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Feedback control system with PWA load dependent reference buffer occupancy for congestion control in computer networks

***Abstract**. Congestion avoidance plays the significant role in increasing network reliability and efficiency. To minimize blockage effects, many methods and algorithms have been proposed. A method of active egress queue length control in use not to over on underutilize buffer occupancy in non-stationary, discrete, dynamical model of communication channel is described in this paper. This approach allows to optimize available network nodes resources to avoid congestions effects or to minimize or alleviate negative impact of these congestion on network throughput.*

***Streszczenie.** W artykule zaproponowano metodę aktywnego sterowania długości kolejki wyjściowej, w celu zminimalizowania niepożądanych efektów zatorów sieciowych. Metoda ta pozwala unikać sytuacji nadmiernego przepełnienia lub opróżnienia bufora wyjściowego. Do badań został wykorzystany niestacjonarny, dyskretny, dynamiczny model kanału komunikacyjnego. Takie podejście umożliwia optymalizację dostępnych zasobów w węzłach sieciowych.(**Sterowanie zatorami w sieciach komputerowych z wykorzystaniem pętli sprzężenia zwrotnego oraz wartości referencyjnej odcinkowo afinicznie zależnej od zajętości bufora**).*

Keywords: congestion control, discrete-time systems, dynamical model, computer networks.
Słowa kluczowe: kolejka sieciowa, sieci komputerowe

Introduction

Many approaches in alleviation the result of network congestion has been presented in the literature [1, 2, 3, 4, 5]. The goal of these deliberation is to optimize utilization of available resources to improve the efficiency of different sorts of transmission grids [1, 2]. The phenomenon of congestion appearance affects network as the data exchange environment and as a collection of many singular communication channels [6, 7]. Modern, dispersed data exchange system relays on fast, uncongested traffic flows. The occurrence of congestions in communication networks is connected as well with limited interlinks bandwidth as finite hardware resources of network nodes involved in the packets transmission [5]. To alleviate the results of congestions appearance in data exchange networks, variety of methods and algorithms are proposed like sliding-mode algorithm [3, 8], fuzzy logic [9] and others [10, 11, 12]. Remarkable attention is recently paid to modelling and methods for piece-wise affine (PWA) systems [13, 15, 19, 21] nonlinear systems [14, 16]. Stability of these systems is wider discussed e.g. in [15, 17, 19]. Particle swarm optimization (PSO) algorithm is also successfully implemented in power distribution grids to alleviate effects of overload and minimize operational costs [1, 2, 18]. A non-stationary, discrete dynamical system model of data exchange communication channel, considered in this paper, is proposed in [20]. Frequency characteristics of this model obtained by the use of simplified frequency characteristics is widely discussed in [22]. Application of PWA control strategy combined with PSO is presented in [23, 24].

The main aim of the paper is to introduce an algorithm controlling egress queue length in the congested node. This can be accomplished by tuning the number of packets requested from the source to assumed egress buffer utilization level in the congested node. This assumed buffer occupancy level should depend on available egress throughput, which is varying in time. This approach helps to minimize buffer overflow issue. The piecewise affine function is used to adopt requested number of packets in non-stationary, discrete dynamical system. In order to tune coordinates in piecewise affine function, modified Newton's method is applied [25, 26].

The first part of the paper describes non-stationary, discrete, dynamical model taken under consideration. Then the control strategy chosen for chosen model is described. The summary of taken considerations is illustrated in numerical example.

Model of network section

The network section, presenting an example of communication channel is shown in Fig. 1. This model is discussed in detail in [20]. It consists of some specified number of network nodes. Three of them are distinguished. These are: source S, destination D and congested node CN, in order like is shown in Fig. 1.

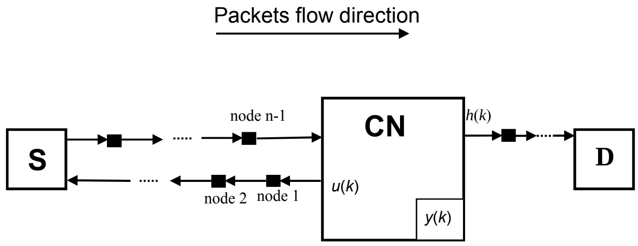

Fig. 1 Block diagram of network sector with time varying delay.

Let's note that the number of packets, which can potentially be sent from the CN towards D, should be limited and can be modeled as a certain, unknown, restricted function of time. This function can be specified as $d(k)$ and is additionally constrained by available bandwidth for CN:

$$0 \le d(k) \le d_{\max} \quad (1)$$

where: $d_{\max}$ – maximum available bandwidth at any moment of time, $d(k)$ – available bandwidth for CN in time k

Another limitation affecting the number of packets that can be sent form CN toward D is the amount of data stored in CN's output buffer. This satisfies the following inequalities:

$$0 \le h(k) \le d(k) \le d_{\max} \quad (2)$$

$$0 \le h(k) \le y(k) \quad (3)$$

where: $h(k)$ – the number of packets successfully transmitted at time k from CN in the direction of the destination, $y(k)$ – queue length of CN in time k

Taking under consideration that the throughput between source and congested node is limited, following assumption is done:

$$u(k) \le u_{\max} \quad (4)$$

Having in mind definitions (1)-(4), a full model in the state variables can be written like follows:

(5)
$$\begin{aligned} x_1(k+1) &= q_1(k)x_1(k)+u(k) \\ &\vdots \\ x_{j+1}(k+1) &= \bar{q}_j(k)x_j(k)+q_{j+1}(k)x_{j+1}(k) \\ &\vdots \\ x_n(k+1) &= \bar{q}_{n-1}(k)x_{n-1}(k)+x_n(k)-h(k) \\ y(k) &= x_n(k) \end{aligned}$$

where: $x_j(k)$ – the number of packets in node *j* in time *k*, $q_j(k)$ – queuing factor $q_j(k)=\begin{cases} 0 \text{ - transmission} \\ 1 \text{ - congestion} \end{cases}$, $\bar{q}_j(k)=1-q_j(k)$, $u(k)$ – number of packets requested from the source by congested node

At each step time *k,* node j sends all accumulated packets x_j to the adjacent node *j*+1 towards the destination. It takes place exclusively, when queuing factor q_j equals 0. It is when congestion doesn't occurs. In this deliberations it is assumed that no bandwidth restrictions have impact to the internode throughput. When a bottleneck appears, no data is transferred to another node and all packets are stored in node j buffer. Only congested node CN can be in a state than some portion of accumulated data is transferred, due to available egress bandwidth, while the rest is kept in egress buffer. In that manner, the difference between packets coming into the congested node and packets outgoing to the destination increases the buffer occupancy in CN when it is positive or decreases when it is negative. The amount of accumulated packet in CN buffer *y* is controlled by the controller. Congested node sends the control signal *u*(*k*) backwards to the source. This is done to adjust the number of packets sent from source to destination through the congested node to network conditions, which vary in time.

Strategy of congestion control

Ability of network environment to avoid blockages strongly depends on buffers utilization of network nodes. These buffers should be in such utilization level, which allows to accumulate packets in case of congestion appearance. When a buffer occupancy is equal or close to maximum capacity, the node is not able to accept any incoming pieces of data and incoming packets are dropped. That leads to retransmission attempts by terminals taking part in data exchange process. It results in increasing network occupancy and decreasing effective network throughput. On the other hand, in case of sudden throughput rise, a buffer should contain enough data not to be completely emptied before new data portion flow in.

This insights lay the foundation for a conception to depend expected buffer occupancy y_{ref} of CN to available throughput, which varies in time. PWA method is applied to design this dependency. The piecewise affine method can be presented in the following way:

(6)
$$y_{ref}(d(k))=\begin{cases} z_3 & d(k)\le z_1 \\ \dfrac{(z_4-z_3)(d(k)-z_1)}{(z_2-z_1)}+z_3, & z_1<d(k)<z_2 \\ z_4 & d(k)\ge z_2 \end{cases}$$

where: y_{ref} – expected buffer occupancy of congested node, z_1-z_4 – coordinates of the PWA function.

The outline of relations presented in (6) is illustrated in Fig. 2.

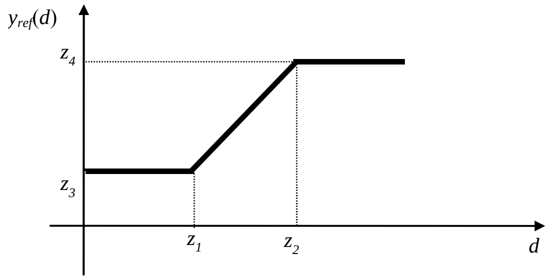

Fig. 2. Piecewise affine adaptive reference queue length

Coordinates z_1-z_4 can be determined by numerical optimization. It concerns also variable z_5 which is the proportional controller gain:

(7)
$$u(k)=z_5\left(y_{ref}(k)-y(k)\right)$$

A Modified Newton's Method is used to obtain a vector Z=[z_1 z_2 z_3 z_4 z_5]. Constraints that do not change the general considerations are as follows:

(8)
$$z_2\ge z_1\ge 0, z_4\ge 0, z_3\ge 0, z_5>0$$

To adjust the control to the selected design requirements, we define a cost function. It can be described as follows:

(9)
$$J(z_1,z_2,z_3,z_4,z_5)=\sum_{k=6}^{N}\delta(k)$$

where: *y*(*k*) – congested node's queue length at time *k,*

(10)
$$\delta(k)=\begin{cases} 0 & |y(k)-2500|\le 1000 \\ (y(k)-2500)^2, & |y(k)-2500|>1000 \end{cases}$$

At the very beginning of simulations all buffers are empty. Regardless of chosen control algorithm some time is needed until requested packets reach CN. Taking into consideration delays occurring in the system, we don't take account of first five time steps. This protects control algorithm against no fault phenomenon

Given that the system is described with model (5) and the controller (6), the optimal controller can be determined by solving the following optimization problem:

(11)
$$\min J(z_1,z_2,z_3,z_4,z_5)$$

Simulation results

In order to illustrate proposed control system, it is assumed that the system can be described by the following discrete non-stationary linear model:

(12)
$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}(k)\mathbf{x}(k)+\mathbf{B}(k)u(k)+\mathbf{F}(k)h(k) \\ y(k) &= \mathbf{C}(k)\mathbf{x}(k) \end{aligned}$$

where:

(13)
$$\begin{aligned} \mathbf{A}(k) &= \mathbf{A}_\kappa, \\ \mathbf{B}(k) &= \mathbf{B}=[1,0,0,...,0]^T, \\ \mathbf{C}(k) &= \mathbf{C}=[0,0,...,0,1], \\ \mathbf{F}(k) &= \mathbf{F}=[0,0,...,0,1]^T \\ \kappa &= floor\left(rem\left(\frac{k}{\varepsilon},0,04\right)\right) \end{aligned}$$

(14)
$$u(k)=k_p(y_{ref}-y(k))$$

In this research, the numerical simulation of the communication channel with time-varying delay is carried out. The subject of analysis is the egress queue length in the congested node. The order of system is assumed to be 30. It is done to fit delays in examined model to those existing in real computer networks.

Matrix A_0 is like in [23] and represents a state of the communication channel model, without congestion in the intermediate nodes. Matrix A_1 illustrates the state, when blockage occurs in the 7th intermediate node. It is based on matrix A_0 with following differences: element $A_1(7,7)=1$ and element $A_1(8,7)=0$. The system state, in which node 21st can't forward packets is mapped by a matrix A_2. It's built on A_0 pattern, but $A_2(21,21)=1$ and $A_2(22,21)=0$. Matrix A_3 represents a model of congestion in the 14th node. Like previous values, it's based on A_0 with two different elements: $A_3(14,14)=1$ and $A_3(15,14)=0$. Vectors **B**(k), **C**(k), and **F**(k) are constant in time.

For purposes of numerical simulation of model (12)-(14) like in [23], it has been assumed that u_{max} is 100 packets per sample. Maximum buffer capacity of congested node is 5000 packets. Sampling period is 10 ms. Initial conditions equal:

$$\mathbf{x}(0)=[0,0,0,...,0]^T$$

Assumed bandwidth $d(k)$ actually available for the congested node towards destination is like in [23] and is shown in Fig. 3.

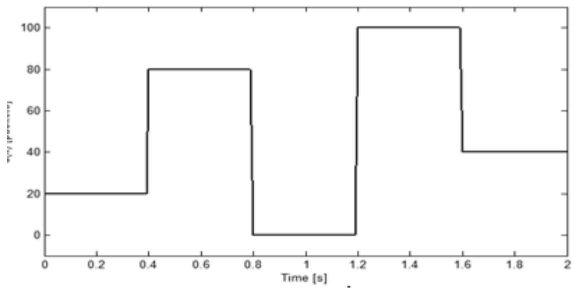

Fig. 3. Outgoing bandwidth $d(k)$ available for the congested node.

On the basis of relations (6) of the model (5), values of the matrix (13), and cost function (9), using the algorithm described in section 4, vector defined by formula (9), (10), (11) is calculated, the following coordinates are obtained:

(15) $Z^*=[z_1^* \quad z_2^* \quad z_3^* \quad z_4^* \quad z_5^*]=[1 \quad 90 \quad 259 \quad 3944 \quad 3.2]$

Fig. 4 illustrates controller response. It presents the requested number of packet that the source receives from the deployed controller in CN. This number takes into account u_{max} value.

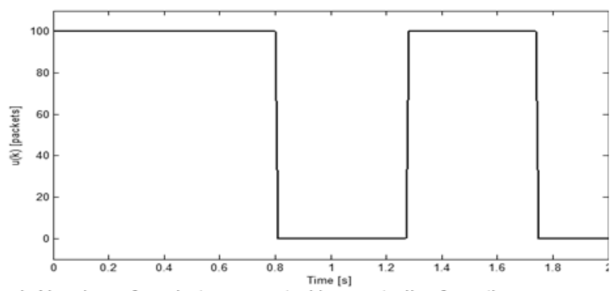

Fig. 4. Number of packets requested by controller form the source, $u(k)$.

Appling the controller (6) with (15) and model (12), numerical simulation is performed. The queue length of congested node is illustrated in Fig. 5.

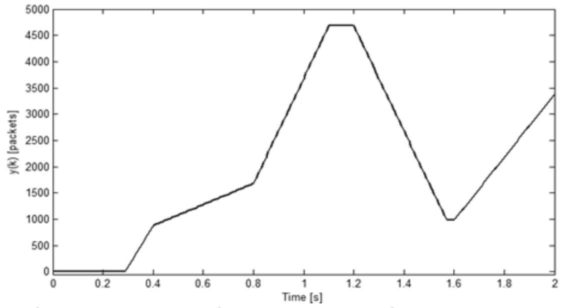

Fig. 5 Queue length $y(k)$ of congested node CN.

Conclusion

The paper covers the issue of congestion avoidance in data exchange networks. Proposed method rely on active control of egress queue length as a function of available output bandwidth. This solution enables significant improvement of network throughput in comparison to control strategy applied in former papers. Modified Newton's method combined with piecewise affine algorithm are used to designate optimal egress buffer level.

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