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# A TYPICAL FUZZY CONTROLLER

***In the article was made an analysis of the Bandwidth capacity data, which are indicating that when using the PI-method, the bandwidth capacity of channel with overload decreases with increase of the UDP-stream density.***

***A typical controller based on fuzzy logic (Fuzzy Logic Controller, FLC) is described in the article. Functional scheme of the FLC is presented. The structure of fuzzy controller is given. The table of fuzzy rules of the controller and its architecture is presented. Experimental data on queue lengths are presented. A review of controllers based on REM-method of active queue management (FREM, STREM, FEM) is given and conclusions concerning their impact on the router parameters are made.***

***It is proved that when the PI-method is used, the bandwidth capacity of channel with overload decreases with increase of the UDP-stream density. The RED-method has more stable bandwidth capacity when the UDP-stream density is varied. However, the highest and the most stable results are observed when using the FLC controller. The main advantage of the FLC-controller is that the length of the queue is stable with variation of the network parameters.***

***Keywords: fuzzy controller, fuzzy controller architecture, the membership functions of the input and output variables.***

**Introduction**. In the article was made an analysis of the Bandwidth capacity data, which are indicating that when using the PI-method, the bandwidth capacity of channel with overload decreases with increase of the UDP-stream density. The RED-method has more stable bandwidth capacity when the UDP-stream density is varied. However, the highest and the most stable results are observed when using the FLC controller.

The main advantage of the FLC-controller is that the length of the queue is stable with variation of the network parameters.

Typical controller based on fuzzy logic, membership functions of the input and output variables and fuzzy rules used for the controller are described in the paper. Response surface of fuzzy controller is presented. Topology and results of simulations are presented.

**Problem statement.** The buffers of network routers are overloaded due to non-uniform growth of capacities of channels. Basic methods of active queue management and congestion avoidance (RED, PI, REM) can not fully cope with the management of traffic with complex dynamics, high burst and non-linearity of load changes. As a result, an overload of the router buffer occurs and global synchronization of TCP flows takes place [1]. This in turn reduces the effective data rate and degrades quality parameters, such as packet loss ratio, delays and delay variations.

When using DropTail, a passive queue management method for TCP traffic manadement, the global synchronization takes place. This phenomenon is that when the buffer is overflowed, a reset of all incoming packets takes place, and all the transmitters of TCP/IP network initially reduce the TCP window, and then synchronously increase it, causing a new overload. As a countermeasure to global synchronization, the REM-algorithm of randomly-exponential drop/labelling of incoming packets during the buffer overflow was developed. The algorithm is based on a mesure ("price") of overload.

There are also some modifications of REM (FREM, STREM, FEM) which were developed for improvement of the network characteristics.

A controller based on fuzzy logic (FLC) is used to ensure the normal operation of the active queue management systems based on the REM-method. The FLC showed good results in management of non-linear systems with complex dynamics.

A typical controller based on fuzzy logic (FLC) is described in the article. A review of controllers based on REM-method of active queue management (FREM, STREM, FEM) is given and conclusions concerning their impact on the router parameters are made.

**Results of calculations and oscillogramms.** The theory of fuzzy sets describes and operates by imprecise concepts, and also makes vague conclusions. Fuzzy control is particularly useful when the investigated processes are too complex for analysis and when the information sources are interpreted qualitatively. Availability of mathematical tools for description of vagueness allows to build an adequate model of reality.

The FLC (Fig. 1) decides to change the current value of the probability of the package drop/labeling Pdrop taking into account the following parameters: errors of current queue length Qerror, its change during the measurement derror, and appropriate set of rules based on expert judgment. For the input variables, the value of membership function u is calculated, i.e. the degree of confidence that the input variable is the fuzzy (linguistic) variable, such as "large", "small" and "medium". The membership functions are selected from condition that the sum of all the functions of the input variable should be equal to one.

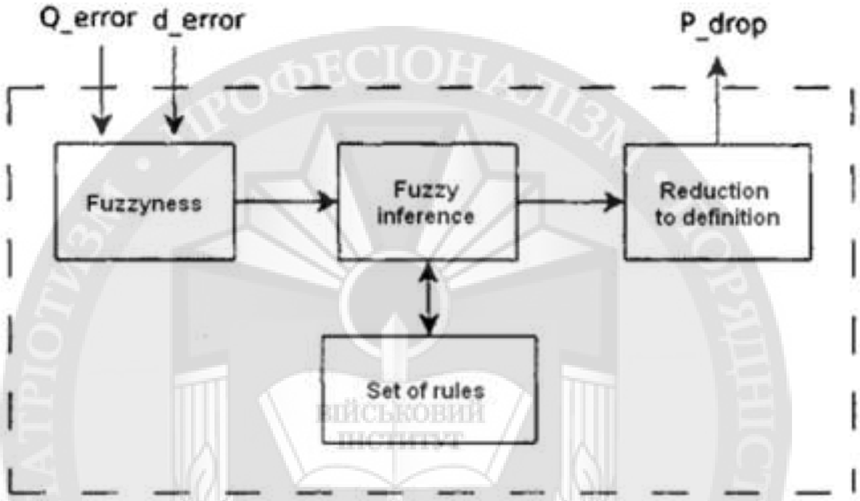


Fig. 1. Architecture of FLC

One of the most common algorithms of fuzzy inference is the Mamdani algorithm. Fuzzy inference is based on a set of rules: the value of truth for each rule premise is calculated (operation minimum). An example of linguistic rule: IF ($Q_{error}$ = "LARGE") and ($d_{error}$ = "SMALL") THEN ($P_{drop}$ = "MEDIUM"). All fuzzy sets derived from rules are aggregated together and a single fuzzy set $^{C}$ is formed (operation maximum). Reduction to definition is done, for example, by using a discrete method of "center of gravity":

$$P_{drop} = \frac{\sum_{j=1}^{m} y_j \cdot \mu_C y_j}{\sum_{j=1}^{m} \mu_C y_j}, \quad (1)$$

where $y_j$ is a discrete value of the output variable from $^{m}$ values,

and $\mu_C$ is membership function of aggregated set $^{C}$.

The main advantage of the congestion control algorithms based on fuzzy logic, is that they do not use the mechanism of dropping packets, but calculate packet losses according to a pre-configured fuzzy logic with use of queue length and the buffer usage ration [3]. So, the proposed algorithms reach higher bandwidth capacity, more stable values of the queue length. As a result, they improve the ability of routers to manage congestion in TCP/IP networks in comparison with schemes which use basic AQM-algorithms. The main objective of the AQM methods is tracking the congestion level in the network and notification the message sources (input packets) about this, in order to reduce their transmission rate. In actual practice, overloads occur when the required bandwidth exceeds the available capacity of the communication channel, which results in drastic deterioration of the network characteristics since the packet loss increases and the channel usage decreases. In order to prevent these problems, a fuzzy logic is widely used in TCP/IP networks which can well adapt for dynamic environment without accurate model and provides the non-analytic approach in design of dynamic and fast control schemes.

The main element of the AQM system is a fuzzy controller (Fig. 2), which does not use the mechanism of packets dropping, but calculates the packet losses according to the input queue length and the buffer usage ratio. This allows to improve performance of routers in the IP networks with dynamic environment [2].

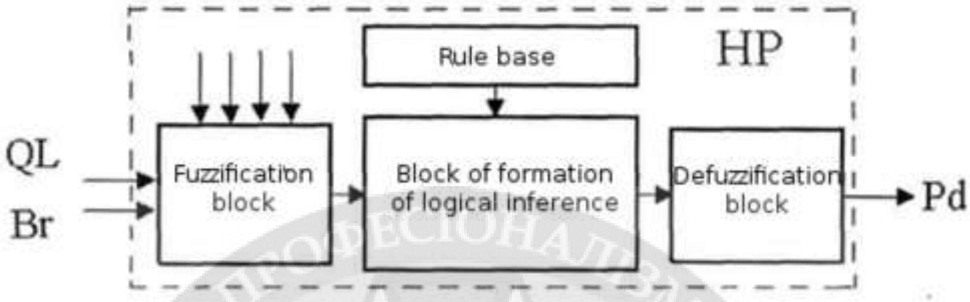


Fig. 2. Structure of fuzzy controller

A typical fuzzy controller includes three main blocks:

1. fuzzification block;
2. block of formation of logical inference;
3. defuzzification block.

The fazzificator is necessary to convert the input data into an appropriate set of linguistic variables that are needed in the decision making block. A number of fuzzy control rules that characterize dynamic behavior of the system is defined in the FLC rule base. Decision making block is used to form inferences from the fuzzy control rules.

The FLC has two inputs, which are designed to obtain information on the queue length (QL) and the buffer usage ratio Br. The packet-dropping probability Pd is transmitted to the FLC output. The controller calculates the probability of packet dropping according to the queue length, current buffer usage ratio and a set of fuzzy linguistic rules. The linguistic rules are generally defined as follows:

1) Rule 1 : ;
2) Rule 2 : ;

……………………….

3) Rule $^{k}$ : **IF QL = $A_k$ AND Br = $B_R$ THEN Pd = $c_k$;**

Symmetric triangular and trapezoidal membership functions are used as the membership functions. The queue length is classified in three linguistic variables: QL = (short, medium, long), where "short" means that the queue length is in normal state, "medium" means that the queue is in state of overload prevention, "long" means that the queue length is overloaded. Figure 3a shows the membership function of the "queue length" variable.

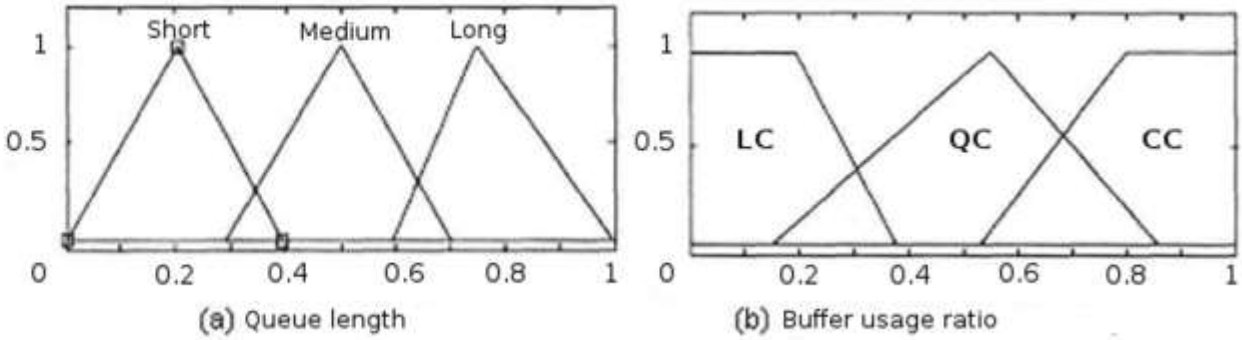


Fig. 3. Membership functions of input variables
"queue" and " buffer usage ratio"

The buffer usage ratio (Figure 3.b) is determined by Br variable, which has three states:

1. "low congested" (LC);
2. "quite congested" (QC);
3. "completely congested" (CC).

The probability function of packet dropping Pd is shown in Fig. 4 for five possible values:

1) Very low (VL);
2) Low (L);
3) Medium (M);
4) High (H);
5) Very high (VH).

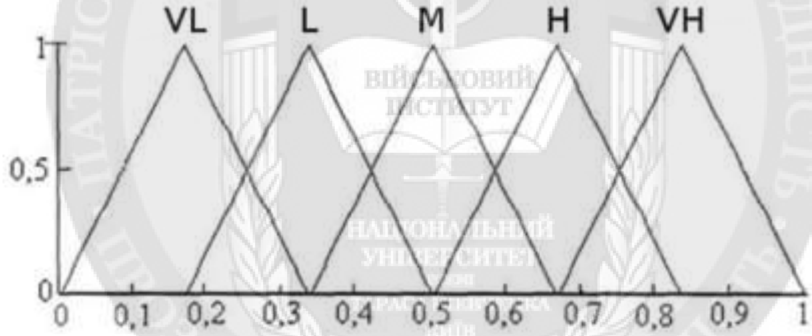


Fig. 4. The membership functions of the output variable "probability of packets dropping"

The fuzzy rules of the controller are written in Table 1

Table 1

| Queue length QL | Buffer usage ratio Br | | |
|---|---|---|---|
| | Normal state | Prevention of overloads | Overloads |
| Short | VL | VL | M |
| Medium | VL | L | H |
| Long | L | M | VH |

Complete links between the input and output variables (response surface) of fuzzy controller are presented in Fig. 5.

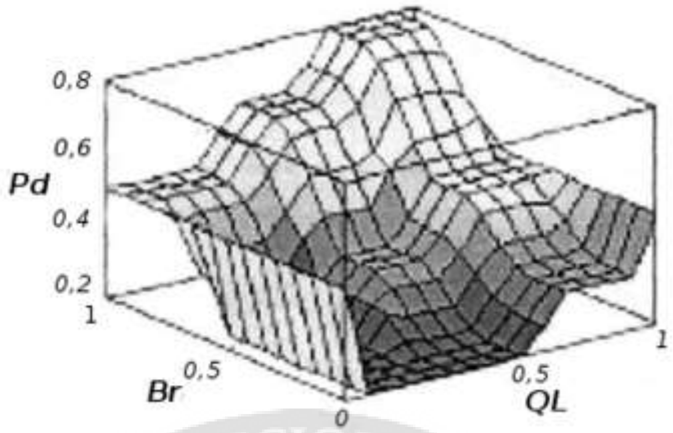


Fig. 5. Response surface of fuzzy controller

Fig. 6 shows the architecture of a fuzzy algorithm **AQM**, which includes classifying model (CM), models of packets dropping (MPD) and model of fuzzy controller (FLC). The CL denotes communication link. The input-to-output ratio is expressed by the set of linguistic rules.

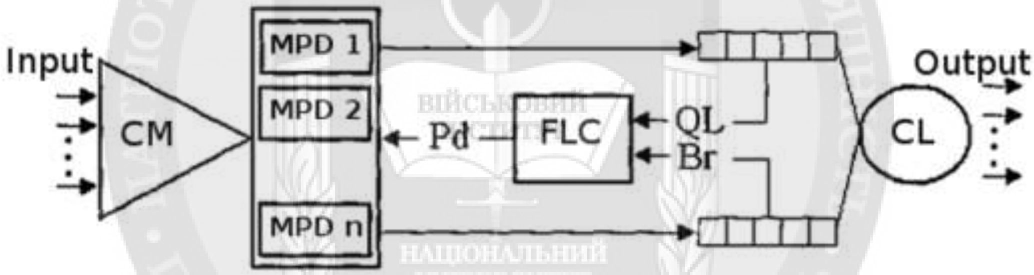


Fig. 6. Architecture fuzzy AQM algorithm

When the queue length is short and the buffer usage ratio is low, the probability of packet dropping is low. When the queue length is large and the buffer usage ratio is high, the probability of packets dropping is high. In this system, the algorithm can correspondingly adapt the probability of packets dropping by means of "learning."

Let us consider modeling the TCP/IP network operation with use of a fuzzy controller and AQM-methods (RED and PI) [1-4]. Topology of the simulated network is shown in Fig. 7.

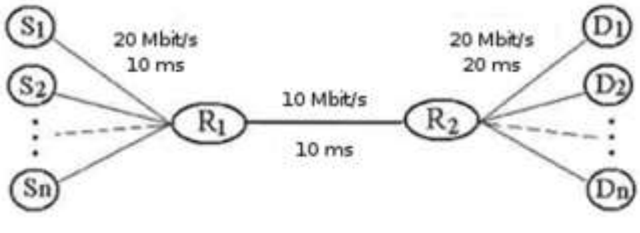


Fig. 7. Topology of modeling

The simulated TC/IP network consists of message sources $S_1$, $S_2$, .- $S_n$, message receiving devices $D_1$, $D_2$, .-$D_n$ and two routers $R_1$ and $R_2$ between which there is an overloaded line with 10 Mb/s bandwidth of 10 ms delay. The buffer size of the router is 300 packages, and the expected queue length is 100 packages. In addition, support for explicit congestion notification (ECN) is activated in all sources. Duration of simulation was 100 seconds.

In the first stage of modeling, N = 100 (Fig. 8, a) and N = 600 (Fig. 8, b) message sources are included into the system.

When the number of sources is 100, the queue length never exceeds the buffer size of the router. As Fig. 8a shows, the queue length is the highest when the RED-algorithm is used. The queue slightly oscillates when the PI-method is used, while the queue length of the FLC is lower and more stable.

When N = 600, the queue length for RED-method also has a high value and unstable character since RED-algorithm requires some time respond to the increasing number of connections. Queue length for PI-method has a stable character, but the reaction is slow. When using the FLC, the lowest queue length is observed with increasing number of network connections. When dealing with uncertain events, the fuzzy algorithm utilizes advantage of fuzzy logic. Even without an accurate model, it can effectively use resource of the buffer to avoid oscillations caused by the increase of the number of connections and provides a stable queue length.

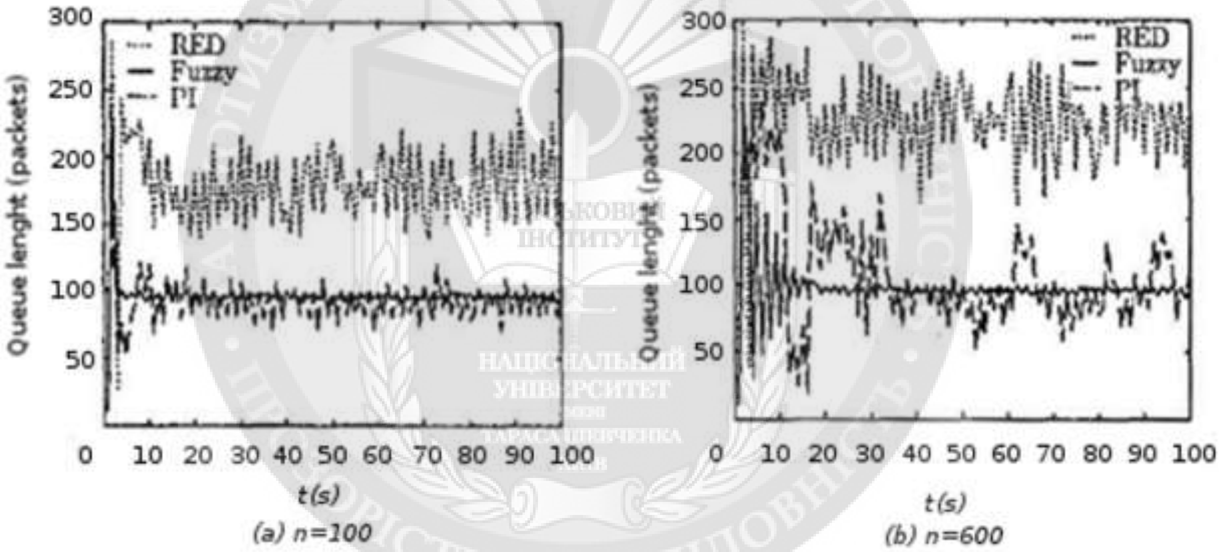


Fig. 8. Queue length for various TCP connections

So, the FLC provides the lowest possible and more stable queue length when the number of connections is changed.

At the second stage of simulation, the bandwidth capacity of the given methods was studied. Results of experiments are shown in Fig. 9.

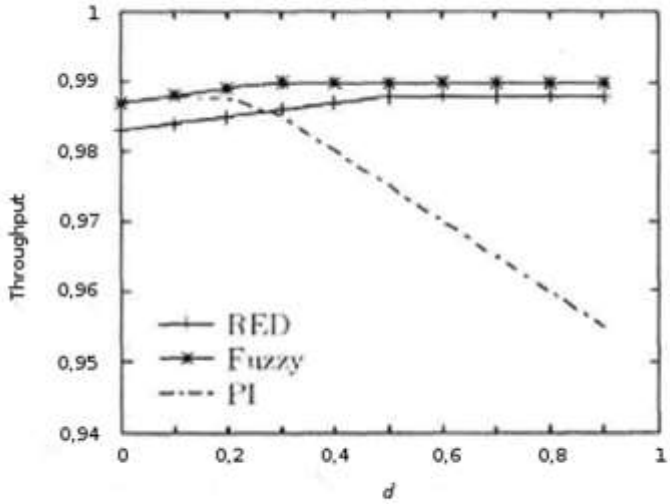


Fig. 9. Bandwidth capacity

The subject of studies at this stage was the impact of UDP-streams. The **UDP** stream density varied from 0.1 to 0.9.

**Conclusions.** The data presented in Fig. 9 indicate that when using the PI-method, the bandwidth capacity of channel with overload decreases with increase of the UDP-stream density. The RED-method has more stable bandwidth capacity when the UDP-stream density is varied. However, the highest and the most stable results are observed when using the FLC controller.

The main advantage of the FLC-controller is that the length of the queue is stable with variation of the network parameters.

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## ТИПОВИЙ НЕЧІТКИЙ РЕГУЛЯТОР

***У статті проаналізовано показники пропускної здатності, які вказують, що коли використовується PI-метод, то пропускна здатність перевантаженого каналу зменшується зі збільшенням щільності UDP-потоку.***

***У статті описаний типовий регулятор на основі нечіткої логіки (РНЛ). Представлена функціональна схема КНЛ, а також структура нечіткого контролера. Репрезентована таблиця нечітких правил контролера і його архітектури. Описані експериментальні дані по довжині черги. Проведено огляд контролерів на основі REM-методу активного управління чергою (FREM, STREM, FEM), також зроблені висновки про їх вплив на параметри маршрутизатора.***

*Доведено, що при використанні PI-методу, пропускна здатність каналу з перевантаженням зменшується зі збільшенням щільності UDP-потоку. RED-метод має більш стабільну пропускну здатність при зміні щільності UDP-потоку. Проте, найвищі і найстабільніші результати спостерігаються при використанні КНЛ. Основною перевагою РНЛ є те, що довжина черги стабільна при зміні параметрів мережі.*

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## ТИПИЧНЫЙ НЕЧЕТКИЙ РЕГУЛЯТОР

*В статье был проведен анализ показателей пропускной способности, которые указывают, что когда используется PI-метод, то пропускная способность перегруженного канала уменьшается с увеличением плотности UDP-потока.*

*В статье описан типичный регулятор на основе нечеткой логики (РНЛ). Представлена функциональная схема РНЛ, а также структура нечеткого контроллера. Репрезентирована таблица нечетких правил контроллера и его архитектуры. Описаны экспериментальные данные по длине очереди. Произведен обзор контроллеров на основе REM-метода активного управления очередью (FREM, STREM, FEM), также сделаны выводы о их влиянии на параметры маршрутизатора.*

*Доказано, что при использовании PI-метода, пропускная способность канала с перегрузкой уменьшается с увеличением плотности UDP-потока. RED-метод имеет более стабильную пропускную способность при изменении плотности UDP-потока. Тем не менее, самые высокие и самые стабильные результаты наблюдаются при использовании РНЛ. Основным преимуществом КНЛ является то, что длина очереди стабильна при изменении параметров сети.*