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## TECHNOLOGIES OF COMPUTER CONTROL

## DATORVADĪBAS TEHNOLOĢIJAS

# COMPARISON OF NETWORK DELAY PREDICTION METHODS IN THE REAL-TIME MODE

# TĪKLA AIZKAVES PROGNOZĒŠANAS METOŽU SALĪDZINĀJUMS REĀLA LAIKA REŽĪMĀ

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## 1. Introduction

Networked control systems become commonly used in the industrial automation. Connection of control system components via communication network allow to reduce wiring costs and make it easier to introduce additional components into the system. In 2007 IEEE organization publish a special issue on technology of networked control systems with information on current and future research directions on this field [1]. Networked control systems can be studied at [2].
Relevant problems of packet switching networks in control systems are irregularity if transmission time delay and packets lost. These problems are especially obvious in the Internet network. In the last years several papers about Internet-based teleoperation are published. Another wide group of papers is about question of stability of networked control systems [3]. One of the main research directions is network time delay modeling. The accurate model of time delay improves a stability of control system and quality of control.
In this paper, simulation of Internet time delay prediction is described. Average, simple moving average, exponential moving average and least linear squares methods are used. Prediction real-time simulation is realized in MATLAB. Results of simulation and estimation of prediction accuracy are presented.

## 2. Prediction of the time delay

### 2.1. RTT measurement

MATLAB simulation of the time delay prediction is realized. Ping tool is used for time delay measurement between local and remote hosts. It sends "echo request" packet to the target host and measures the time until receiving of the “echo replay” packet. Measured time is called round trip time (RTT) and normally is in milliseconds. MATLAB can get RTT time value from DOS system by command:

```
[s w] = dos('ping -n 1 target_name')
```

The local host is the personal computer at Faculty of Computer Science and Information Technology in Riga. The remote host is intensively used WEB server in Vienna. Every 1 second 32 bytes “echo request” packets are generated. Control program cyclically execute RTT requests and prediction calculations until predefined number of measurements will be reached.
For RTT value prediction average (A), simple moving average (SMA), exponential moving average (EMA) and least linear squares (LLS) methods are applied.

### 2.2. Prediction methods

Method of average is based on the calculating of the average value of all previous measurements. Equation can be written as:

$$\hat{y}_{k+1} = \frac{\sum_{i=1}^{k} y_i}{k} \quad (1)$$

where:

$\hat{y}_{k+1}$ - next RTT prediction;
$y_i$ - i-th RTT value;
$k$ - actual number of measurements.

Method of simple moving average is based on the calculating of the average value of predefined number of latest measurements. Equation can be written as:

$$\hat{y}_{k+1} = \frac{\sum_{i=k-n+1}^{k} y_i}{n} \quad (2)$$

where:

$\hat{y}_{k+1}$ - next RTT prediction;
$y_i$ - i-th RTT value;
$n$ - number of latest measurements used in prediction calculations.

In method of exponential moving average for measurements applies weighting factors which decrease exponentially. And as in previous method the prediction is based on average value of predefined number of latest measurements. Equation can be written as:

$$\hat{y}_{k+1} = \alpha y_k + (1-\alpha)\hat{y}_k \quad (3)$$

where:

$\hat{y}_{k+1}$ - next RTT prediction;
$\hat{y}_k$ - k-th RTT prediction;
$y_i$ - i-th RTT value;
$\alpha$ - smoothing constant.

At calculation of the first prediction assume that $\hat{y}_k = y_k$.
Finally, the fourth method is least linear squares. Equations can be written as:

$$\hat{y}_{k+1} = \beta_0 + \beta_1 x_{k+1} \tag{4a}$$

$$\beta_0 = \bar{y} - \beta_1 \bar{x} \tag{5a}$$

$$\beta_1 = \frac{\sum_{i=1}^{k} (x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{k} (x_i - \bar{x})^2} \tag{6a}$$

Equations 5-7 can be converted to:

$$\hat{y}_{k+1} = \beta_0 + \beta_1 T(k+1) \tag{4b}$$

$$\beta_0 = \bar{y} - \beta_1 \frac{T(k+1)}{2} \tag{5b}$$

$$\beta_1 = \frac{\sum_{i=1}^{k} (Ti - \frac{T(k+1)}{2})(y_i - \bar{y})}{\sum_{i=1}^{k} (Ti - \frac{T(k+1)}{2})^2} \tag{6b}$$

where:

$\hat{y}_{k+1}$ - next RTT prediction;
$y_i$ - i-th RTT value;
$\bar{y}$ - RTT average;
$k$ - actual number of measurements;
$T$ - time period of measurements;
$\beta_0$, $\beta_1$ - parameters.

More information about mentioned methods can found in [4].

### 2.3. Estimation of the prediction accuracy

For the prediction accuracy estimation absolute error (AE) and mean squared error (MSE) are calculated. For all models calculation starts at step $n+1$, after first prediction of SMA model will be calculated. General expression for the absolute error is:

$$AE_i = \begin{cases} 0, i <= n, \\ |y_i - \hat{y}_i|, i > n, \end{cases} \tag{8}$$

where:

$y_i$ - i-th RTT value;
$\hat{y}_i$ - i-th RTT prediction;
$n$ - number of measurements used in SMA model.

Expression for the mean squared error is:

$$MSE_i = \begin{cases} 0, i <= n, \\ \dfrac{\sum_{i=n}^{k} (y_i - \hat{y}_i)^2}{k-n}, i > n, \end{cases} \quad (9)$$

where:

| | |
|---|---|
| $y_i$ | - i-th RTT value; |
| $\hat{y}_i$ | - i-th RTT prediction; |
| $k$ | - actual number of measurements; |
| $n$ | - number of measurements used in SMA model. |

## 3. Prediction simulation

### 3.1. Choose of $n$ for SMA model and $\alpha$ for EMA model

For $n$ and $\alpha$ selection the training set $E$ of $RTT_i$, $i = 1:(1):300$ values is measured. The plot and histogram of set $E$ are shown in Figure 1.

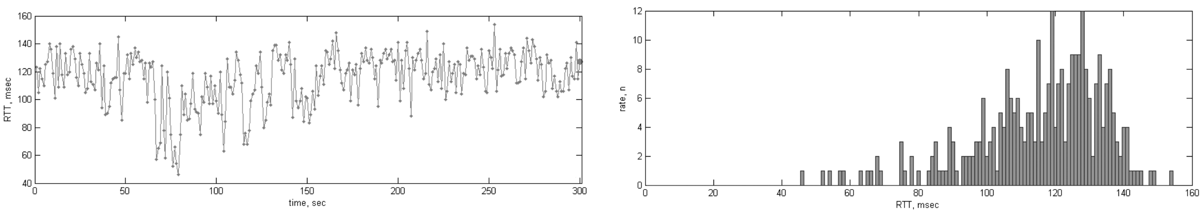


**Fig.1.** Plot (left) and histogram (right) of RTT value from set $E$

SMA and EMA are simulated on the set $E$ for $n = 2:(1):6$ and $\alpha = 0.1:(0.1):0.6$ respectively. MSE are represented in Figure 2 for different $n$ in SMA model and for different $\alpha$ in EMA model.

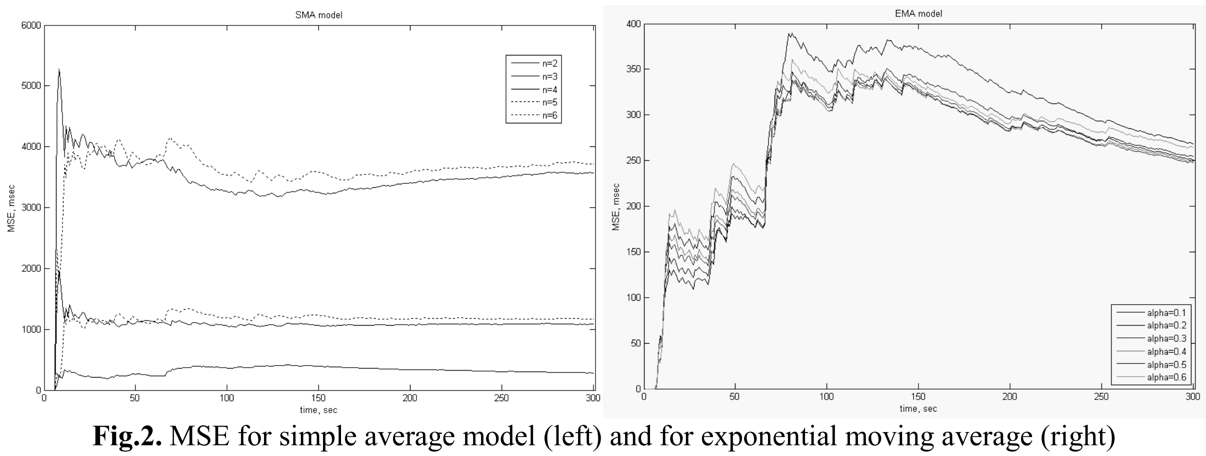


**Fig.2.** MSE for simple average model (left) and for exponential moving average (right)

In Figure 3 can see that the smallest MSE in SMA model is for $n = 4$. And it is not such obvious but in the end of simulation the smallest MSE in EMA model is for $\alpha = 0.3$. These values will be applied for a real-time simulation in the next section.

### 3.2. Real-time simulation

The simplified block diagram of the simulation program is shown in Figure. 3.

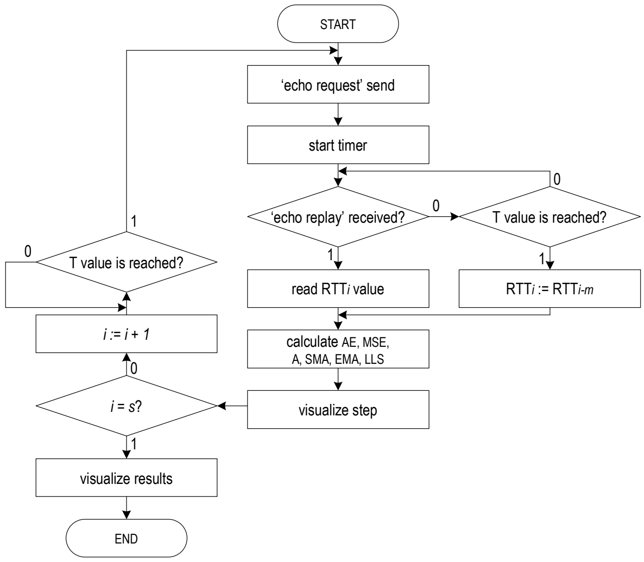


**Fig.3.** Simplified block diagram of simulation program

Before start of simulation the total number $s$ and time period $T$ of measurements should be defined. At cycle beginning program generates "echo request" packet and waiting for response. If program did not get "echo replay" packet in time $T$, then for the predictions calculation is applied nearest successive RTT value. At every step new RTT value, predicted values and errors are outputted to the plot figure. In the end of simulation process total results of measurements are calculated and outputted to the plot and histogram figures.
Results of the simulation with $s = 600$ and $T = 1\text{sec}$ are represented in Figures 4, 5.

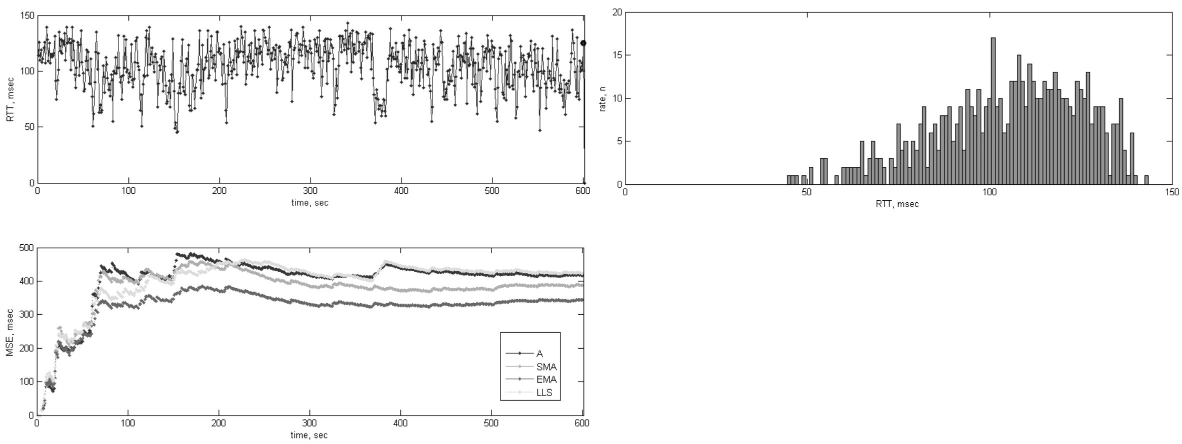


**Fig.4.** RTT plot (top left), RTT histogram (top right) and prediction MSE (bottom left)

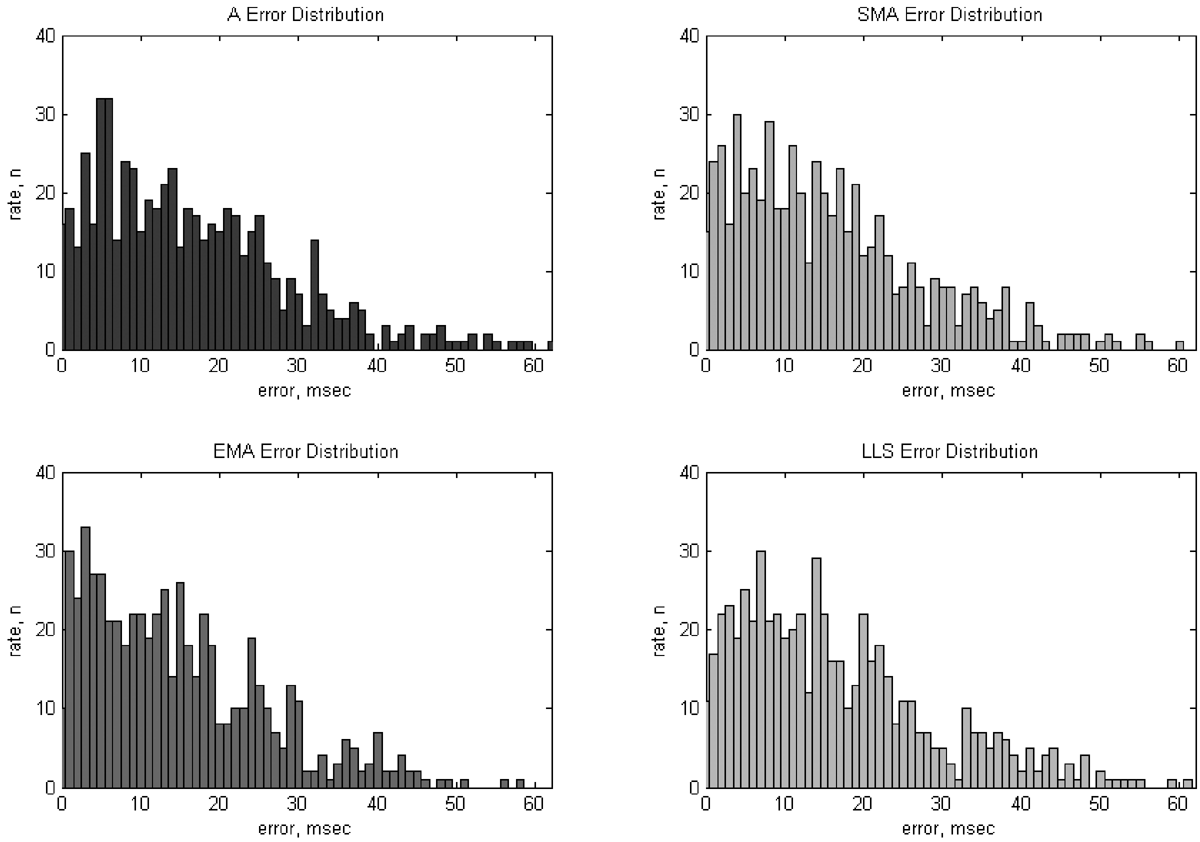


**Fig.5.** Histogram of absolute error for A (top left), SMA (top right), EMA (bottom left) and LLS (bottom right) models

After 600 steps mean squared error of A model 412.87 ms, of SMA model 383.65 ms, of EMA model 339.53 ms and of LLS model 419.54 ms. In case of wide distribution of RTT value more conservative A and LLS models are less accurate than SMA and EMA models.

## 4. Conclusions

In this paper a comparison of network time delay prediction methods is presented. Average, simple moving average, exponential moving average and least linear squares methods are considered. Parameters of models of second and third methods are defined by simulation on training set of RTT values. The simulation result show that most accurate is exponential moving average prediction model. But it is necessary to remark that for another connection with different RTT distribution and dynamics results will be different.

Next goal is improvement of prediction models accuracy. Research of typical features of time delay in IP networks should be realized. Information about these features makes it possible to improve prediction models in the real-time: optimize the parameters of the model depending of the time delay dynamics, use prediction models switching.

## References


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**Safins R. Tīkla aizkaves prognozēšanas metožu salīdzinājums reāla laika režīmā**
*Tīkla vadības sistēmas ir plaši pielietotas industriāla automātikā. Vadības sistēmas iekārtu savienošana ar komunikācijas tīkla palīdzību ļauj samazināt elektroinstalācijas izmaksas un atvieglot papildu elementu pieslēgšanu sistēmai. Neregulāra datu pārraides laika aizkave pakešu komutācijas tīklos var pieviest pie sistēmas nestabilitātes. Raksts ir veltīts Internets tīkla laika aizkaves prognozēšanas simulācijai reāla laika režīmā. Izmantotas vidēja, slīdoša vidēja, eksponenciāla slīdoša vidēja un mazāko kvadrātu metodes. Prognozēšanas modeļu parametri ir nodefinēti ar apmācošas izlases palīdzību. Prognozēšanas simulācija ir veikta MATLAB programmā. Simulācijas programma ģenerē „echo request" paketes caur DOS sistēmu attālinātam hostdatoram ar nodefinētu laika intervālu un atpakaļ saņem atbilde ar nomērītu aprites laika vērtību. Nākama aprites laika prognoze un iepriekšējas prognozes precizitāte tiek aprēķinātās reāla laikā. Prognozes precizitātes novērtēšanai pielieto absolūtu un vidējo kvadrātisko kļūdas. Ir doti simulācijas programmas un laika aizkaves mērīšanas apraksti. Raksta beigās attēloti simulāciju rezultāti un prognozēšanas novērtējumi. Secinājumos var atrast nākotnes pētījumu virzienus tīkla vadības sistēmu nozare.*

**Safins R. Comparison of network delay prediction methods in the real-time mode**
*Networked control systems become commonly used in industrial automation. Connection of control system components via communication network allow to reduce wiring costs and make it easier to introduce additional components into the system. Irregular transmission time delay of packet switching networks can lead to unstable operation of such systems. In this paper, real-time simulation of Internet time delay prediction is described. Average, simple moving average, exponential moving average and least linear squares methods are used. Parameters of prediction models are defined at training set of time delays. Prediction simulation is realized in MATLAB. Simulation program via DOS system generates "echo request" packets to remote host with predefined time interval and give back answer with measured round trip time value. The predictions of next round trip time and accuracy of the previous prediction are calculated in real-time mode. For estimation of prediction accuracy the calculation of absolute error and mean squared error are applied. The descriptions of simulation program and time delay measurement are given. At last, results of simulation and estimation of prediction accuracy are presented. In conclusions directions of the future research at networked control systems are discussed.*

**Сафин Р. Сравнение методов прогнозирования задержки сети в режиме реального времени**
*Сетевые системы управления нашли широкое применение в индустриальной автоматике. Соединение устройств системы управения через коммуникационную сеть позволяет снизить затраты на электроинсталяцию и упростить процедуру внедрения дополнительных устройств в систему. Нерегулярная временная задержка передачи данных в пакетных сетях может привести к нестабильной работе подобных систем. В представленной работе описывается симуляция прогнозирования временной задержки Интернет сети в режиме реального времени. Использованы методы: среднего, скользящего среднего, экспоненциального скользящего среднего и наименьших квадратов. Параметры используемых моделей определены по обучающей выборке. Симуляция прогнозирования реализована в программе MATLAB. Симуляционная программа генерирует пакеты "echo request" удалённому компьютеру через DOS систему с заданным интервалом времени и получает ответ с измеренным времени ответа. Прогноз следующего времени ответа и точность последнего прогноза расчитываются в реальном времени. Для оценки точности прогноза используются абсолютная и среднеквадратическая ошибки. Приведено описание программы симуляции и измерения временной задержки. В конце даны результаты симуляции и оценка качества прогнозирования. В выводах обсуждаются направления будущих исследований сетевых систем управления.*