The comparison of network congestion avoidance algorithms in data exchange networks.

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Abstract. Effective congestion control strategies allow in maintaining low delay and high throughput in data exchange networks. These requirements seem to be the most desired by network environment participants. Wide range of algorithms are proposed in the literature to approximate to these ideal parameters. All of these approaches are focused on alleviating the results of sudden, unexpected network state changes. This paper discuss a comparison of four control strategies, focused on congestion avoidance. All of them are in charge of queue length control in active network nodes. For research purpose, non-stationary, discrete, dynamical model of communication channel has been used. Research results are presented in table and chart form.

1. Introduction
Modern data exchange networks are facing huge continued traffic increase. This phenomenon appears both in business and consumer sector. This boom cannot be balanced by worldwide hardware efficiency development. It results in network congestion appearance. To keep networks reliable and efficient, some congestion avoidance algorithm must be implemented. Different approaches focused on alleviating unfavorable effects of bottlenecks, like [1], [2] and [3]. In fact, blockage forming is characteristic in wide range of network types like power networks [4], waterworks and discussed data exchange networks [5]. Each network system can be considered as a collection of certain number of nodes and links [5]. Such decomposition facilitates designing, building and troubleshooting in network environment. In fact congestion phenomenon comes from limited hardware resource of active nodes and limited bandwidth between them [6]. Many approaches leading to eliminate or mitigate congestion results are discussed and presented in the literature [7]. Among wide spectrum of algorithms we can distinguish sliding-mode [8], fuzzy logic [9],[10] and predictive methods [11], [12], [13]. But there are also other approaches like [14],[15],[16]. Piecewise affine method is a frequent method of shaping control trajectory [17],[18],[19]. Invaluable input into solving congestion issues in computer networks has been made, using algorithms operating in higher level of ISO Open Systems Interconnection Reference Model [20], [21], [22] and [23].

In this research, a non-stationary, discrete dynamical model of packet exchange network is taken into calculation and discuss. To simplify considerations just single communication channel between two participants is included in taken model. Particular aspects of congestion control in similar models are presented in [24],[25],[26],[27]. In contrast to other approaches, this model is characterized by volatility of delays in time. It reflects the real network environment. Stability of these systems is widely presented
in [28] and [29]. The analysis of them with the use of simplified frequency characteristics is described in [28].

The goal of this paper is the comparison of different control strategies of the same plant. In general these strategies can be divided into two groups. One group is based on quasi strict knowledge of disturbance level and the second one is not. This disturbance is an unknown and varying in time bandwidth, available for congested network node. To calculate optimal controller set, PSO algorithm has been used. This method can be also successfully applied to decrease the impact of overloads in other sort of networks, like power distribution grids [30], [31].

First part of the paper is focused on short presentation of discrete, non-stationary and dynamical mathematical model. Consecutive sections discuss different control strategies and they present simulation results in charts and table form.

2. Model description

Model taken into calculations in this research has been introduced in [32], [33] and developed in [34] and [35]. It belongs to non-stationary, discrete dynamical systems group and assumes delays varying in time. It makes a complementary and development to other models, which do not assume delay variation. Considered model presents a fragment of a packet network and consists of source and destination. On the packets path there are certain number of intermediate nodes. These nodes are the source of varying packet delay, because in each time step any node can be experienced by bottleneck. There is also a distinguished node called congested node (CN). Congestion control in this case is focused on maintaining egress buffer occupancy of CN on some assumed or optimal level. The main goal is not to overload or empty the buffer. Graphical illustration is shown in Figure 1.

![Figure 1. Block diagram of communication channel with time-varying delay.](image-url)

Taking into calculation following constraints:

\[
0 \leq h(k) \leq d(k) \leq d_{\text{max}}
\]

\[
0 \leq h(k) \leq y(k)
\]

\[
u(k) \leq u_{\text{max}}
\]

A full model of described communication channel in in vector-matrix notation, can be described as follows:

\[
x(k+1) = \begin{bmatrix}
1 \\
0 \\
0 \\
-1
\end{bmatrix} \cdot u(k) + \begin{bmatrix}
0 \\
0 \\
0 \\
-1
\end{bmatrix} \cdot h(k) + \begin{bmatrix}
q_1(k) & 0 & 0 & \ldots & 0 \\
q_2(k) & 0 & 0 & \ldots & 0 \\
\pi_1(k) & q_2(k) & 0 & \ldots & 0 \\
\pi_2(k) & \pi_2(k) & q_1(k) & \ldots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & \ldots & 0 & q_{n-1}(k) & 1
\end{bmatrix} \cdot x(k)
\]

\[
y(k) = \begin{bmatrix}
0 & 0 & \ldots & 0 & 1
\end{bmatrix} \cdot x(k)
\]
where:

- \( h(k) \) – number of packets sent from CN toward the destination in time \( k \).
- \( d(k) \) – available egress bandwidth for CN in time \( k \).
- \( d_{\text{max}} \) – maximum number of packets that can be sent towards destination
- \( y(k) \) – number of packets in output buffer of CN in time \( k \).
- \( u(k) \) – number of packets, that CN orders from the source
- \( x_j(k) \) – number of packets in node \( j \) in time \( k \).
- \( q_j(k) \) – queuing factor
  \[
  q_j(k) = \begin{cases} 
  0 & \text{transmission} \\
  1 & \text{congestion}
  \end{cases}
  \]
- \( \bar{q}_j(k) = 1 - q_j(k) \)

In each time step, for every intermediate node a bottleneck can pause further packet transmission. Model simplification assumes, that these intermediate nodes can either do not forward any data, or push their all buffer content in one step to the next node, depending if it's experiencing congestion or not. In contrast, CN is can forward accumulated data in number related to available egress bandwidth. Packets incoming into CN and not forwarded towards the destination, increase the buffer occupancy. The length of the queue in the CN is presented as \( y(k) \) and is controlled by the controller. This paper discusses the use of four different controllers. Congested node CN sends the control signal backwards to the source. This is performed to adjust the number of packets sent from source to destination through the congested node to network conditions, which vary in time.

Wider description of given model is presented in [32]-[35].

### 3. Congestion control strategies

One of the most important factor which affects blockage forming in data exchange networks, is the level of nodes buffer utilization. This level cannot float near maximum capacity, or stay close to 0. In these circumstances we are experiencing either packet dropping and packet retransmissions or lack of data to be forwarded. Not wanting to face this disadvantages, a safe margin of buffer utilization must be absolutely maintained.

In order to ensure effective bandwidth utilization and buffer occupancy, four control strategies have been proposed and tested. All of these algorithms have no strict feedback concerning available bandwidth for CN. Figure 2 presents block diagrams of the control system.

![Figure 2. Block diagram of the control system.](image)

Table 1 presents all four numbered control strategies (CS), starting from the simplest with assumed, constant reference que level utilization and proportional gain, and approaching more generalized. Used controllers trajectory is described in each line. In fact either proportional controller or piecewise affine (PWA) could be chosen.
Table 1. Characteristics of researched control systems.

| CS | C1 – gain                      | C2 – constant     |
|----|--------------------------------|-------------------|
| 1  | Optimized proportional gain    | Assumed value     |
| 2  | Optimized proportional gain    | Optimized variable|
| 3  | Optimized PWA gain             | Assumed value     |
| 4  | Optimized PWA gain             | Optimized variable|

Particular strategies are presented in following subsections:

3.1. Control strategy 1
The first control strategy is the simplest layout and can be treated as reference trajectory supplier. In this case, wanted vector $z$ is single dimensional $z = [z_1]$. Reference queue length is assumed to be a half of maximum buffer capacity: $y_r = 2500$ and the proportional controller gain is:

$$u(k) = z_1(y_r - y(k)) = z_1(2500 - y(k))$$  \(6\)

3.2. Control strategy 2
In this strategy, reference value is subjected to be optimized. It follows that wanted vector $z$ contains additional component: $z = [z_1 \ z_2]$. Reference queue length takes value $y_r = z_2$. It this case, the gain of the controller is proportional too:

$$u(k) = z_1(y_r - y(k)) = z_1(z_2 - y(k))$$  \(7\)

3.3. Control strategy 3
Like in the first strategy, reference queue length is assumed to be a half of maximum buffer capacity $y_r = 2500$. Control signal $u(k)$ takes value:

$$u(k) = g(y(k))(y_r - y(k)) = g(y(k))(2500 - y(k))$$  \(8\)

The gain parameter $g(y(k))$ can be related to the current buffer utilization with the use of piecewise affine method:

$$g(y(k)) = \begin{cases} 
    z_1, & y(k) \leq z_1 \\
    (z_2 - z_1)(y(k) - z_1) + z_3, & z_1 < y(k) < z_2 \\
    z_1, & y(k) \geq z_2 
\end{cases}$$  \(9\)

The outline of relations presented in (9) is illustrated in Figure 3.

![Figure 3. Piecewise affine gain trajectory.](image-url)
As it can be seen, wanted vector $z$ is four dimensional $z = [z_1, z_2, z_3, z_4]$

### 3.4. Control strategy 4

The most comprehensive control strategy is the development of the third one. Unlike in previous subsection reference queue length is subjected to be optimized $r_y = z_4$. First four coordinates, which reflect gain parameter, are determined exactly like in (9). With these assumptions control signal can be written:

$$u(k) = g(y(k))(y_r - y(k)) = g(y(k))(z_5 - y(k))$$

(10)

Then, wanted vector $z$ has additional variable $z = [z_1, z_2, z_3, z_4, z_5]$

### 3.5. Common assumptions

We define a single cost function to adjust controller’s sets to described design requirements. The same cost functions has been used for all seven systems and it is listed below:

$$J(z) = \sum_{k=1}^{N} \delta(k)$$

(11)

$$\delta(k) = \begin{cases} 0 & |2500 - y(k)| \leq \text{margin} \\ (2500 - y(k))^2 & |2500 - y(k)| > \text{margin} \end{cases}$$

(12)

Optimized variables in $z$ vector can be determined by numerical optimization. A particle swarm optimization (PSO) method is used in these optimization iterations. Dependly on control strategy number, vector $z$ has from one to five dimensions. We assume, that the total buffer capacity is 5000 packets. Construction of used cost function increases its value in two cases. First case is when the buffer utilization is less than 1/2 of buffer capacity reduced by some margin. Second case is when the buffer utilization is more than 1/2 of buffer capacity enlarged by the same margin.

The optimal controller can for each control strategy can be determined by solving the following optimization problem:

$$\min J(z)$$

(13)

### 4. Simulation results

Relating to (4) and (5), our discrete, non-stationary and dynamical model takes linear form:

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

(14)

Vectors $B$, $C$ and $F$ are constant in all time horizon, whereas matrix $A$ takes different values depending on which intermediate node is congested. Construction of discrete non-stationary linear model taken into research process as well as detailed description of its components is presented in [32] and [33]. For purpose of numerical simulation some necessary assumptions have been made:

- $u_{\max} = d_{\max} = 100$ packets per sample
- maximum buffer capacity of congested node is 5000 packets
- Sampling period is 10 ms
- Initial conditions equal: $x(0)=[0,0,0,...,0]^T$
Assumed bandwidth $d(k)$ actually available for the congested node towards destination is like in [33],[34] and is shown in Figure 4.

![Available outgoing bandwidth for the congested node.](image)

**Figure 4.** Available outgoing bandwidth for the congested node.

Optimization process has been conducted for each control strategy (CS) with three different margin levels. On the basis of presented strategies, calculated cost functions ($J$) are printed in table 2.

| Margin | CS | $J$       |
|--------|----|-----------|
| 0      | 1  | 552.4236e+006 |
|        | 2  | 512.3824e+006 |
|        | 3  | 415.4589e+006 |
|        | 4  | 335.6319e+006 |
| 1000   | 1  | 248.0248e+006 |
|        | 2  | 150.9136e+006 |
|        | 3  | 96.6898e+006  |
|        | 4  | 92.9182e+006  |
| 2000   | 1  | 154.6280e+006 |
|        | 2  | 13.3188e+006  |
|        | 3  | 9.9518e+006   |
|        | 4  | 8.2174e+006   |

These data are presented in graphical form in Figure 5.

![Values of cost functions for different margins and control strategies CS.](image)

**Figure 5.** Values of cost functions for different margins and control strategies CS.
Graphical simulation results are divided into three subsections in view of these margin levels.

4.1. First cost function with margin = 0
Assuming margin=0, cost function increases when queue length of CN differs from assumed 2500 packets. Table 3 displays calculated coordinates of $z$ vector for each control strategy.

| Margin | CS | $z$                        |
|--------|----|---------------------------|
| 0      | 1  | $z = [2.5748e+003]$       |
|        | 2  | $z = [122.7930e+000, 3.3803e+003]$ |
|        | 3  | $z = [1.8861e+003, 1.9327e+003, 38.4705e-003, 238.1142e+000]$ |
|        | 4  | $z = [2.5889e+003, 3.1697e+003, 30.1896e-003, 1.1785e+009, 3.3124e+003]$ |

Research results are presented in Figure 5 and 6.

![Figure 6](image1.png)

**Figure 6.** Queue length $y(k)$ of the congested node CN, calculated with margin = 0.

![Figure 7](image2.png)

**Figure 7.** Control signal $u(k)$, calculated with margin = 0.

As it can be seen, CS1 and CS2 lead to total fulfillment of egress buffer. This situation takes place when available outgoing bandwidth shown in Figure 4 equals 0. While stored packets cannot be forwarded, new pieces of data, ordered previously, are incoming and it causes overfill. These two strategies also generate similar control signal. It can be seen, that the controller detects congestion and stops ordering data from the source, but ordered number is too big to avoid packet dropping.

4.2. Second cost function with margin=1000
Second cost function is built on the base of the first one. As it is presented in (12), it accepts buffer utilization in range between 1500 packets and 3500 packets, what reflects half buffer capacity with margin 1000 (2500-1000, 2500+1000). Table 4 displays calculated coordinates of vector $z$ for each control strategy.
4.3. Third cost function with margin=2000

Third cost function gives the widest spectrum of buffer utilization level acceptance. It can be in range between 500 packets and 4500 packets. Table 5 displays calculated variables of vector for each control strategy.

Table 4. Vector \( z \) values, calculated \( z \) with margin=1000.

| Margin | CS | \( z \) |
|--------|----|--------|
| 1000   | 1  | \([2.9596e+003]\) |
|        | 2  | \([611.0730e+000, 1.2935e+003]\) |
|        | 3  | \([1.9793e+003, 3.7832e+003, 39.9978e-003, 474.2351e+000]\) |
|        | 4  | \([2.1579e+003, 2.3406e+003, 35.2209e-003, 69.1476e+000, 2.8392e+003]\) |

Figure 8. Queue length \( y(k) \) of the congested node CN, calculated with margin = 1000.

Figure 9. Control signal \( u(k) \), calculated with margin = 1000.

We can observe increasing difference between \( y(k) \) trajectories. CS1 still leads to total fulfillment of egress buffer, while CS2 leads to total emptiness.

Table 5. Vector \( z \) values, calculated \( z \) with margin=2000.

| Margin | CS | \( z \) |
|--------|----|--------|
| 2000   | 1  | \([862.9197e+000]\) |
|        | 2  | \([4.7499e+003, 1.2450e+003]\) |
|        | 3  | \([1.7398e+003, 2.1901e+003, 32.1632e-003, 633.3482e-003]\) |
|        | 4  | \([1.4286e+003, 2.3881e+003, 37.4055e-003, 277.3974e+000, 2.2024e+003]\) |
Together with tolerance increase of cost functions, CS3 and CS4 runs are approaching to each other. These strategies fulfill control expectations in the best way.

5. Conclusions
The paper discusses a comparison of network congestion avoidance algorithms. Particle swarm optimization method is applied for tuning controllers set for each three values of the margin. Presented four control strategies are focused on queue length control in active network nodes. It can be seen clearly, the improving trend in each group together with control strategy development. The best results were obtained with the most comprehensive algorithm, which takes more parameters under optimization process. In the first approach we define reference queue length and we optimize only the level of constant proportional gain. The second iteration, uses also constant gain value, but allows to optimize also the reference queue utilization level. Second and fourth iteration are modifications first two control strategies. They are depending controller gain level on egress queue utilization.

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