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*Research Article*

# Control and Optimization of Network in Networked Control System

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In order to avoid quality of performance (QoP) degradation resulting from quality of service (QoS), the solution to network congestion from the point of control theory, which marks departure of our results from the existing methods, is proposed in this paper. The congestion and bandwidth are regarded as state and control variables, respectively; then, the linear time-invariant (LTI) model between congestion state and bandwidth of network is established. Consequently, linear quadratic method is used to eliminate the network congestion by allocating bandwidth dynamically. At last, numerical simulation results are given to illustrate the effectiveness of this modeling approach.

## 1. Introduction

In the past decade, the unprecedented interactions and penetrations between developments in computer, communication, and control have accelerated the progress of the networked control. Feedback control systems wherein the control loops are closed through a real-time network are called networked control system (NCS). Motivations for using the networked framework in control systems come from lower cost, ease of maintenance, great flexibility, and sharing of information resources, which make networked control systems (NCS) more and more popular. The nature characteristic of NCS is that information, such as reference input, plant output, and control signals, is exchanged among the control systems by communication network and multisubsystems sharing the information to accomplish their respective control tasks. These above features make NCS the preferred architecture in modern large-scale complex system. Examples comprise spatially distributed resource allocation networks, supervisory control of continuous plants, intelligent vehicle highway systems, power generation and distribution networks, mobile sensor networks, remote surgery, and many others. Consequently, some considerable attentions have been devoted to the study of NCS; see for example, the survey papers [1–4], the recent special issues [5, 6], and the references therein.

The NCS architecture involves control system and communication network. Generally speaking, when "control" meets "network" in NCS, there are two implications: one is *control over network* which refers to the closed-loop feedback control which is carried out by employing the communication network as the medium of data transmission; the other is *control of network* which is concerned with providing reliable communication channels and/or networks to make them suitable for real-time NCS. The former mainly focuses on the issues of control system analysis, synthesis, and design with a view to the influence of the inherent characteristics of the communication network. The objectives are to minimize the effects of communication constraints, such as network-induced delays, data rate limitations, quantization effects, and medium access constraints, and to guarantee the quality of performance (QoP) of the control system. The latter aims at the very fact of the limited network resources and the purposes are to achieve the effective management and rational allocation of these resources so that the quality of service (QoS) provided by the communication network can

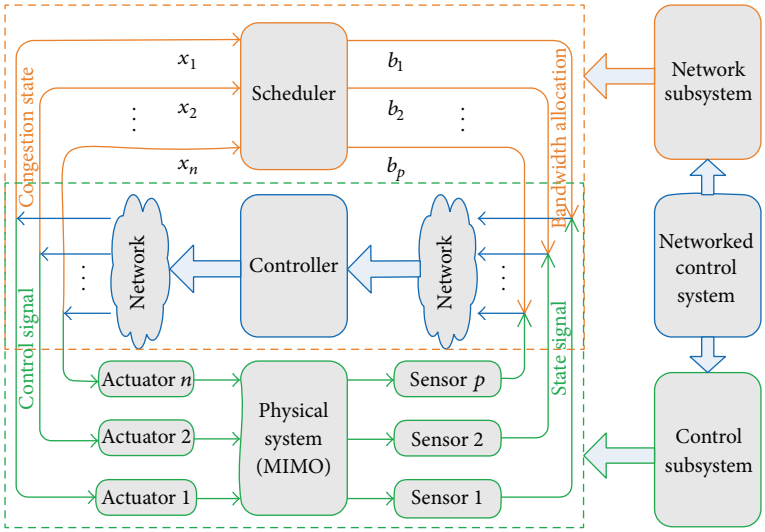


Figure 1: Schematic diagram of NCS.

be ensured. The topics span wide horizons and contain almost all aspects of communication network, such as bandwidth allocation, data rate control, congestion control, and routing selection. Although are different from each other in themes and contents, there are overlaps between *control over network* and *control of network*. In fact, the performance of control system and communication network in NCS restricts and influences each other dramatically and they have reached a common view that the overall performance of NCS is associated with not only control algorithms but also with network resources allocation. Namely, a successful NCS design should consider QoP and QoS simultaneously. Hence, the thought of control and communication codesign is put forward in [7].

The basic idea of codesign is that the network characteristics should be taken into account in NCS design rather than focusing on the control system only. Related works in this field are mainly focused on the control algorithms design [8–14]. These thoughts of controller design are to improve QoP by combining network characteristics, that is, time delay and packets dropout. Bandwidth allocation strategies [15–19] and sampling period adjustment methods [20, 21] are proposed to realize the optimization for network resource. Related works about network resource management mainly only focus on single or several network characteristics while the whole running state of network is neglected [22–24]. In fact, the stability of network is the prerequisite to realize the expected control performance. To avoid the control performance degradation caused by network congestion, it is necessary to monitor the running state of the communication network and implement the real-time control.

In NCS, sampling period plays an important role between control system and communication network. In a word, a larger sampling period means lower data transmission rate and lesser bandwidth occupation, which can help to reduce the network-induced time delay and information conflict in a communication network. However, it will lead to the sacrifice of control performance and the reduction of the network utilization, which affects the overall performance of NCS. On the contrary, a smaller sampling period makes the best use of the network utilization and will improve the control performance consequently but aggravates the network congestion and may result in delays and packet dropouts, which will also affect NCS performance. Inspired by the above-mentioned facts, the problems of network congestion and bandwidth allocation associated with sampling period are considered in this paper. Firstly, the linear time-invariant (LTI) model of network is established by defining the congestion and then bandwidth occupation as the state and control variables. Further, the network congestion control is carried out by allocating bandwidth dynamically. The objective of this paper is to realize the control and scheduling codesign of NCS by guaranteeing that the running state of network and bandwidth occupation are employed to control and optimize network from the point of view of control theory.

The rest of this paper is organized as follows. In Section 2, the basic problems are formulated and LTI model between network congestion and bandwidth is established. On this basis, the control strategy of network congestion is presented with linear quadratic regulator (LQR) method in Section 3. In the following, the numerical simulation results are shown and conclusions are obtained in Sections 4 and 5, respectively.

## 2. System Description and Problem Statement

*2.1. System Setup.* The NCS considered here consists of a MIMO plant, a remote controller, and an integrated scheduler, as shown in Figure 1. The $p$ inputs of the plant are sampled with sensors and then transmitted to the controller through communication network. The $n$ outputs of the controller are transmitted to the plant through network and then the closed-loop control is carried out by actuators. Meanwhile, the controller outputs are also sent to the scheduler as a basis for bandwidth allocation of communication network and sampling period decision of control system. The

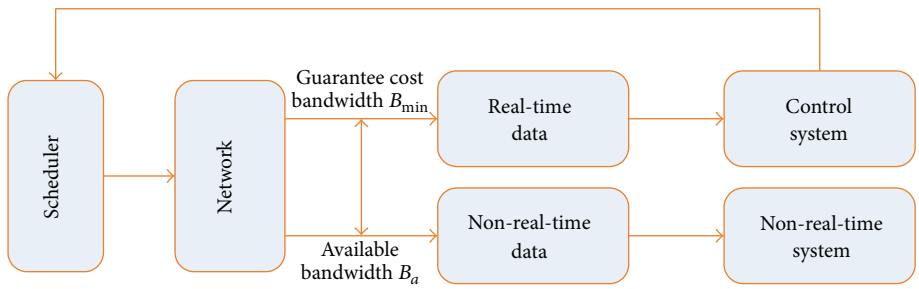


Figure 2: Bandwidth mechanism in NCS.

network congestion state which defined as $x_j$ $(j = 1, 2, \ldots, n)$ is collected by scheduler. Then, the scheduler allocates the bandwidth $b_i$ $(i = 1, 2, \ldots, p)$ for each channel based on congestion state $x_j$ of network. In a word, the scheduler mechanism takes QoS and QoP into account at the same time which can realize control and scheduling codesign of NCS. In this sense, the NCS can be divided into control subsystem and network subsystem.

For control subsystem, the main problem is how to design an appropriate controller to achieve the desired performances under communication constraints. In our NCS setup, the scheduler provides the basis for bandwidth allocation and sampling period selection. This leads to the control problems of NCS with variable sampling period, which have been discussed in depth in the existing works [20, 21].

For network subsystem, bandwidth is used to measure information transmitting capability and the running state of network can be represented by the level of network congestion. The bigger bandwidth means more data can be transmitted in unit time and little network congestion occurred. The smaller bandwidth means a little data can be transmitted in unit time and serious network congestion occurred. Moreover, the data transmitting in network can be divided into real-time and non-real-time data, as shown in Figure 2. Generally, the data satisfying control requirement can be deemed as real-time data while others are non-real-time data. They all occupy a certain bandwidth. The deadline demand needs to be satisfied because the control system becomes unsteady when oversized time delay emerges. So the bandwidth of real-time data can be defined as guaranteed cost bandwidth and of non-real-time data can be defined as available bandwidth. The bandwidth of non-real-time data can be released to guarantee cost bandwidth when control system becomes instable and real-time data are needed. The above-mentioned bandwidth mechanism in NCS provides the possibility for bandwidth adjustment, which is expected to achieve the congestion control.

Denote $B_g$ as the global bandwidth of communication network which contains guaranteed cost bandwidth $B_{\min}$ and available bandwidth $B_a$ as shown in Figure 2 and the similar method of bandwidth division can be found in [25]. The main purpose of this paper is to control and optimize network congestion by adjusting the bandwidth dynamically.

*2.2. Preliminaries.* To present the main results of this paper, the following definition and assumptions are needed.

*Definition 1.* The maximum amount of data transmitted through network for a given bandwidth of each channel when there is no congestion occurring is defined as *primary data*. The data lead to network congestion is defined as *extra data*. The corresponding bandwidth for primary data and extra data is defined as *primary bandwidth* and *available bandwidth*.

*Remark 2.* A certain quantity of data can be transmitted through network for a given bandwidth. But there is more data that should be transmitted compared to the original data when control system is perturbed which needs to be stabilized. In this case, the bandwidth capacity is inadequate to transmit more data and network data becomes congested. The very more data is defined as extra data in this paper. In short, the quantity of data is limited to a certain range if there is no network congestion occurring based on the *primary bandwidth*. However, different closed loops need different primary bandwidth. When more extra data needs to be transmitted, the network congestion occurrs.

*Assumption 3.* If there is no network congestion, the designed controller is effective and the state of network can be regarded as zero (steady) state. In addition, the controller has no influence on network behavior.

*Assumption 4.* The linear relationship between bandwidth and state of network is supposed and the LTI model of communication network can be represented by

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{1}$$

where $x = [x_1, \ldots, x_n]^T \in R^n$ represents the network congestion state and $u = [u_1, \ldots, u_p]^T \in R^p$ represents control signal which denotes bandwidth occupation of each loop. Matrixes $A$, $B$ are of compatible dimensions.

The proposed method in this paper tries to maximize control performance and minimize bandwidth consumption. The scheduler adjusts the sampling period of each control loop according to the state-variables feedback from network. Therefore, the relation between bandwidth and sampling period for each control loop is given by

$$b_j = \frac{\alpha^j}{T_j}, \qquad \sum_{j=1}^{n} \frac{\alpha^j}{T_j} = B_{\min}, \tag{2}$$

where $b_j$ is assignable partial bandwidth, $T_j$ is the sampling period to the $j$th channel, and $\alpha^j$ denotes the time spent on messaging required to perform each closed-loop operation [13]. Any change on $b_j$ will directly imply a change on $T_j$ (and vice versa). So, either $b_j$ and $T_j$ will be used to denote bandwidth (or sampling period).

Furthermore, network congestion level can be measured by extra data which will transmit in a certain time. Generally the certain time is known as sampling period which implies data rate and multirate sampling in NCS. The more extra data is transmitted through the primary bandwidth, the more serious network congestion emerges. So the network congestion can be measured by the following equation:

$$x_j = \frac{\alpha^j d_j(t)}{T_j}, \quad j = 1, 2, \ldots, n, \tag{3}$$

where $d_j(t)$ represents the extra data which is transmitted through network.

## 3. Solution to Control and Optimization of Network

Under the aforementioned assumptions, it is obvious that the control of network congestion is a classical linear quadratic problem. For the sake of engineering application, infinite horizon optimal control is more suitable for real-time control.

*3.1. Optimization Problem Description.* The real-time data is the prerequisite of realizing the control function. Therefore, the data flow needs great attention. For a MIMO network, how to allocate the bandwidth for each channel to adapt the change of data flow is a pivotal issue so as to avoid network congestion. Considering (2) and (3) in view of data flow, it can be further illustrated by

$$\Lambda \dot{d}(t) = A\Lambda d(t) + Bu, \tag{4}$$

where the definitions of $A$, $B$, and $d(t)$ are the same as the above description.

At first, the different *primary bandwidth* is needed according to the characteristics of each closed loop. In order to take into account the bandwidth according to data flow of different closed loops in the course of controller design, the *primary bandwidth* matrix is given as follows:

$$\Lambda = \begin{bmatrix} \frac{\alpha^1}{T_1} & & \\ & \ddots & \\ & & \frac{\alpha^n}{T_n} \end{bmatrix}. \tag{5}$$

Consequently, the feedback control law which contains the bandwidth adjustment is designed:

$$u = -K\Lambda d(t), \tag{6}$$

where $K = \begin{bmatrix} k_{11} & & \\ & \ddots & \\ & & k_{pn} \end{bmatrix}$ is *bandwidth gain* according to diagonal matrix $\Lambda$.

*Remark 5.* For the control law (6), $b_j$ is very important as a link between bandwidth allocation and network congestion; $k_j(\alpha^j/T_j)$ indicates the actual change of bandwidth. Contemporarily, the bigger $d_j$ in the context of given primary sampling period $T^j$ implies more serious network congestion. So the $(\alpha^j/T^j)d_j(t)$ can represent the network congestion state.

In addition, the following condition also needs to be satisfied:

$$\sum_{j=1}^{p} k_j \frac{\alpha^j}{T_j} \le B_g, \tag{7}$$

where $B_g$ is the total bandwidth of network.

At last, the main purpose of this network optimization strategy is to eliminate network congestion through bandwidth allocation based on the designed controller (6), such that the following quadratic cost function is minimized:

$$J = \frac{1}{2}\int_0^\infty \left[d^T(t)\Lambda^T Q\Lambda d(t) + d^T(t)\Lambda^T K^T RK\Lambda d(t)\right] dt, \tag{8}$$

where $Q \ge 0$, $R > 0$ are quadratic weighted matrices of state and input vectors, respectively.

*Remark 6.* Because the integration upper bound $t_f \to \infty$, it is possible for performance function $J$ to be unbounded. In order to ensure that $J$ is bounded, the controllability demands on system (2) are put forward. In other word, pair $(A, B)$ is controllable.

*3.2. Optimal Solution and Stability Analysis*

**Lemma 7.** *If the given pair $(A, B)$ is controllable and pair $(A, \Sigma)$ is observable, there is a unique optimal control which can be written as*

$$u^* = -R^{-1}B^T P\Lambda d(t). \tag{9}$$

*The optimal performance index is*

$$J^* = \frac{1}{2}d^T(0)\Lambda^T P\Lambda d(0), \tag{10}$$

*where $d(0) = d_0(t)$ is the initial amount of extra data of network.*

In what follows, the gain $K = R^{-1}B^T P$ is obtained through linear quadratic method and it can be used to adjust bandwidth according to the diagonal matrix $\Lambda$ which represents the primary bandwidth of each communication channel. However, positive definite symmetric matrix $P$ is the solution of the following Riccati equation:

$$PA + A^T P - PBR^{-1}B^T P + Q = 0. \tag{11}$$

In order to realize control and scheduling codesign of NCS, the running state of network should be stable as the same as a common controlled object.

**Proposition 8.** *Suppose that the pair $(A, B)$ is controllable and the pair $(A, \Sigma)$ is observable, where $Q = \Sigma\Sigma^T$. Then, for the infinite horizon case the optimal control policy is a steady-sate policy and is given by control law (6). Namely, if $u^* = -R^{-1}B^TP\Lambda d(t)$ for network subsystem, the optimum closed-loop system (12) is stable:*

$$\Lambda \dot{d}(t) = \left(A - BR^{-1}B^TP\right)\Lambda d(t). \tag{12}$$

*Proof.* The change of data flow can reflect the change of network congestion state. Construct a Lyapunov function based on congestion state:

$$V(t) = d^T(t)\Lambda^T P\Lambda d(t). \tag{13}$$

For simplicity, the control of data flow $d(t)$ is still represented by network congestion $x(t)$ based on constant matrix $\Lambda$. Taking a derivate of time $t$ for (13):

$$\dot{V}(t) = \dot{x}^T(t)Px(t) + x^T(t)P\dot{x}(t). \tag{14}$$

Because of $(\alpha^j/T^j) > 0$, if $\dot{V}(t) \le 0$, the optimum closed-loop network system is stable. According to (12) and (13), (14) can be written as

$$\begin{aligned}\dot{V}(t) &= x^T(t)\left[\left(A - BR^{-1}B^TP\right)P + P\left(A - BR^{-1}B^TP\right)\right]x(t)\\ &= -d^T(t)\Lambda^T\left(Q + PBR^{-1}B^TP\right)\Lambda d(t).\end{aligned} \tag{15}$$

Because of $Q \ge 0, R > 0, \dot{V}(x) \le 0$ is satisfied. Obviously, if and only if $x_0 = 0$ (the equilibrium state of network), $\dot{V}(t) = 0$.

In the meantime, suppose that network congest state $x(t) \ne 0$ and combine the fact that $x(t) = \Lambda d(t)$, $\dot{V}(t) \equiv 0$; then

$$d^T(t)\Lambda^T P\Lambda d(t) = 0, \tag{16}$$

$$d^T(t)\Lambda^T PBR^{-1}BP^T\Lambda d(t) = 0. \tag{17}$$

Substituting (6) in (17),

$$u^{*T}(t)Ru^*(t) = 0. \tag{18}$$

Because of $R > 0$, we obtain $u^{*T}(t) = 0$. System (4) has only zero input response and it can be represented as

$$x(t) = e^{At}x_0, \quad \forall x_0 \ne 0. \tag{19}$$

Substituting (19) in (16),

$$d_0^T(t)\Lambda^T(t)e^{A^Tt}\Sigma\Sigma^Te^{At}\Lambda d_0(t) = 0, \tag{20}$$

where $\Sigma\Sigma^T = Q$.

From (19), it is clear that

$$\Sigma^Te^{At}\Lambda d_0^T(0) = 0. \tag{21}$$

However, (18) conflicts with the observability of pair $(A, \Sigma)$.

So, the stability of network subsystem (5) with optimal bandwidth allocation is proved. □

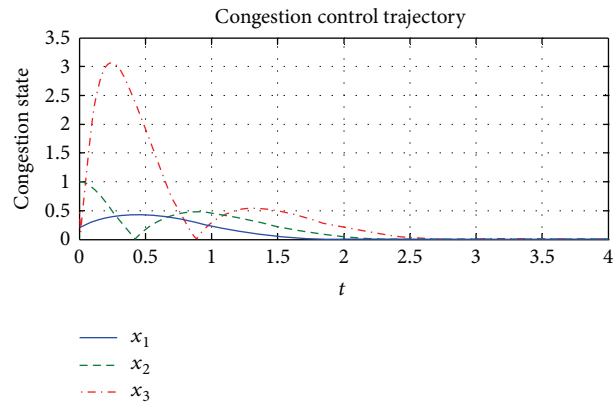


FIGURE 3: Network congestion state of each loop.

## 4. Numerical and Simulation Results

In order to verify the effectiveness of this network congestion control strategy in NCS, the numerical example and simulation results are illustrated under MATLAB environment.

Considering a third-order NCS, for simplicity, let $\alpha^j/T_j = 1$, $x_j > 0$, the congestion state can be obtained through measurement data $d_j(t)$. The network congestion control model can be represented by

$$\dot{d}(t) = \begin{bmatrix} 0 & 2 & 1 \\ 1 & 0 & 1 \\ 0 & 4 & -6 \end{bmatrix} d(t) + \begin{bmatrix} 0 \\ 3 \\ 1 \end{bmatrix} b(t), \tag{22}$$

where $b(t)$ is the bandwidth vector.

The main purpose of the proposed bandwidth allocation strategy is to reflect the adjustment of $K$, so the selective of matrix $R = 1$, $Q = I$ is reasonable. Let initial network congestion state $x_0 = d_0 = [0.2, 1, 0.5]^T$.

Subsequently, the state feedback controller gain is obtained as

$$K = [0.0143 \quad 0.1107 \quad 0.0676] \tag{23}$$

and the solution of positive definite symmetric matrix for Riccati equation is obtained as

$$P = \begin{bmatrix} 4.2625 & 2.4957 & 0.0143 \\ 2.4957 & 2.8150 & 0.1107 \\ 0.0143 & 0.1107 & 0.0676 \end{bmatrix}. \tag{24}$$

The network congestion trajectories are shown in Figure 3.

Obviously, the network congestion is eliminated after 2.7 seconds. At the same time, the time varying bandwidth curve is given in Figure 4 and optimal performance index $J = 2.0571$.

The response curve can reflect the change of available bandwidth consumption but it does not mean that bandwidth of each closed loop is zero when the network state is steady. If the network congestion is eliminated, the bandwidth maintains the *primary bandwidth*. Besides, this bandwidth allocation strategy can realize the monitoring the running state of network. In addition, the *primary bandwidth* can be limited to necessary scope according to differential service [26] or control performance.

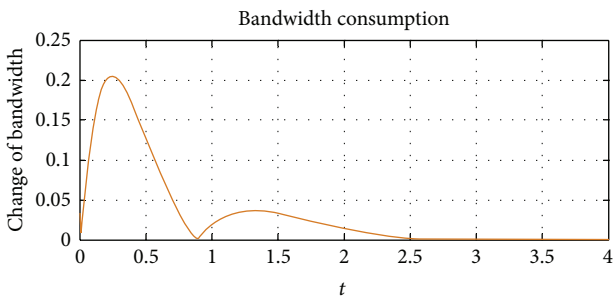


Figure 4: Bandwidth change and consumption.

## 5. Conclusions

In this paper, network as controlled object is analyzed with LQR method and bandwidth is considered as "energy" to eliminate network congestion. The central purpose of this study is to realize the control and optimization of network in NCS codesign. Firstly, control of network focused on QoP and QoS simultaneously and QoP can be easily achieved when QoS is improved. Further, bandwidth is a crucial factor for control of network. On the one hand, optimal bandwidth consumption guarantees the stability of network. On the other hand, the requirement bandwidth based on control system can improve control performance. At last, control theory can also be employed to realize network scheduling.

In essence, the open loop of bandwidth management which is realized by closed-loop scheduling in this paper implies that control and scheduling are inseparable in codesign of NCS. In addition, this bandwidth adjustment strategy based on control of network also indicates that control theory can be adopted to solve the problem of network resource management and scheduling.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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