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IMPROVING QoS GUARANTIES VIA ADAPTIVE PACKET SCHEDULING

Abstract

In this paper the problem of packet scheduling in the node of packet-switched computer communication network is considered. Packet scheduling in the network node is one of the crucial mechanisms essential for delivery of required level of quality of services (QoS). In order to satisfy QoS guaranties for each connection belonging to one of distinguished traffic classes, packet scheduling algorithm must make decisions basing on current state of the scheduling system (e.g. buffer lengths) and actual characteristics of the serviced traffic (e.g.: connections lengths, packet intensities within connections, etc.) [3].

Here we propose a new packet scheduling algorithm based on Weighted Round Robin (WRR), which weights are adapted according to changes of system and traffic characteristics. By means of computer simulation, on representative examples, we show, that utilization of additional knowledge in the process of packet scheduling may improve QoS guaranties for serviced traffic.

Key words
QoS, Packet scheduling, Adaptation

1. Introduction

One of the most important mechanisms for delivering the quality of services (*QoS*) in computer communication packet-switched networks is packet scheduling in network nodes. Delivering *QoS* consists of guaranteeing for each separate stream of packets (e.g. connection) certain values of communication parameters, such as: maximum or average packet delay, jitter, packet loss ratio, etc. Required values of communication parameters depend on the traffic class, to which separate streams of packets belong to. Traffic classes are often distinguished basing on applications, which generate the traffic. *QoS* requirements are, in general, different for different traffic classes and depend on specific values of communication parameters required by various applications, necessary for them to run correctly. The task of packet scheduling algorithm is to service packets belonging to different streams in such a way, that *QoS* requirements are met for each separate stream of packet [6].

In order to satisfy *QoS* requirements of each separate stream of packets, scheduling decisions must be made basing on current state of the scheduling system (e.g. buffer lengths) and actual characteristics of the serviced traffic (e.g.: connections lengths, packet intensities within connections, etc.) [3]. Unfortunately, not all of necessary characteristics are available to the scheduling algorithm at the moment of decision making. Moreover, complexity of the scheduling algorithm increases with the number of parameters taken into account in the decision making process, what strongly affects efficiency of the scheduling algorithm and systems throughput [9].

To overcome these difficulties, we propose a new scheduling algorithm, which bases on estimation of traffic characteristics and adaptation of *Weighted Round Robin* (*WRR*) algorithm. The main advantage of such an approach relies on facts, that scheduling and adaptation are two separate processes and that single adaptation step may be several orders of magnitude longer, than step of primary scheduling algorithm. In fact, the duration of single adaptation step is bounded by the frequency of major changes of the traffic characteristics. Therefore, utilization of simple *WRR* as the primary scheduling algorithm enables fast decision making and high systems throughput, while more complex adaptation provides required level of *QoS*. Additionally, estimation of traffic characteristics allows to improve the quality of scheduling by prediction of future values of traffic parameters (such as connection lengths).

2. Traffic model

For the purpose of this paper, it is assumed, that the aggregated stream of packets incoming into the network node is composed of substreams of packets characterized by the same source and destination addresses. Throughout the paper, such a substream of packets, is referred to as connection. Each connection belongs to one of certain number (say K) of distinguished traffic classes. Each j-th connection c_j can be characterized by: class number k_j, arrival time t_j, duration τ_j and the sequence of arrival times of packets belonging to this connection $\{t_{j1}, \ldots, t_{ji_j}\}$ (see fig. 1).

$$c_j =< k_j, t_j, \tau_j, \{t_{j1}, \ldots, t_{ji_j}\} >, \qquad (1)$$

where $k_j \in \{1, \ldots, K\}$ and i_j is the number of packets within connection c_j.

It is also assumed, that parameters characterizing connections from the same traffic class k are realizations of random variables described by the same probability distributions. Therefore, each traffic class $k \in \{1, \ldots, K\}$ can be characterized by three probability distribution functions: $f_{k\delta}(\boldsymbol{\delta}_k)$, $f_{k\tau}(\boldsymbol{\tau}_k)$ and $f_{k\alpha}(\boldsymbol{\alpha}_k)$ describing respectively: time interval δ_j between arrival of two consecutive connections (c_{j-1} and c_j), duration τ_j of connection and time interval α_{ji} between arrival of two consecutive packets within single connection. Vectors $\boldsymbol{\delta}_k$, $\boldsymbol{\tau}_k$ and $\boldsymbol{\alpha}_k$ are

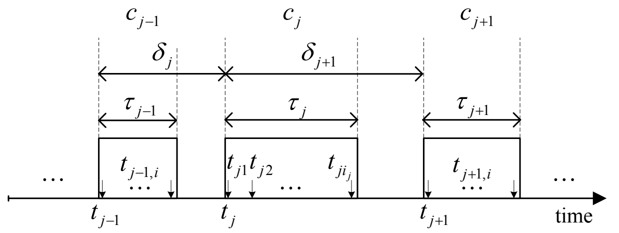

Fig 1. Model of connections from k-th traffic class

parameters of corresponding distribution functions.

3. Adaptive packet scheduling

3.1. Problem formulation

Assume following model of the network processor as the multi-queue single-processor queuing system (fig. 2). Network processor consists of processing unit ***P*** and K queues q_k, each buffering packets from corresponding traffic class.

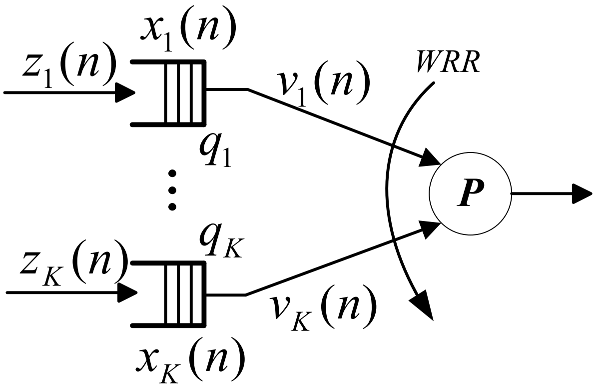

Fig 2. Network processor as the multi-queue single-processor queuing system

Packets from queues q_k are scheduled according to *WRR* algorithm. In each *WRR* cycle $n = 1, 2, \ldots$ processing unit ***P*** serves $v_k(n)$ packets from k-th queue. Vector $\mathbf{v}(n)$ of number of packets served from all queues is proportional to the vector $\mathbf{w}$ of *WRR* weights:

$$\mathbf{v}(n) = \mu \mathbf{w}, \tag{2}$$

where μ is the speed of processing unit ***P***.

In the same time $\mathbf{z}(n)$ packets arrive to all queues. Denote by $\mathbf{x}(n)$ and $\mathbf{x}(n+1)$ vectors of numbers of packets from each class, buffered in queues at the beginning and at the end of n-th cycle, respectively. Obviously, the state of the processors queues can be described by following flow equation [1]:

$$\mathbf{x}(n+1) = \mathbf{x}(n) - \mathbf{v}(n) + \mathbf{z}(n) = \mathbf{x}(n) - \mu\mathbf{w} + \mathbf{z}(n). \tag{3}$$

Let $\mathbf{q}(n)$ be the vector of measured delays of connections from all traffic classes in the n-th cycle. Vector $\mathbf{q}(n)$ can be calculated as certain function $\overline{h}$ of queues state $\mathbf{x}(n)$ and numbers of incoming $(\mathbf{z}(n))$ and outgoing $(\mathbf{q}(n))$ packets [8]:

$$\mathbf{q}(n) = \overline{h}(\mathbf{x}(n), \mathbf{v}(n), \mathbf{z}(n)) \widehat{=} h(\mathbf{x}(n), \mathbf{w}, \mathbf{z}(n)). \tag{4}$$

The task of scheduling algorithm is to minimize certain quality of service index $\varphi(\mathbf{q}(n))$ (e.g. average traffic delay) and to guarantee required values of delay for each connection belonging to each traffic class. Denote by $\mathbf{Q}$ the vector of delay requirements of all traffic classes. Now, the task of scheduling can be formulated as the following optimization problem:

For given:
- queues state $\mathbf{x}(n)$ at the beginning of n-th cycle,
- numbers of packets $\mathbf{z}(n)$ from all classes which arrive to the system during n-th cycle,
- function $\overline{h}$ describing the influence of queue lengths $\mathbf{x}(n)$ and numbers of packets entering $\mathbf{z}(n)$ and leaving $\mathbf{v}(n)$ the system on delays of serviced connections,
- quality of service index φ.

Find:
Such a vector $\mathbf{v}^*(n)$ of scheduling decisions, which minimizes the quality of service index $\varphi(\mathbf{q}(n))$

$$\begin{aligned} \mathbf{v}^*(n) &= \arg\min_{\mathbf{v}(n)} \varphi(\mathbf{q}(n)) \\ &= \arg\min_{\mathbf{v}(n)} \varphi\left(\overline{h}(\mathbf{x}(n), \mathbf{v}(n), \mathbf{z}(n))\right) \end{aligned} \tag{5}$$

with respect to *QoS* constraints:

$$\mathbf{q}(n) \leq \mathbf{Q}. \tag{6}$$

Since decisions $\mathbf{v}(n)$ can be affected only by changing weights $\mathbf{w}$, then, according to (4), equation (5) can be rewritten as:

$$\mathbf{w}^*(n) = \arg\min_{\mathbf{w}(n)} \varphi\left(h(\mathbf{x}(n), \mathbf{w}(n), \mathbf{z}(n))\right). \tag{7}$$

3.2. Algorithm

The task of adaptive packet scheduling is defined by formula (7) and constraints (6). Unfortunately, it cannot be directly solved, due to the fact, that function h defining connection delays and vector $\mathbf{z}(n)$ of numbers of packets incoming to the system during the n-th cycle are unknown.

In order to approximate the solution, the problem must be decomposed into four simpler subproblems, which are iteratively solved:

1. Estimation of parameters $\boldsymbol{\delta}_k$, $\boldsymbol{\tau}_k$ and $\boldsymbol{\alpha}_k$ of probability distribution functions $f_{k\delta}$, $f_{k\tau}$ and $f_{k\alpha}$ characterizing connections from each traffic class $k = 1, \ldots, K$.
2. Prediction of the vector $\overline{\mathbf{z}}(n)$ of numbers of packets from all traffic classes, which arrive to the system during the n-th cycle.
3. Approximation of function h by assumed model $\Phi(\boldsymbol{\theta})$.
4. Minimization of the quality of service index $\varphi\left(\Phi(\mathbf{x}(n), \mathbf{w}(n), \overline{\mathbf{z}}(n); \boldsymbol{\theta}(n))\right)$ with respect to *QoS* constraints (6).

The above decomposition allows to utilize solution algorithms known from such fields as: estimation, prediction, identification and optimization. In this work, following algorithms were applied. In the case, when classes of distributions were known, the *maximum likelihood method* was used to estimate distribution parameters.

Analysis of stochastic processes build upon distributions $f_{k\delta}$, $f_{k\tau}$ and $f_{k\alpha}$ allows to predict values of each element of vector $\overline{\mathbf{z}}(n)$ as the product of expected values of processes describing the number of active connections from each traffic class and the number of packets from a single connection belonging to each traffic class, which arrive to the system during one cycle. For example, when distributions $f_{k\delta}$, $f_{k\tau}$ and $f_{k\alpha}$ are exponential with parameters δ_k, τ_k and α_k, the expected value of k-th element of $\overline{\mathbf{z}}(n)$ can be calculated as [4]:

$$\overline{z}_k(n) = \Delta\alpha_k \left(\frac{\tau_k}{\delta_k} \left(1 - e^{-\frac{\Delta t}{\tau_k}} \right) + l_k(n-1)e^{-\frac{\Delta t}{\tau_k}} \right) \quad (8)$$

where Δt is the length of scheduling cycle and $l_k(n-1)$ is the measured number of active connections in $(n-1)$-th cycle. If distributions $f_{k\delta}$, $f_{k\tau}$ and $f_{k\alpha}$ are unknown, it is convenient to use adaptive *autoregressive moving average* filter (*ARMA*) as the predictor of $\overline{\mathbf{z}}(n)$.

As the model of delays of connections from all traffic classes $\overline{\mathbf{q}}(n) = \Phi(\mathbf{x}(n), \mathbf{w}(n), \overline{\mathbf{z}}(n); \boldsymbol{\theta}(n))$ a *diagonal recurrent neural network* (*DRNN*) [7] was used. Models parameters $\boldsymbol{\theta}(n)$ were approximated according to *back-propagation through time* (*BPTT*) algorithm [2].

In order to find optimal values of *WRR* weights $\mathbf{w}^*(n)$, which minimize the quality of service index $\varphi(\Phi(\mathbf{x}(n), \mathbf{w}(n), \overline{\mathbf{z}}(n); \boldsymbol{\theta}(n)))$ with respect to *QoS* constraints (6), *simulated annealing* metaheuristic was applied. However, for the cases, when the number K of distinguished traffic classes is not high ($K \leq 5$), exhaustive search may be used.

The abovementioned algorithms and models applied in four step iterative process, to which the task of adaptive scheduling (7) was decomposed to, constitute the *Adaptive Weighted Round Robin* (*AWRR*) algorithm.

4. Simulation study

In order to evaluate the quality of service delivered by proposed *AWRR* algorithm, it was compared to other known scheduling algorithms: *WRR* and *PRIO*. *WRR* is the simple weighted round robin with weights proportional to classes priorities. *PRIO* is the priority scheduling algorithm, which allocates all system resources to class with the highest priority.

In the simulations, it was assumed, that there is $K = 3$ traffic classes. Connection from each class were generated by certain number of *ON/OFF* sources. Priorities of classes were set to $p_1 = 1$, $p_2 = 5$ and $p_3 = 10$. *QoS* requirements of classes were $Q_1 = \infty$, $Q_2 = 100$ and $Q_3 = 50$. Above assumptions mean, that the first traffic class was the *best effort* traffic.

Exemplary results obtained for the *AWRR* algorithm are presented on figure 3. The chart presents average delay of connections from each traffic class during the simulation period. It is easy to notice, that proposed *AWRR* algorithm allocates to the high priority traffic class (class 3) only such amount of resources, which is necessary to deliver required level of connection delays. Remaining resources are allocated to the lower priority classes allowing them to experience lower delays.

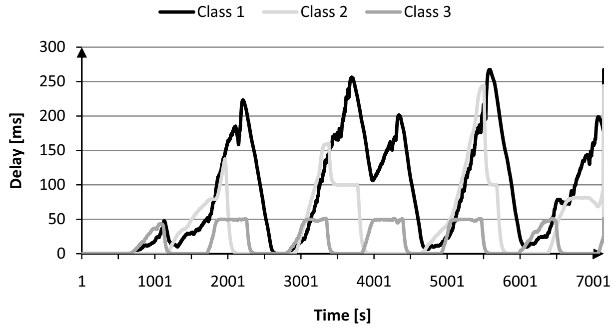

Fig 3. Connection delay for three traffic classes delivered by AWRR

Unfortunately, *QoS* requirements cannot be met for all traffic classes (e.g. class 2). The reason is, that overall traffic volume incoming to the network node is sometimes higher, than nodes processing capabilities. Thus, strict *QoS* guaranties for all traffic classes cannot be delivered without additional *QoS* mechanisms [5], such as: admission control, traffic shaping, etc.

Each one of compared algorithms guarantied the required level of connection delays for the high priority traffic class (class 3). Moreover, for each of algorithms, requirements of second traffic class were violated, when traffic intensity was high. Therefore, the quality of scheduling of evaluated algorithms can be measured as the average delay of best effort traffic (class 1) under condition, that requirements of high priority traffic (class 3) are met.

Average delay of connections from first traffic class, delivered by compared algorithms, are presented on figure 4. One can notice, that the lowest delays are obtained for the proposed *AWRR* algorithm and the highest delays are obtained for classic *WRR*. Sample results of algorithms comparison are gathered in table 1.

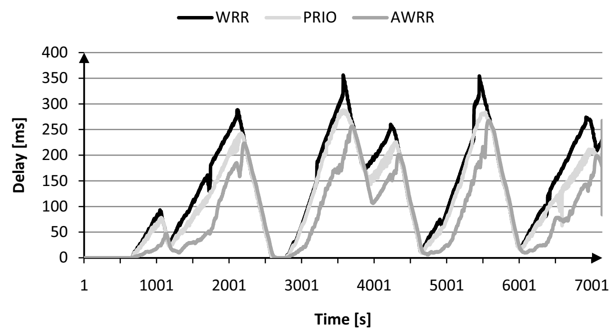

Fig 4. First class delay delivered by compared algorithms: WRR, PRIO, AWRR

Both *WRR* and *PRIO* allocate systems resources to second and third traffic class and deliver low average delay for these two classes. Obviously, resources can be allocated more fairly, allowing the first class to experience

Table 1

Average connection delay for three traffic classes delivered by compared algorithms: *WRR*, *PRIO*, *AWRR*

Algorithm	Class 1 avg. delay	Class 2 avg. delay	Class 3 avg. delay
WRR	156,43	33,30	3,98
PRIO	151,10	26,98	0,03
AWRR	98,81	97,62	44,84

lower delays, while requirements of high priority classes are still met (*AWRR* row in table 1).

5. Final remarks

WRR is a simple static scheduling algorithm, which does not react to any changes in traffic and system characteristics. On the other hand, priority scheduling (*PRIO*) can be treated as degenerated adaptive *WRR*, which assigns only binary weights to traffic classes, basing on classes priorities and queues lengths. *AWRR* is a fully adaptive scheduling algorithm, which responds to any changes in the serviced traffic.

Results of performed simulations show, that estimation of traffic characteristics and utilization of gathered knowledge in the process of packets scheduling may significantly improve (up to 30% for first traffic class) the level of delivered quality of services.

Presented approach to adaptive packet scheduling is based on adaptation through identification methodology. Identification refers to prediction of future *QoS* parameters of serviced traffic, basing on values of parameters of primary scheduling algorithm. Adaptation relies on choosing new parameter of primary scheduling algorithm, which minimize certain quality of service index and deliver required level of *QoS* for actual traffic characteristics.

The choice of connection delays as the *QoS* parameters and *WRR* as the primary scheduling algorithm was based on the simplicity of implementation of proposed solutions in the simulator. Presented adaptive scheduling approach, however, can be applied for arbitrary *QoS* measure and scheduling methodology. The only difference for other *QoS* measures and scheduling algorithms is the assumed model Φ of predicted *QoS* parameters. For example, vector $\mathbf{q}(n)$ of delivered *QoS* may describe average delay and jitter for each traffic class. In such a case vector $\mathbf{q}(n)$ would consist of $2K$ elements.

In the future work, the performance of presented approach should be evaluated for different measures of *QoS* (e.g.: maximal delay, jitter, packet loss ratio, etc.). Moreover, it should be compared, to other commonly used scheduling algorithms. Interesting results may be obtained by evaluation of the *QoS* level delivered by proposed approach in systems with admission control mechanisms.

Acknowledgements

This work was supported by the Polish Ministry of Science and Higher Education under Grant No. N N 516 3838 34 (2008-2009).

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