On Kleinrock's Independence Assumption

Adrian Popescu[1] and Doru Constantinescu[2]

[1] Blekinge Institute of Technology, Sweden
adrian.popescu@bth.se
[2] Telenor Connexion, Sweden
doru.constantinescu@telenor.com

Abstract. This chapter is concerned with the impact of traffic correlations on the end-to-end delay of packets in a chain of IP routers represented by an open tandem queueing system. Particular consideration is given to Kleinrock's independence assumption on the performance impact of traffic correlation on packet switched networks with Poisson arrival processes and exponential packet length distributions. According to this assumption, any traffic correlations can be ignored and the effect on delay performance is negligible, subject to sufficient traffic mixing and moderate-to-heavy traffic loads. In this context, results associated with measurements, traffic modeling and delay analysis of an actual chain of IP routers are reported from experiments conducted at the Blekinge Institute of Technology in Karlskrona, Sweden. It is shown that no experimental evidence was found in support of Kleinrock's independence assumption as traffic correlation has an adverse effect on the end-to-end delay of the tandem queueing system.

1 Introduction

As the Internet has emerged as the backbone of worldwide business and commercial activities, end-to-end (e2e) Quality of Service (QoS) for data transfer becomes a significant factor. In this context, one-way delay is an important QoS parameter. It is a key metric in evaluating the performance of networks as well as the quality of service perceived by end users. This parameter is defined by both the IETF (One Way Delay for IP Performance Metrics) and the International Telecommunications Union - Telecommunications Standardization (IP Packet Transfer Delay).

Today, network capacities are deliberately being overprovisioned in the Internet so that the packet loss rate and the delay are low. However, given the heterogeneity of the network and the fact that the overprovisioning solution is not adopted everywhere, especially not by backbone teleoperators in developing countries, the question arises as to how the delay performance impacts the e2e performance. There are several important parameters that may impact the e2e delay performance in the link, e.g., traffic self-similarity, routing flaps and link utilization [16, 18].

Several publications report on the e2e delay performance, and both Round-Trip Time (RTT) and One-Way Transit Time (OWTT) are considered [4, 6, 18, 19].

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Traffic measurements based on both passive measurements and/or active probing are used. As a general comment, it has been observed that RTT and OWTT show large "peak-to-peak" variations, in the sense that maximum delays far exceed minimum delays. Although a range of more than 10:1 in RTTs seems to be common, most of connections have RTTs between 15 and 500 s [12]. Further, it has been observed that OWTT variations (for opposite directions) are generally asymmetric, with different delay distributions. They also seem to be correlated with packet loss rates [19]. Periodic delay spikes and packet losses have been observed, which seem to be a consequence of routing flaps [18].

Typical distributions for OWTT have been observed to have a Gamma-like shape and to possess heavy tail [4,17]. The parameters of the Gamma distribution have been observed to depend upon the path (e.g., regional, backbone) and the time of the day. The heavy tail behavior is due to the presence of self-similarity in Internet packet delay [3]. Typical queueing models like M/M/1, M/G/1 and using Fractional Brownian Models (fBm) for traffic models have been shown to underestimate average queueing delays for link utilization below 70% [18]. Furthermore, another important question is regarding the impact on OWTT performance of diverse correlations existent in a tandem queueing system and whether Kleinrock's independence assumption [14] is valid. Leonard Kleinrock suggested that, under specific conditions (e.g., Poisson arrival processes, packet lengths that are nearly Exponentially distributed, a densely connected network with sufficient traffic mixing and moderate-to-heavy traffic loads), the effects of correlations may become small and therefore completely ignored.

The paper is reporting on some of the results obtained in experiments done at the Blekinge Institute of Technology (BTH) in Karlskrona, Sweden, on measurements, modeling and analysis of delay in a chain of IP routers. Particular focus is given to validating Kleinrock's independence assumption regarding the effect of correlations in a tandem queueing system. Our results show that this assumption is not valid in our experiments.

The paper is organized as follows. In Section 2 we describe the delay components associated with the OWTT in a chain of IP routers. In Section 3, we give an overview on queueing delay in a chain of IP routers, with particular focus on correlations and Kleinrock's independence assumption. In Section 4 we shortly describe the experiments done at BTH. We briefly report in Section 5 on the results obtained in our experiments on measurement, modeling and analysis of delay in a chain of IP routers with particular focus on the validation of Kleinrock's independence assumption. In Section 6 we conclude the paper.

2 One-Way Transit Time Components

One-Way Transit Time (OWTT) is measured by timestamping a specific packet at the sender, sending the packet into the network, and comparing then the timestamp with the timestamp generated at the receiver [1]. Packet timestamping can be done either by software (for the case of delay measurements at the application level) or by hardware (for the case of delay measurements at the network level), and in this case special hardware is used. Clock synchronization between the sender and the receiver nodes is important for the precision of one-way delay measurements [1].

OWTT has several components:

$$OWTT = D_{prop} + \sum_{i=0}^{N} D_{n,i} \quad (1)$$

where the delay per node i, $D_{n,i}$ is given by:

$$D_{n,i} = D_{tr,i} + D_{proc,i} + D_{q,i} \quad (2)$$

The components are as follows:

- D_{prop} is the total propagation delay along the physical links that make up the Internet path between the sender and the receiver. This time is solely determined by the properties of the communication channel and the distance. It is independent of traffic conditions on the links.
- N is the number of nodes between the sender and the receiver.
- $D_{tr,i}$ is the transmission time for node i. This is the time it takes for the node i to copy the packet into the first buffer as well as to serialize the packet over the communication link. It depends on the packet length and it is inversely proportional to the link speed.
- $D_{proc,i}$ is the processing delay at node i. This is the time needed to process an incoming packet (e.g., to decode the packet header, to check for bit errors, to lookup routes in a routing table, to recompute the checksum of the IP header) as well as the time needed to prepare the packet for further transmission, on another link. This delay depends on parameters like network protocol, computational power at node i, and efficiency of network interface cards.
- $D_{q,i}$ is the queueing delay in node i. This delay refers to the waiting time in output buffer, and depends upon traffic characteristics, link conditions (e.g., link utilization, interference with other IP packets) as well as implementation details of the node. It is mentioned that we consider routers with best-effort service model, i.e., routers where an output port is modeled as a single output queue.

Statistics like mean, median, maximum, minimum, standard deviation, variance and peakedness are usually used in the calculation of delay for non-corrupted packets. Typical values obtained for OWTT range from tens of μs (between two hosts on the same LAN) to hundreds of ms (in the case of hosts placed in different continents) [5].

For a general discussion, the OWTT delay can be partitioned into two components, a deterministic delay D_d and a stochastic delay D_s:

$$OWTT = D_d + D_s \quad (3)$$

D_{prop}, D_{tr} and (partly) D_{proc} are contributing to the deterministic delay D_d, whereas the stochastic delay D_s is created by D_q and, at some extent, D_{proc}. The stochastic part of the router processing delay can be observed especially in the case of low and very low link utilization, i.e., when the queueing delays are minor.

3 Queueing Delay in Chained IP Routers

An important delay component in IP networks is the queueing delay in routers and switches and the jitter that may appear in the case of large queueing delays. In a chain of IP routers, there may be many transmission queues (e.g., output ports in routers) that may interact with each other in the sense that a traffic stream leaving a queue enters others queues, likely after merging with other traffic streams coming from other queues (Figure 1).

The direct effect of traffic merging in packet networks is that the character of the arrival process at a downstream queue changes. Since the same packets visit more queues in a tandem queueing system, the service times of each packet at the visited successive queues are typically positively correlated. Furthermore, given that the service times at two queues are dependent, then the packet interarrival times become correlated with packet lengths at the downstream queue. Long packets typically wait less time than short packets at a downstream queue, which is because they need longer time for service at the upstream queue. The consequence is that the downstream queue has more time to empty out.

A similar situation is in the case of a slow truck traveling on a narrow street, with one track only. The truck typically has empty space ahead but more faster cars following behind the truck. Simulation studies have shown that in real situations, when interarrival times and service times are strongly correlated, the average delay per packet at the downstream queue tends to be less than in the case the dependence was not existent. On the other hand, under heavy loads, the average delay tends to be dramatically less. A reverse situation is valid under light traffic conditions as well [11].

Leonard Kleinrock studied the problem of correlations between service and interarrival times in the context of a queueing network model for communication networks [14]. He observed that, if there is sufficient mixing of traffic, then the dependence effect may become small, and therefore it can be completely ignored. Kleinrock suggested consequently that merging several packet streams on a tandem queueing system has an effect similar to restoring the independence of interarrival times and packet lengths. This means that each time a packet is received at a node in a network, an Exponential distribution can be used to generate a new length for the specific packet. This is clearly false since packets

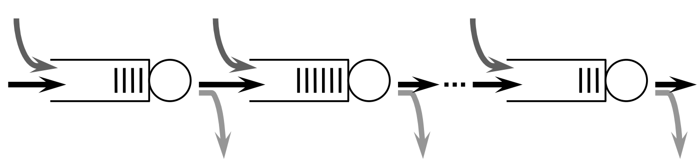


Fig. 1. Tandem queueing

maintain their lengths as they pass through the network, but Kleinrock showed that the effect on delay performance is negligible.

Based on these arguments, it was concluded that it is appropriate to adopt an M/M/1 queueing model for every queue in a tandem queueing system regardless of the interaction of traffic with other traffic flows. This is known as *Kleinrock's independence assumption*, which amounts to ignoring correlations. This assumption seems to be a good approximation for the case of Poisson arrival processes, packet lengths that are nearly Exponentially distributed, a densely connected network with sufficient traffic mixing and moderate-to-heavy traffic loads [2, 14]. It can however significantly overestimate delays in tandem queueing systems with little traffic mixing, where there is strong positive correlation between service and interarrival times.

The process of changing the character of the arrival process at downstream queues is very complex. It is heavily influenced by different aspects, like the presence of different traffic classes (with specific traffic characteristics) sharing the same queue, the presence of Long-Range Dependence (LRD) in traffic, the presence of tandem links with different link utilization and the presence of a large number of traffic sources sharing the network. Today, the situation is such as it is not clear what the arrival processes at downstream queues are, and therefore it is impossible to do a precise analysis like, e.g., in the case of M/M/1 or M/G/1 queueing systems. Delay models based on Poisson assumptions are totally inappropriate for analysis at downstream queues and no analytical solutions are actually known for even a simple tandem queueing system with Poisson arrivals and Exponentially distributed service times [2, 4, 18].

There are several classes of correlations in a queueing system, all of them contributing to the complexity of the process of changing the character of the arrival process at downstream queues [11]. These are:

- autocorrelations in packet interarrival times
- autocorrelations in packet service times
- crosscorrelations among packet interarrival times and packet service times
- crosscorrelations in packet service times for tandem queues

Generally, successive packet interarrival times are often positively correlated [11]. This is valid for successive packet service times as well. Diverse factors like the presence of LRD in traffic and segmentation of large messages into IP packets with maximum 1500 bytes length heavily influence the appearance of correlations. On the other hand, packet interarrival times and packet service times are often negatively correlated with each other. Altogether, the above-mentioned types of correlations tend to make packet delays larger than in the case of independent and identically distributed (iid) packet lengths where there is no dependence [11].

4 Experiments

Measurement of one-way delay relies on time-sensitive parameters and time synchronization of both sender and receiver is required. The BTH research group has done a number of measurement and modeling experiments on OWTT and the associated convolution products in a chain of IP routers, as reported in [7,8,9,20]. A novel measurement system to do delay measurements in IP routers has been developed, which follows specifications of the IETF RFC 2679 [1]. The system uses both passive measurements and active probing. Dedicated application-layer software has been developed to generate UDP traffic with TCP-like characteristics. The generated traffic matches well traffic models observed for the World Wide Web, which is one of the most important contributors to the traffic in Internet [13]. The well-known interactions between TCP sources and network are avoided. UDP is not aware of network congestion, and this means that we could do experiments where the focus was on the network only and not on terminals. The combination of passive measurements and active probing, together with using the DAG monitoring system [10], gave us an unique opportunity to perform precise traffic measurements and also the flexibility needed to compensate for the lack of analytic solutions.

The real value of our work lies in the hop-by-hop instrumentation of the devices involved in the transfer of IP packets. The mixture of passive and active traffic measurements allows us to study changes in traffic patterns relative to specific reference points and to observe different contributing factors to the observed changes. This approach offers us the choice of better understanding of diverse components that may impact on the performance of OWTT as well as to accurately measure queueing delays in operational routers.

In the case of delay measurements through a single router, the one-way delay is given by the time difference between the timestamp reading corresponding to the first bit of packet n approaching DAG interface j (output of the router) and the timestamp reading corresponding to the first bit of the same packet n approaching DAG interface i (input of the same router). In other words, OWTT for a router is defined as the time difference between the moment when the first bit of packet leaves the router and the moment when the first bit of the same packet arrives to router (Figure 2). A similar procedure is used in the case of OWTT measurements through several routers.

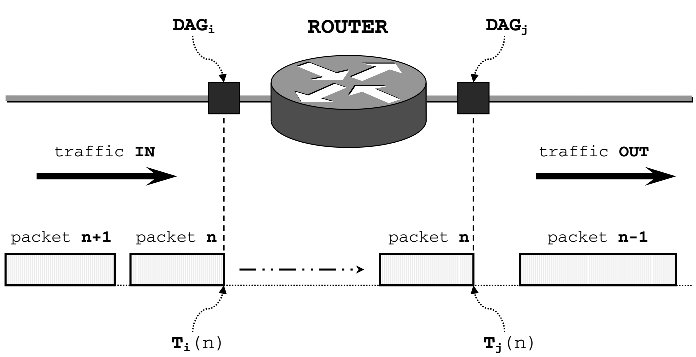


Fig. 2. Timestamping a packet

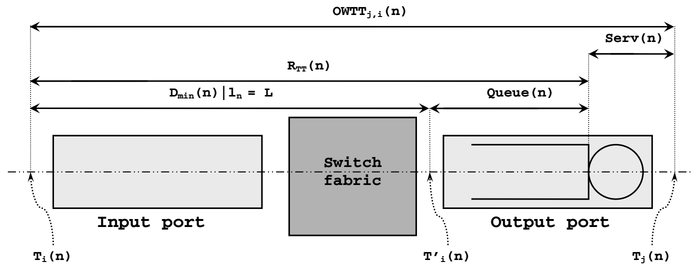


Fig. 3. Router delay model

The consequence therefore is that this measurement methodology allows us to estimate different delay components of OWTT (Figure 3):

$$D_{router} = D_{read} + D_{proc} + D_q \tag{4}$$

where D_{read} represents the time it takes for router to copy the packet into the input port (including the time to parallelize the packet coming from the communication link), D_{proc} represents the processing delay at a router and D_q represents the queueing delay at a router. Note that the router transmission time D_{tr} contains D_{read} as well as the time to serialize the packet from the output port onto the communication link.

Three classes of experiments have been carried out, which correspond to possible situations existent in IP networks. The experiments cover the delay process for three different scenarios, i.e., delay for a router with a single data flow (no interfering traffic), delay for a router with several traffic flows (crossing traffic) and delay for a chain of three routers (with both crossing and merging traffic).

A number of traces have been generated for every experiment, with specific values for the Hurst parameter H and link utilization L_u.

The reported results are in form of several statistics regarding processing and queueing delays of a router, router delay for a single data flow, router delay for multiple data flows as well as end-to-end delay for a chain of routers [7, 8, 9, 20]. Figure 4 shows an example of results obtained in our experiments for a chain of three routers. The results are in the form of OWTT and the associated histogram measured at the output of the third router. A indicates the source host generating traffic and B, C and D indicate the hosts generating cross traffic. The parameter α is the shape parameter of the generated Pareto traffic model and the parameter ρ is the link utilization. In the upper left corner is the plot for the traffic that enters the chain of IP routers. The associated histogram is plotted at the right of the figure. Below is plotted the traffic at the output of the chain, together with the associated histogram.

Our results confirm results reported earlier that the delay in IP routers is generally influenced by traffic characteristics, link conditions and, to some extent, details in hardware implementation and different Internetwork Operating System (IOS) releases. The delay in IP routers may also occasionally show extreme values, which are due to improper functioning of routers.

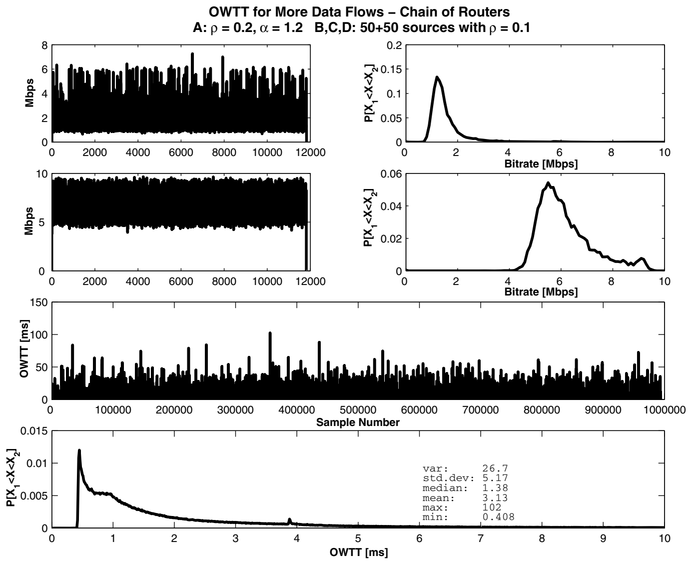


Fig. 4. Example of results on OWTT and the associated histograms

Furthermore, new results have been obtained that indicate that the delay in IP routers shows heavy-tailed characteristics, which can be well modeled with the help of several distributions, either in the form of a single distribution or as a mixture of distributions. There are several components contributing to OWTT in routers, i.e., processing delay, queueing delay and service time. The obtained results have shown that, e.g., the processing delay in a router can be well modeled with the Normal distribution, and the queueing delay is well modeled with a mixture of Normal distribution for the body probability mass and Weibull distribution for the tail probability mass [7, 8, 9, 20]. Furthermore, OWTT has several component delays and it has been observed that the component delay distribution that is most dominant and heavy-tailed has a decisive influence on OWTT. Dual Generalized Pareto distributions are typical examples of distributions that can be used to model OWTT. These distributions correspond to the body probability mass and the tail probability mass, respectively.

A detailed description of the measurement setup, the set of measurements done, the associated modeling methodology as well as the set of results obtained in our experiments are presented in [7, 8, 9, 20].

5 Some Observations

Some of the most important results regarding validation of Kleinrock's independence assumption can be summarized as follows.

5.1 Kleinrock's Independence Assumption

As mentioned above, Kleinrock suggested to adopt an M/M/1 queueing model for each queue in a tandem queueing system regardless of the interaction of these queues and the statistical properties of the traffic streams. Under this assumption, tractable analysis is possible.

The OWTT delay in a chain of IP routers can be partitioned into two components, a deterministic delay D_d and a stochastic delay D_s. D_d is composed of the propagation delay (D_{prop}), transmission delay (D_{tr}) and (partly) processing delay in routers (D_{proc}). On the other hand, D_s is primarily influenced by the router queueing delay D_q. The e2e delay created by the queueing delays in a chain of N routers is thus

$$D_Q = \sum_{i=1}^{N} D_{q,i} \tag{5}$$

where $D_{q,i}$ is the queueing delay in router i.

The Complementary Cumulative Distribution Function (CCDF) of $D_{q,i}$ is

$$P(D_{q,i} > x) = e^{-\varphi_i x}, \qquad \varphi_i = \mu_i(1 - \rho_i) \tag{6}$$

where μ_i is the average service rate on link i and ρ_i is the utilization factor on link i. The CCDF of D_Q is thus [21]

$$P(D_Q > x) = \sum_{i=1}^{N} \theta_i e^{-\varphi_i x} \tag{7}$$

where

$$\theta_i = \prod_{j=1, j\neq i}^{N} \frac{\varphi_i}{\varphi_j - \varphi_i}, \qquad \sum_{i=1}^{N} \theta_i = 1 \tag{8}$$

Equation 7 shows that D_Q has a CCDF that should decay Exponentially. Figure 5 shows however that this is not the case. This figure shows an example of the CCDF of OWTT measured in our experiments and the corresponding Exponential distribution, i.e., an Exponential distribution with the same mean as the one for the measured OWTT. It is observed a clear difference in the sense that OWTT decays more slowly than the Exponential distribution. The conclusion is that Kleinrock's independence assumption is not valid in these experiments.

5.2 End-to-End Delay in a Chain of Routers

The distribution of a sum of independent random variables whose individual distributions are known, is obtained by *convolution*. This operation is equivalent to multiplying individual functions in the frequency domain. Our experiments show however that this is not the case in a chain of IP routers, due to the dependence that may exist among queueing delays in different routers.

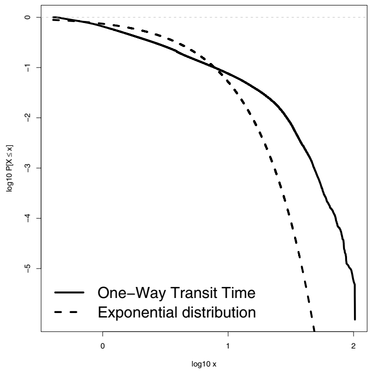


Fig. 5. OWTT and Exponential distribution

Assume a number of N M/G/1 queues with load ρ_i $(i = 1, \ldots, N)$ where all queues have i.i.d service times given by a common Probability Density Function (PDF) $f(t)$ and, therefore, identical Laplace-Stieltjes Transform (LST) denoted by $\mathcal{F}_i(s)$. If w_i denotes the waiting time in queue i, $w_i(x, \rho_i)$ the PDF and $W_i(x, \rho_i)$ the Cumulative Distribution Function (CDF) of w_i, then the Pollaczek-Khinchin formula can be used to calculate the LST of the delay in an M/G/1 system [15]

$$\mathcal{W}(s, \rho_i) = \frac{1 - \rho_i}{1 - \rho_i \mathcal{R}_i(s)} \tag{9}$$

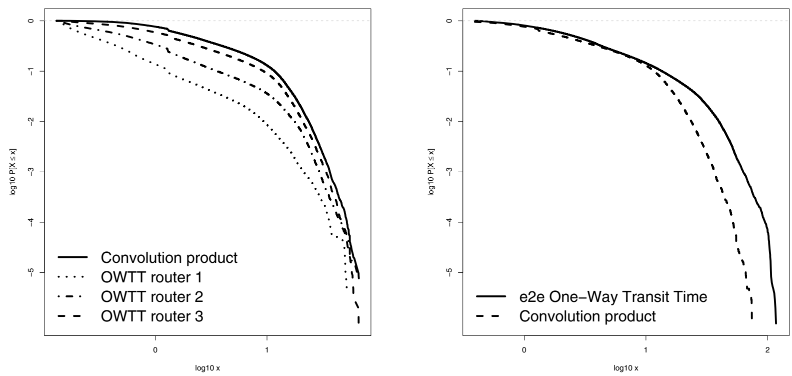
where $\mathcal{R}_i(s)$ is the LST of the remaining service time

$$\mathcal{R}_i(s) = \frac{1 - \mathcal{F}_i(s)}{s f_i} \tag{10}$$

and f_i is the mean service time, i.e., $f_i = E\left[\mathcal{F}_i(s)\right]$. Accordingly, the PDF of the sum of waiting times in N queues, i.e., $w = w_1 + w_2 + \ldots + w_N$, yields the convolution of the waiting times in each queue, provided that they are independent. Then, the LST of the convolution is [22]

$$\mathcal{W}(s, \rho_1, \ldots, \rho_N) = \prod_{i=1}^{N} \frac{1 - \rho_i}{1 - \rho_i \mathcal{R}_i(s)} \tag{11}$$

This result implies that the e2e delay in a tandem queueing system can be completely described by the convolution product of the individual delay components at each queue. Our experiments show however that this is not the case. For instance, Figure 6 shows an example of CCDF of e2e OWTT measured in our experiments. Figure 6(a) illustrates the CCDF of individual router delays measured for three chained IP routers as well as the convolution product of these delays. Figure 6(b) shows the CCDF of the measured e2e OWTT of the three chained routers and the convolution product of the individual router delays.



(a) CCDF of individual OWTT and convolution product

(b) CCDF of e2e OWTT and convolution product

Fig. 6. OWTT and convolution product

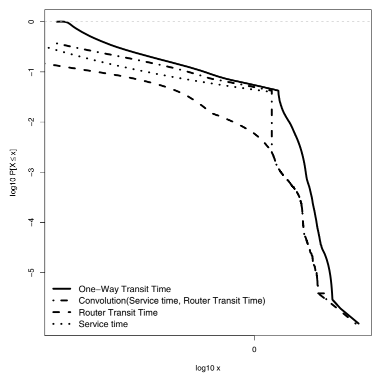


Fig. 7. Router delay and components

It is observed that there is a clear difference between the measured e2e OWTT and the convolution product of the individual router delays and that this difference is most significant in the tail of the distribution. The conclusion therefore is that e2e delay in a chain of routers is not given only by the convolution product of individual router delays. This is because of, e.g., correlations that may exist among queueing delays in different routers.

5.3 Router Delay

Similar to the observations done on e2e delay, we have also observed that the delay in a single IP router is not given only by the convolution product of queueing time and service time. This is due to crosscorrelations that may exist between interarrival times and packet service times within the same router [8].

This observation is sustained, e.g., by the results obtained in our experiments (Figure 7). This figure shows an example of router delays and components.

We observe a clear difference between the measured OWTT (solid line) and the convolution product of the router transit time ($\mathrm{R_{TT}}$) and the service time (dotdashed line). This difference is most significant in the tail of the OWTT.

In other words, the formula

$$F(x) = p \cdot F_1(x) + (1 - p) \cdot F_2(x) \tag{12}$$

is not sufficient in this case. Here $F(x)$ represents the CDF of OWTT, $F_1(x)$ the CDF of $\mathrm{R_{TT}}$, $F_2(x)$ the CDF of service time and p is the probability mass for the body of the OWTT distribution. Consequently, $(1 - p)$ corresponds to the tail probability mass in the OWTT distribution. There are more parameters contributing to the OWTT like, e.g., crosscorrelations that may exist between interarrival times and packet service times.

6 Conclusions

The paper has reported on results obtained in experiments done at the Blekinge Institute of Technology in Karlskrona, Sweden, on measurements, modeling and analysis of delay in a chain of IP routers. Particular focus has been given to validating Kleinrock's independence assumption regarding the effect of correlations in a tandem queueing system. Our results show that this assumption is not valid in our experiments, and this has been particularly observed in the end-to-end delay distribution.

Planned future work is to further analyze and to model the correlations observed in our measurements as well as to understand their effect on the delay performance in a chain of IP routers.

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