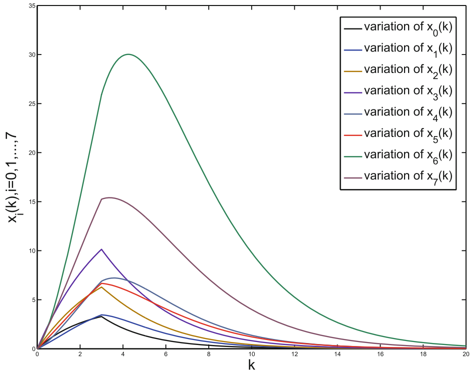

Fig. 3. The variations of error state $x_i(k), i = 1, 2, \ldots, 7$ with eight QoS priorities to represent its variation in the presence of propagation delay and external interference.

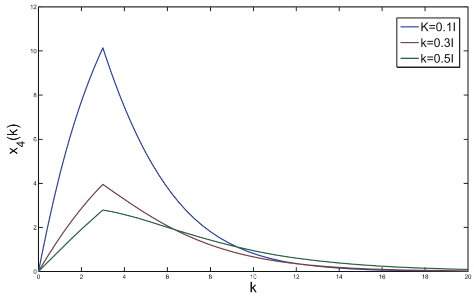

Fig. 4. The variations of error state $x_4(k)$ (at QoS priority levels $i = 4$) with different control strength K in the presence of propagation delay and external interference.

6 Conclusion

This paper have adopted robust control to tackle the problems of keeping the network stable during congestion control in NFVs and WSDNs. A robust control model with propagation delay and external interference is presented by using Lyapunov-Krasovskii functionals. The sufficient conditions have been formulated by LMIs. The numerical simulation has conducted to indicate the effectiveness of the proposed scheme. The approach that we have presented can possibly be extended to model and analyze more complex robust control approaches in WSDNs. For future studies, more complex control algorithms modeled in WSDNs would be discussed.

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