Analyzing Cross Traffic Effects on Packet Trains Using a Generic Multihop Model

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Abstract— **To develop accurate measurement methods based on active probing, an understanding (at the packet level) of how probe flows and cross traffic flows interact with each other is required. Several existing measurement methods rely on packet-train probing. In this paper, we use a multi-hop model to describe how cross traffic packets affect a packet train.**

When one packet within a packet train is delayed, the dispersion (i.e. packet separation) of at least two (and possibly more) probe packets will change. Furthermore, the dispersions are not independent, which may bias dispersion average calculations. Many methods use dispersion averages in the calculation of bandwidth estimates and predictions.

We have identified and analyzed three major cross traffic effects on packet trains - chain, quantification, and mirror patterns. Experiments have been performed in a testbed to explore these patterns.

In histograms of delay variations for adjacent probe packets, these patterns are manifested as different identifiable signatures.

Keywords— **Active measurement, performance, delay variation, probe trains, cross traffic, histogram, patterns.**

I. Introduction

Measurement of the end-to-end available bandwidth of a network path is getting increasingly important in the Internet. Verification of service level agreements, streaming of audio/video flows, and Quality-of-Service management are all examples of Internet activities that need or can benefit from measurements of bandwidth availability.

Many methods that attempt to measure end-to-end bandwidth actively probe the network path by injecting probe packets in predetermined flight patterns. Common flight patterns include pairs of probe packets, so called *packet-pair probing* [1], [2], [3], [4], [5], [6] and its extension into longer sequences of probe packets [1], [7], [8], [9], which we will refer to as *packet-train probing*.

In both packet-pair methods and packet-train methods, the dispersion (in time) of the probe packets after they have traversed the network path is used to calculate the bandwidth estimate. The dispersion is caused by the link with the least capacity but is also affected by competing cross traffic flows on the path. The former dispersion effect is typically utilized to estimate the bottleneck bandwidth (the bandwidth of the link with the least bandwidth) whereas the impact of cross traffic is exploited to estimate the available bandwidth.

In this paper, we use a multi-hop model developed by [10] to describe how cross traffic packets affect a packet train and thereby have an impact on the dispersion values. We have identified three major cross-traffic effects on packet trains - chain, quantification, and mirror patterns, respectively. Each of these patterns are analyzed in the paper, both theoretically and experimentally using histograms constructed from network testbed measurements.

An apparent advantage of train probing is that each packet inside a train can be used to construct two dispersion values. One is with the packet ahead of it and one is with the packet behind it. This way, only $N+1$ packets are required to construct N measurement pairs, as compared to $2N$ packets in the traditional packet-pair case. This reduces the amount of probe traffic that will burden the network during the measurement.

Because most packets in packet-train probings are used for two dispersion values rather than one, there will be correlations between dispersion values. One cross traffic packet will affect at least two dispersion values in the train probing case.

The rest of this paper is organized as follows: Section II describes the multi-hop model that we use for the analysis of packet trains. It is followed by Section III that describes the three identified cross traffic effects on packet trains. In that section, biases in packet-train analysis are also discussed. Section IV presents the network testbed where our experiments have been performed. Section V show how the cross traffic effects on packet trains generate identifiable signatures in δ_i-histograms. The paper ends with an analysis of two additional experiments, followed by conclusions and acknowledgments.

II. Using a generic multiple-hop model for route delay variation

To analyze the behavior of packet trains, some mathematical definitions and derivations has to be made. In this paper, the analysis rely on a generic multiple-hop model, presented in [10]. That model focuses on expressing the delay variations of adjacent probe packets. In this section the concepts of that model are explained.

A. One-hop definitions

In what follows, the meaning of a hop is one router (r) including its queue (q) and the outgoing link from that router, see Figure 1. This means that the arrival time of an arbitrary packet to hop h_y is equal to the departure time of the same packet from the previous hop h_x. Each router can have multiple outgoing and incoming links.

When a packet (i) arrives to the queue of hop h at time τ_i, it begins its service time $x_i > 0$ after a waiting time of $w_i \geq 0$. The packet leaves the hop after a constant propagation delay D at time τ_i^*. Thus, for the packet the one-hop delay is

$$d_i \equiv \tau_i^* - \tau_i = w_i + x_i + D. \qquad (1)$$

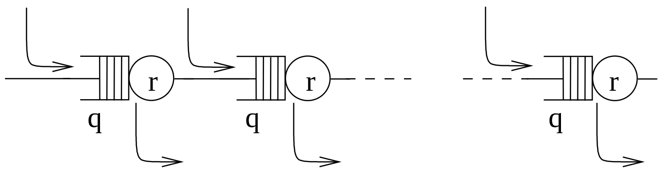

Fig. 1. Multiple hop router model. One hop is limited to one router, its queue, plus the following outgoing link.

In what follows, the index (i) corresponds to the indexing of probe packets.

Using the definition of the one-hop delay for one probe packet (Equation 1), we can compare the one way delay of two adjacent probe packets with each other. Three equations are derived (in [10])

$$\begin{aligned}
\text{inter-arrival time: } t_i &\equiv \tau_i - \tau_{i-1} \\
\text{inter-departure time: } t_i^* &\equiv \tau_i^* - \tau_{i-1}^* \\
\text{delay variation: } \delta_i &\equiv d_i - d_{i-1} \\
&= t_i^* - t_i \\
&= (x_i - x_{i-1}) + \\
&\quad\; (w_i - w_{i-1}).
\end{aligned}$$

When probing a network, sequences of t_i^* are measured at the receiver side. However, since t_i is part of the packet-train design, and therefore known, the transformation between δ_i and t_i^* is easily done.

The waiting time of two successive packets in an infinite FIFO buffer is described by Lindley's equation

$$w_i = [w_{i-1} + x_i - t_i]^+ + c_i \tag{2}$$

where $[x]^+ = max(0, x)$. The term c_i is the waiting time caused by cross traffic entering the current hop between τ_{i-1} and τ_i.

A queue in a router can in principle be in two states - busy and idle. When a router is in the busy state, it is constantly forwarding packets from its in-queue, while in the idle state the queue is empty. Probe packets can consequently be divided into two categories, **I**nitial and **B**usy packets (adapting the notation in [10]).

An initial probe packet is by definition the first probe packet of a busy period. That is, an I packet is never queued behind another probe packet, which is equivalent to state that $[x]^+$ of Equation (2) should be equal to 0. The B packets on the other hand are those probe packets that are queued behind other probe packets (i.e. $[x]^+ > 0$).

With this categorization of probe packets, the delay variation δ_i can be expressed in two ways, depending on whether a probe packet is I or B [10]

$$\textbf{I:} \quad \delta_i = (x_i - x_{i-1}) + (w_i - w_{i-1}) \tag{3}$$

$$\textbf{B:} \quad \delta_i = (x_i - t_i) + c_i \tag{4}$$

where Equation 4 is derived from Equations 2 and 3.

B. Multiple-hop extension

The one-hop model is extended in [10] to handle multiple hops. This extension relies on the following fact: If a probe packet is I or B at hop (j) and B at the next hop $(j + 1)$, δ_i is overwritten and replaced by equation (4). However, the history of earlier hops is not completely overwritten, some history remains in the c_i term. If, on the other hand, the probe packet is I at hop $(j + 1)$ then the term of (3) is added to the existing δ_i.

This means that if a probe packet traverses the whole H-hop network path without ever becoming a B packet, its delay variation can be expressed as

$$\delta_i = \sum_{h=1}^{H}(x_i^h - x_{i-1}^h) + \sum_{h=1}^{H}(w_i^h - w_{i-1}^h). \tag{5}$$

If the probe packet is B on at least one hop, it will be B for the last time at some hop in the path, which can be any hop in the network path. That hop is denoted s_i. This means that the delay variation for such a probe packet will obey

$$\begin{aligned}
\delta_i = {} & (x_i^{s_i} - t_i + c_i^{s_i}) + \sum_{h=1}^{H}(x_i^h - x_{i-1}^h) + \\
& + \sum_{h=1}^{H}(w_i^h - w_{i-1}^h).
\end{aligned} \tag{6}$$

These multi-hop equations for δ_i can be extended to handle different packet sizes [10]. However, our approach is to use one fixed packet size when sending packet trains (see our assumptions in Section III-A). Hence, we limit this multi-hop description to handle only one packet size within each packet train.

III. CROSS TRAFFIC EFFECTS ON PACKET TRAINS

Methods that probes a network path are typically divided into two categories. Either a sequence of well separated packet pairs or a number of packet trains are injected into the network. In packet pair methods, the two packets in a pair affect each others delay variation, assuming that the pairs are well separated. Cross traffic packets can increase or decrease the dispersion of the two packets. However, that effect does not influence the delay variation of other packet pairs. In a packet train these issues get more complex. Cross traffic packets have the possibility to induce affects that are propagated across several adjacent probe packets.

It is easily understood that the displacement of one probe packet, which is not the last packet of the packet train, will change the delay variation of at least itself and the following probe packet, hence there will be dependencies between adjacent probe packets in the packet train. This issue is discussed in Section III-E.

In this paper three patterns have been identified and examined - chain, quantification and mirror patterns. These patterns are described in subsections III-B, III-C and III-D.

A. Assumptions

In the rest of this paper we assume FIFO router queues, where there is no isolation of flows as in for instance fair queuing. It is also assumed that the router operate on the packets in a store-and-forward fashion.

The dispersion of adjacent packets in a packet train is equal, when leaving the probing generator. This dispersion is varied to achieve different probe rates. The packet size is fixed.

B. Chain patterns

B.1 Basic definition

When a packet train traverses the network path, cross traffic may affect it. If the cross traffic delays one probe packet, (i), in such a way that at least $(i+1)$ and $(i+2)$ are transformed from I to B, and makes the involved packets (i), $(i+1)$ and $(i+2)$ back-to-back after the hop, a chain patterns has arisen.

This is the definition of a *pure chain pattern*. If other probe packets within the scope of the chain pattern are delayed by cross traffic, a quantification pattern will arise. Quantification patterns are described in Section III-C.

Low link capacity can also force probe packets to travel back-to-back as B packets. This is often referred to as the bottleneck spacing effect (described in [11]). However, this effect is not a chain pattern in its pure form, since our definition of a chain pattern is based on the delay of probe packets caused by cross traffic.

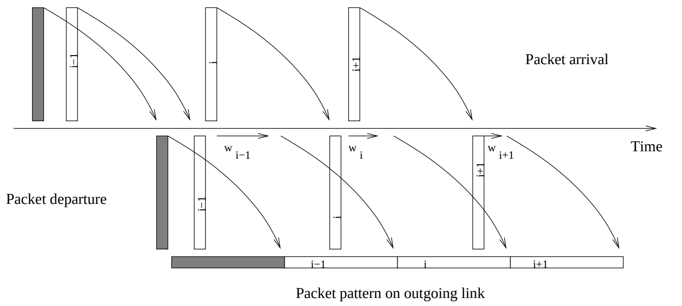

Fig. 2. Arrival and departure times for cross traffic (shaded box) and probe packets (white boxes) entering a router. Before the router the probe packets are equally separated, while after the hop they are back-to-back with each other. Cross traffic and probe traffic enter the router from different links, but depart on the same link.

An example of a chain pattern is shown in Figure 2. The vertical packets above the time line show when in time the first bit of a probe packet (white boxes) or a cross traffic packet (shaded box) arrives to the router. The arc defines when the reception of a packet is complete, i.e. the arrival time of the last bit. In this example, the cross traffic and the probe packet streams arrive on different incoming links. Hence, the router can start receiving probe packet $(i-1)$ before it has completed the reception of the cross traffic packet. It is assumed that the probe traffic and cross traffic flows depart on the same link.

When the whole cross traffic packet is received, the router can start the transmission of that packet on the outgoing link (the vertical packets below the time line, which indicate when in time the first bit is sent). However, when packet $(i-1)$ is received, it must wait for the cross traffic packet to complete its departure. The waiting time of packet $(i-1)$ is w_{i-1} in Figure 2. The probe packet $(i-1)$ is transmitted back-to-back behind the cross traffic packet after the probe packets waiting time has elapsed, i.e. after the service time of the cross traffic packet. The probe packet $(i-1)$ is in this example by assumption I. That is, it does not have to queue behind any other probe packet.

During the waiting time of packet $(i-1)$, the next probe packet (i) enters the router. Packet (i) has to wait for $(i-1)$ to complete its departure, and is therefore B. That is, the packet (i) must wait w_i time units. After the waiting time, it is sent out back-to-back with $(i-1)$. The same procedure is repeated for packet $(i+1)$.

After the service time of probe packet $(i+1)$ is completed, the packet $(i-1)$, (i) and $(i+1)$ are back-to-back with each other on the link. Also, (i) and $(i+1)$ have transformed from I to B packets since both packets had to queue behind other probe packets (hence, their dispersion and delay variation are dependent of each other). That is, a chain pattern has arisen.

B.2 More details

When a probe packet is part of a chain pattern, its waiting time within the router can be expressed using equation (2). By definition, c_i would be 0, since the probe packets travel back-to-back after the hop.

Having an expression for the waiting time for probe packets within a chain pattern, it is possible to determine whether a probe packet belongs to an ongoing chain pattern, or if it is the first initial probe packet after the chain pattern. If $w_i > 0$ for a probe packet within a chain pattern ($c_i = 0$), it is B with respect to the probe packet ahead, hence it is part of the chain pattern. If the negation holds, the packet is an initial probe packet.

If $c_i > 0$ we will have a quantification pattern, described in Section III-C.

When understanding the properties of a chain pattern, it is also important to define *when* they occur. If packet $(i-1)$ in Figure 2 would create a chain pattern, i.e. both (i) and $(i+1)$ are B and back-to-back after the hop, then $w_{i-1} > (t_i - p/\mu) + (t_{i+1} - p/\mu)$, where p is the packet size and $(t_i - p/\mu)$ is the separation between the first bit of packet (i) and the last bit of packet $(i-1)$ on a link with rate μ.

In general, if a chain pattern should arise with K back-to-back B probe packets, the waiting time w_i of the initial probe packet in the chain pattern has a lower limit of

$$w_i > \sum_{k=1}^{K}(t_k - p/\mu). \tag{7}$$

This means that in a probing scheme where the probe rate is increased gradually, i.e. t_i is decreased, we will see more and more chain patterns. This is investigated in more detail in Section V, by analyzing examples of δ_i histograms. It should be noted that w_i is just a theoretical value since there is an upper limit to the waiting time in a router. The waiting time depends on the traffic, the routing scheduling/forwarding, the number of in- and outgoing links and the buffer size.

C. Quantification patterns

When a cross traffic packet enters the queue between the arrival time of two back-to-back probe packets, the packets will get separated by exactly the service time of that cross traffic packet. Hence there is no idle time gap between the probe packets. This separation is hereafter referred to as a *quantification pattern*. The term quantification pattern is used since the traffic is seen as a discrete transmission, rather than an analytic flow of packets.

When a packet train suffers from a chain pattern, i.e. one packet has been affected by cross traffic and hence will cause several adjacent probe packets to travel back-to-back as B probe packets, it is possible that cross traffic packets from other incoming links will interfere with the probe packets, i.e. creating quantification patterns. The probability of cross traffic interference increases with:

- Cross traffic rate - high cross traffic rate means that the router at a hop cannot serve all incoming back-to-back probe packets without handling cross traffic.
- Low link bandwidth of the link where the probe packets arrive to the hop, compared to other incoming links - lower link bandwidth implies that the service time x of the probe packets will be higher. That is, the possibility that a cross traffic packet arrives during the service time of a probe packet increases.
- Smaller cross traffic packets - if the cross traffic packets get smaller, but the rate is constant, the more often the router must forward cross traffic instead of probe packets.

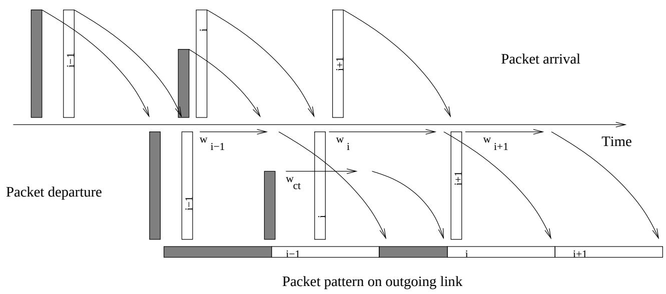

Fig. 3. Arrival and departure times of cross traffic (shaded boxes) and probe packets (white boxes) entering a router. The upper left cross traffic packet causes a chain pattern to arise. The smaller cross traffic packet causes a quantification pattern to arise. Cross traffic and probe traffic enter the router from different links, but depart on the same link.

The quantification pattern has an “upper limit of”

$$q_i = c_i \leq \sum_{j=1}^{J} (\tau_i - \tau_{i-1}) * \mu_j \tag{8}$$

where J is the number of incoming links to a hop and μ is the link rate. This limit is the sum of the maximum number of bits that can interfere with the packet train on each link j, during the time $(\tau_i - \tau_{i-1})$.

An example of a quantification pattern is shown in figure 3. The vertical packets above the time line show when in time a probe packet (white boxes) or a cross traffic packet (shaded box) arrives with its first bit to the router. The arc shows when in time a packet has been received. When all bits are received the packet can be sent out on the outgoing link, which is shown beneath the time line. The horizontal packets show the outgoing packet pattern. In this example we see that the leftmost cross traffic packet creates a chain reaction (also described in Figure 2). The second cross traffic packet entering the hop between probe packet $(i-1)$ and (i) will be sent out back-to-back after $(i-1)$, while (i) is sent out back-to-back with the second cross traffic packet. That is, packet $(i-1)$ has to wait w_{i-1} time units (which has its origin from the large cross traffic packet), while packet (i) has to wait w_i time units (which corresponds to both the big and the small cross traffic packets). A quantification pattern has arisen.

D. Mirror patterns

The mirror pattern arises if a packet train consists of at least three I probe packets $(i-1)$, (i) and $(i+1)$. Assume that packet $(i-1)$ and $(i+1)$ are unaffected by cross traffic (i.e. $w_{i-1} = w_{i+1} = 0$). Then, if packet (i) experiences a waiting time of $w_i > 0$, δ_i will get a positive value. Now, packet $(i+1)$ will have a delay variation described by $\delta_{i+1} = (x_{i+1} - x_i) + (w_{i+1} - w_i) = (w_{i+1} - w_i)$, since the two probe packets have the same size, i.e. the same service time. Of course, in the expression for δ_i the service times can also be eliminated. Since neither packet $(i-1)$ nor packet $(i+1)$ are delayed by cross traffic, the following holds

$$\begin{aligned} \delta_{i+1} &= w_{i+1} - w_i \\ &= -w_i \\ \delta_i &= w_i - w_{i-1} \\ &= w_i \\ &\Longrightarrow \\ \delta_{i+1} &= -\delta_i. \end{aligned} \tag{9}$$

Equation (9) is defined as *perfect mirroring*. An example of perfect mirroring is shown in Figure 4. As in previous figures (2, 3), the vertical packets above the time line show when in time a probe packet (white boxes) or a cross traffic packet (shaded box) arrives at the router. The arc shows when in time all bits of a packet have been received. When all bits are received, the router can to start send the packet, which is shown below the time line. The packet (i) is delayed w_i time units and hence creates a perfect mirror pattern, since the probe packets $(i-1)$ and $(i+1)$ are unaffected.

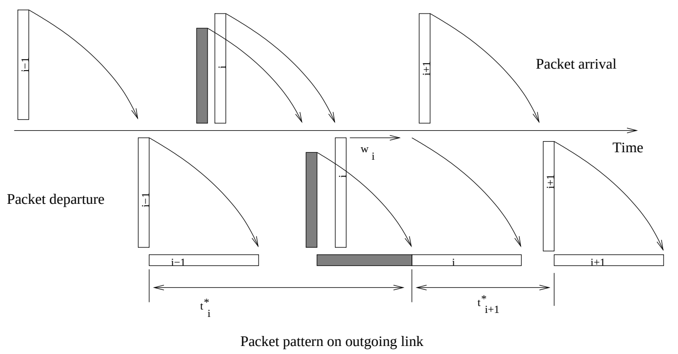

Fig. 4. Arrival and departure times for cross traffic (shaded box) and probe packets (white boxes) entering a router. The shaded cross traffic packet delays (i) in such a way that the inter-departure times of (i) and $(i+1)$ changes. All probe packets are still separated I packets after the hop, i.e. a mirror pattern has arisen. Cross traffic and probe traffic enter the router from different links, but depart on the same link.

In addition to the fact that probe packet (i) can be delayed, there is a possibility that one, or both of the packets $(i-1)$ and $(i+1)$ are affected by cross traffic. This will of course blur the perfect mirror pattern, i.e. equation (9) does not hold. It is obvious that this possibility grows with increasing cross traffic and/or probe rate.

If, for example, both probe packets (i) and $(i+1)$ are delayed by cross traffic the mirror pattern is *displaced* to the next packet pair in the train. That is,

$$\begin{aligned}\delta_i &= w_i \\ \delta_{i+1} &= w_{i+1} - w_i\end{aligned}$$

since in this case $w_{i+1} > 0$. Now, the next probe packet in the train, $(i + 2)$, will have a delay variation of

$$\begin{aligned}\delta_{i+2} &= w_{i+2} - w_{i+1} \\ &= -w_{i+1}\end{aligned}$$

if probe packet $(i+2)$ traverses the path unaffected ($w_{i+2} = 0$). Hence, the positive delay variation of packet (i) gets its negative companion at packet $(i + 2)$. This can be repeated for an arbitrary number of mirror patterns displacements.

If probe packet (i) suffers from a mirror pattern, and the following $(n - 1)$ packets are affected by cross traffic, then we have a chain of displaced mirror patterns. Their delay variations relate to each other in the following way:

$$\begin{aligned}\delta_{i+n} + \ldots + \delta_{i+1} &= (w_{i+n} - w_{i+(n-1)}) + \ldots + \\ &\quad (w_{i+2} - w_{i+1}) + (w_{i+1} - w_i) \\ &= -w_i \\ &= -\delta_i, \qquad (10)\end{aligned}$$

since packet n is unaffected by cross traffic ($w_{i+n} = 0$).

D.1 Quantification and mirror pattern similarities

If we assume that a packet train traverses a network path without any back-to-back probe packets, the packet train can suffer from mirror patterns described above. However, the cross traffic can in some cases fill the entire space between two probe packets. That is, the two packets form a pattern similar to a quantification pattern. When two probe packets only have cross traffic between them, they might end up as B packets. It is, however, hard to determine whether the two probe packets are part of a complex mirror pattern or a quantification pattern.

E. Dispersion average bias

When using dispersion average techniques of adjacent packet pairs in packet trains to calculate link bandwidth or available bandwidth of a network path [5], the three patterns described above must be taken under consideration. That is, because of the dependences of the dispersion, and delay variation, of adjacent packet pairs in a packet train, as described in III. If blindly using the dispersion average of the pairs in a packet train when performing calculations, some cross traffic effects might be lost, whilst others might be interpreted with too much weight.

Assume for example that a packet train is affected by a mirror pattern, such as the one described in Figure 4. The two dispersion values of the three probe packets will be t_i^* and t_{i+1}^*. That is, the average dispersion value of the two packet pairs is $(t_i^* + t_{i+1}^*)/2 = ((t_i + \delta_i) + (t_{i+1} - \delta_i))/2 = t_i$, assuming the same arrival distance of adjacent probe packets to a hop. Information that the train has suffered from a cross traffic packet interference is lost, when using the dispersion average as a measure. A packet train can be affected by several perfect mirror patterns without changing the dispersion average of the packet pairs in the packet train. Hence, some measures must be taken to reveal these patterns when using packet-train techniques, for example using the variance measure.

It is important to understand that these two values, t_i^* and t_{i+1}^*, correspond to the same interfering cross traffic packet, i.e. they are dependent of each other. Hence, using them both in the same calculation should not be done without special care, e.g. in the mirror example above one cross traffic effect is counted twice. When a packet train has suffered from several displaced mirror patterns there will be a long dependence chain, described by Equation 10.

Another example where the dispersion average in trains might be used in a misleading way is when one or several chain patterns arise (see Figure 2 for example). Very little cross traffic (far less than the packet train rate) can cause several and/or long chain patterns within a train, hence the dispersion median value for the packet pairs in the packet train will be very low, despite the low cross traffic rate.

These issues are subject of further study, and hence not in the scope of this paper.

IV. TESTBED SETUP

The testbed network (see Figure 5) used in the experiments consists of three router nodes, one Black Diamond (BD) and two Torrent routers (T1 and T2). There are also a probing generator (PG), a probing receiver (PR), a traffic generator (TG) called IP Traf Gen (internal product of Ericsson[1]) and a traffic receiver (TR) which is an IXIA 1600 Traffic Generator/Analyzer. The links are all 100 Mbps except between the three routers, where the links are limited to 10 Mbps.

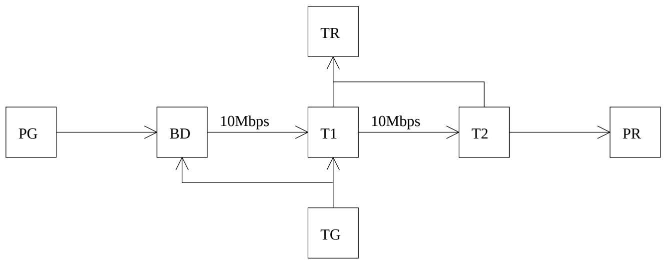

Fig. 5. Testbed setup

Depending on the experiment setup the cross traffic can enter and leave the router chain at different positions. The cross traffic flow can be one or several of the following: TG → T1 → T2 → TR (flow 1), TG → BD → T1 → TR (flow 2) and TG → BD → T1 → T2 → TR (flow 3). The cross traffic flow used in the tests in section V only uses flow 1. All cross traffic is of exponential distribution. Four different cross traffic sizes where used: 64, 148, 482 and 1518 bytes. In the experiments all of these could be used at the same time, or just a selection of them. When all sizes are used, 46% is of size 64, 11% of 148, 11% of 482 and 32% of size 1518 bytes. This distribution of packet sizes has its origin from findings in [12].

The cross traffic intensity is variable within the testbed, in steps of arbitrary size.

[1] www.ericsson.com

The probe traffic is sent through the path PG → BD → T1 → T2 → PR. The probe packet size is 1500 bytes and consists of 32 packets. Normally 5 trains are sent per test run.

The probing generator and receiver is written by the authors[2]. The testbed is built by [13].

V. Signatures

When cross traffic affects packet trains, the train will suffer from different patterns, as discussed in Section III. In this section we illustrate these patterns using real packet trains which are affected by cross traffic. The patterns will show different signatures, in delay variation histograms. A signature is a characteristic that can be detected by some means, at least manually, but preferably by automatic algorithms and tools.

Identifying signatures when trying to measure and predict bandwidth could be important, since they give information about how the cross traffic affects a packet train [10]. Exactly how to use the signatures to improve bandwidth prediction using trains is subject to further study, and hence not in the scope of this paper.

Four signatures are defined and discussed in this section. The two first of them are observed in [10], but in a packet pair probing scenarios. The signatures correspond to one or several of the patterns discussed in section III. Examples from testbed measurements are shown. The testbed is described in Section IV. In the testbed setup for these examples, only one cross traffic packet size is used, in each histogram. Furthermore only one flow of the cross traffic is used (corresponding to flow 1 in the testbed).

A. The independence signature

The independence signature is visible in scenarios where there is no or very little cross traffic interfering with the packet train. This means that there is a strong probability that all probe packets in the train are I.

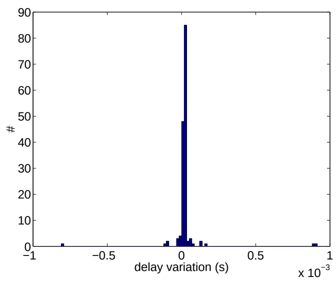

Fig. 6. The independence signature. There is a clearly visible peak near $\delta_i = 0$. Random noise is visible around the independence peak.

The signature arises from the last term of Equation (5). There will be a clearly visible peak near $\delta_i = 0$ since most packets traverse unaffected, i.e. $\sum_{h=1}^{H}(w_i^h - w_{i-1}^h) \approx 0$, see Figure 6. Here the cross traffic rate is 3 Mbps, exponentially distributed and consists of 64 bytes packets. The probe rate is 1 Mbps, using 1500 bytes packets, which are sent in 5 trains consisting of 32 packets in each.

[2]The probing generator and receiver is not yet accessible.

When probing at rates that nearly saturate the link, i.e. rates where chain and quantification patterns arise with a higher probability, very low cross traffic diminish the independence peak. These issues are discussed in the subsections below.

B. The rate signature caused by chain patterns

The rate signature is a peak that arises from the $x_i^{s_i}$ term in Equation (6). This peak is visible when a packet train has chain patterns in it, i.e. the probe packets traverse the network as back-to-back B packets. The rate signature corresponds to the link rate of hop s_i, i.e. the last hop where the probe packets were B. There are also other sources for the rate peak, such as the bottleneck spacing effect, but that effect is not visible in the example histogram described below.

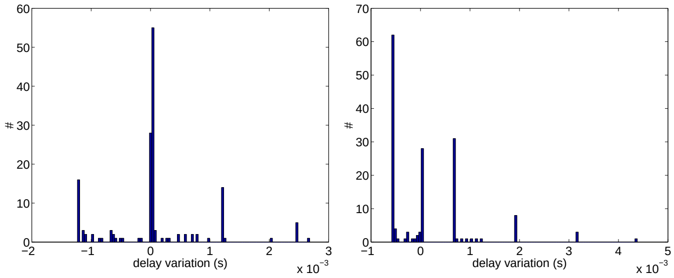

Fig. 7. Two δ-histograms showing the rate peak, the leftmost peak in both the left and the right histogram. The rate peak increases with higher probe rate.

The rate peak grows in size when the rate of the probe stream increases. This is visible in Figure 7. The left histogram shows the rate signature when the probe rate is 4.8 Mbps while the rate is increased to 6.7 Mbps in the right histogram, which is near the available bandwidth (7 Mbps in this experiment). The rate peak is the leftmost peak at negative values in both δ-histograms. The cross traffic rate is 3 Mbps, exponentially distributed and it consists of 1518 bytes packets. The packet train consists of 1500 bytes packets, using 5 trains with 32 packets each.

The other peaks in the histogram correspond to the quantification pattern, signatures originating from that pattern are described below.

If analyzing Equation (7) it is easy to understand that a higher probe rate increases the probability of having chain patterns in a packet train. The reason is that when the probe rate increases, the term $(t_k - p/\mu)$ of Equation (7) decreases. Hence, a fixed waiting time w_i of a probe packet generates a longer chain reaction when the probe rate increases.

The rate peak signature, caused by one or several chain patterns, will survive through the network route if the hop where the chain pattern arose was the last hop where the probe packets involved are B. Otherwise the effects may be overwritten by other B-hops.

C. The mirror signature

The mirror signature is a signature that arises from the last term of Equation (5), i.e. the mirror pattern. If there is very little cross traffic and the probe rate is relatively low, there will be many perfect or displaced mirror pattern. Figure 8 shows two mirror signatures. In the left histogram, the cross traffic packet size is 148 bytes, while in the right one it is 482 bytes. In both histograms the cross traffic rate is 3 Mbps and exponentially distributed. The probe rate is 3.7 Mbps, using 1500 bytes packets with 5 trains consisting of 32 packets in each.

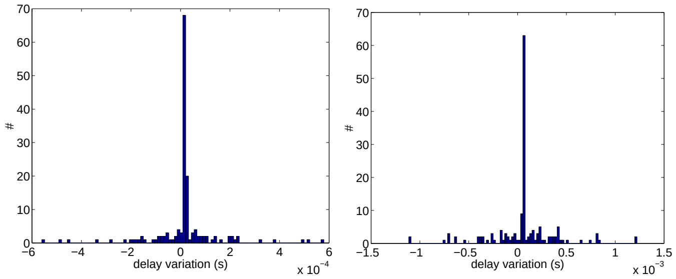

Fig. 8. The mirror signature. A clear independence peak at $\delta_i = 0$ in both histograms. The noise around the independence peaks corresponds to the mirror pattern, but also from other random noise.

Increasing the cross traffic rate forces the mirroring pattern to be displaced, as discussed in Section III-D.

Mirror patterns have a problem to survive from hop to hop in a route, since the delay variation is added according to Equation (5) when traversing hops where the packets are I.

D. Quantification signature

The quantification signature, or distribution peaks, arises from the quantification pattern described earlier. The quantification signature corresponds to the $x_i^{s_i}$ and $c_i^{s_i}$ terms in Equation (6). The locations of the distribution peaks depend on the size of the cross traffic packets and the number of packets of each size that are interfering. Two examples are shown in Figure 9. Both share the same probe stream properties, a probe rate of 8.6 Mbps, using 1500 bytes packets and 5 trains with 32 packets in each. In the left histogram the cross traffic rate is 7 Mbps consisting only of 482 bytes packets, while in the right histogram the cross traffic rate is 3 Mbps consisting only of 1518 bytes packets.

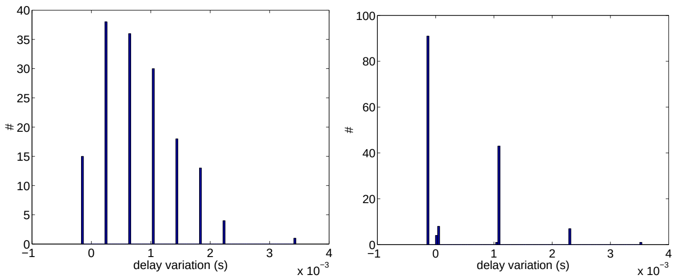

Fig. 9. Quantification patterns that originate from 482 bytes cross traffic packets in the left histogram and 1518 bytes cross traffic packets in the right histogram.

In the left histogram the leftmost peak is the rate peak. The second peak from the left hand side shows the number of probe packets that has a δ_i^* corresponding to the spacing of one 482 byte packet. The next peak corresponds to two such packets, and so forth.

In the right histogram the leftmost peak is again the rate peak. The peak near $\delta_i = 0$ corresponds to unaffected probe packets, while the next peak are probe packets that have a t_i^* corresponding to the space of one 1518 bytes packet.

The quantification signature, caused by the quantification pattern, survives through the network path if the hop where the quantification pattern arose was the last hop where the probe packets involved are B.

VI. Description and analysis of two testbed experiments

In this section two experiments are described and analyzed. We show that the three patterns - chain, mirror and quantification patterns - are visible as signatures in histograms in more complex testbed scenarios.

Both experiments have been made in the testbed described in section IV. The difference from the examples in Section (V) is that these experiments use four cross traffic packet sizes, instead of one. In the first experiment the packet train is affected by cross traffic at one hop, while in the second experiment it is affected at two hops.

A. Experiment 1

In this experiment, all 4 cross traffic packet sizes are used, they are distributed as described in Section IV. The cross traffic uses flow 1 in the testbed setup, i.e. the cross traffic only interferes with the packet train at one hop. The cross traffic rate is 5 Mbps.

The probe traffic consists of 1500 bytes packets in 5 trains with 32 packets each, for each histogram in Figure 10. The probe rate is, starting with the upper left histogram, 1 Mbps, 2.9 Mbps, 4.8 Mbps and 6.7 Mbps.

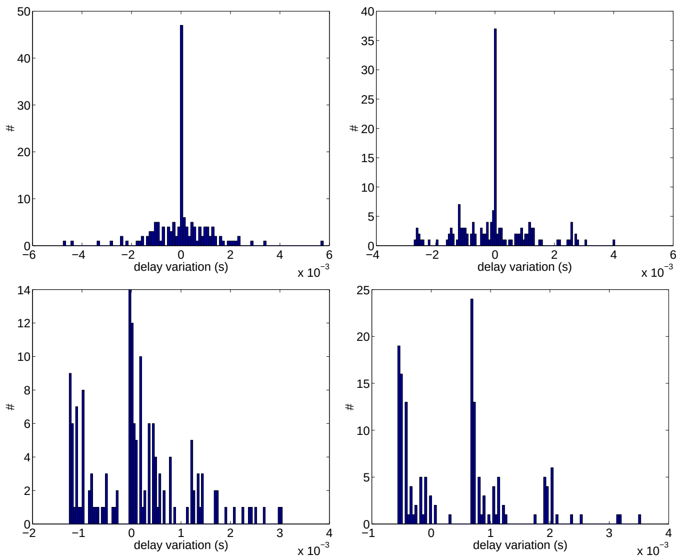

Fig. 10. Using 4 packet sizes and cross traffic flow 1, with a rate of 5 Mbps. The probe rate increases from approximately 1 Mbps (upper left) to 6.7 Mbps (lower right).

In the upper left histogram of Figure 10 there is a clear independence peak near $\delta_i = 0$. This peak originate from the fact that most probe packets traverse the testbed path nearly unaffected. However, some noise exists on both sides of the peak, which corresponds to the mirror pattern and other random noise. Since the probe rate is low compared to the available bandwidth and the link bandwidth, the occurrence of chain and quantification patterns are non-existent.

In the upper right histogram of Figure 10, the probe rate has increased to 2.9 Mbps. The independence peak is still clearly visible and unmistakable (at $\delta_i = 0$). The noise on both sides of the peak is more scattered than in the previous histogram, i.e. more mirror and displaced mirror patterns have occurred. This is because when the probe rate increases, the packet train packets have a higher probability to run into a cross traffic packet, as discussed in previous sections. No chain nor quantification patterns have occurred, since the leftmost peak in the upper right histogram corresponds to a probe send rate of 8.3 Mbps Hence no probe packet has traversed the network path back-to-back with another probe packet.

In the lower left histogram of Figure 10 the probe rate is 4.8 Mbps, which is near the available bandwidth of the probe path. The leftmost peak corresponds to the link rate, i.e. when probe packets travel back-to-back and forms a rate peak. This means that a chain patterns has arisen. When a chain pattern has arisen it is also valid to assume that there exist quantifications patterns within the packet train, as described in Section III-C. The histogram can be divided into three intervals ($[-1.25, 0]$, $[0, 1]$ and $[1, 3]$). In the first interval, $\delta_i \in [-1.25, 0]$, the leftmost peak corresponds to when probe packets travel back-to-back. The rest of the peaks in the interval are derived from different quantification patterns from cross traffic packets of sizes 64, 148, 482 bytes. Observe that no cross traffic packet of size 1518 has interfered with the chain reaction, in this interval. The next interval is $\delta_i \in [0, 1]$. Here the origin of the δ_i partly come from unaffected probe packets (if there exists such probe packets), but also from different quantification patterns where one cross traffic packet of size 1518 has interfered plus various combinations of the other packet sizes. The third interval, $\delta_i \in [1, 3]$, corresponds to when two 1518 bytes cross traffic packets have interfered plus, again, different combinations of the other cross traffic sizes.

In the lower right histogram of Figure 10, the probe rate is 6.7 Mbps, clearly above the available bandwidth. Here we see three well separated regions with peaks. These regions of peaks corresponds to the intervals of the lower left histogram, but when the probe rate is this high the separation of the intervals is more distinct. That is, no probe packet traverse the network path with a delay variation of, for example, $\delta_i \in [0.3, 0.6]$ nor $\delta_i \in [1.2, 1.7]$.

B. *Experiment 2*

In this experiment, 4 cross traffic packet sizes are used. They are distributed as described in Section IV. The cross traffic uses flow 1 and flow 2 in the testbed setup, i.e. the cross traffic interferes with the packet train at two hops. The cross traffic rate on flow 1 is 5 Mbps and 3 Mbps on flow 2.

For each histogram in Figure 11 the probe traffic consists of 1500 bytes packets in 5 trains with 32 packets each. The probe rate is, starting with the upper left histogram, 1 Mbps, 2.9 Mbps, 4.8 Mbps and 6.7 Mbps.

What is visible in the four histograms are essentially the same that was notable in the histograms of experiment 1 in section VI-A. However, when the packet train traverses two hops where cross traffic may affect the packet train, the histogram signatures

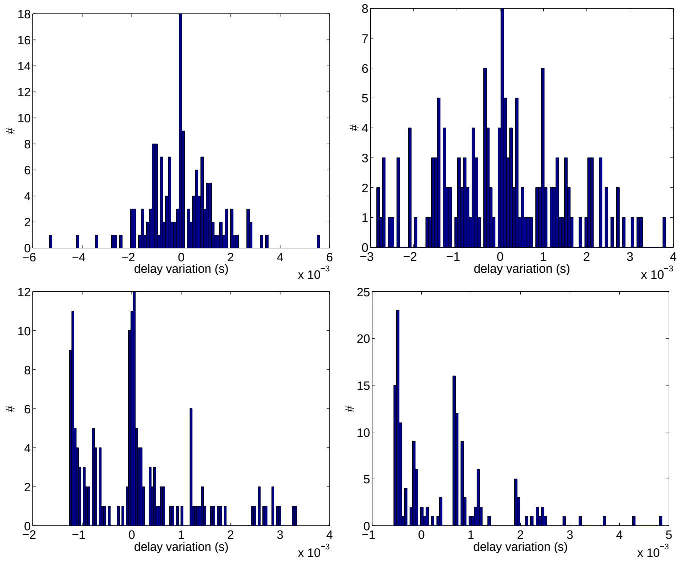

Fig. 11. Using 4 packet sizes. Cross traffi c fbw 1 has the rate 3 Mbps, cross traffi c fbw 2 has the rate 5 Mbps. The probe rate increases from approximately 1 Mbps (upper left) to 6.7 Mbps (lower right).

get less distinct.

When probing at 1 Mbps (the upper left histogram of Figure 11) we see the weakened but still unmistakable independence peak at $\delta_i = 0$. The mirror pattern creates a distribution of δ_i on both the negative and positive side of the independence peak.

When increasing the probe rate to 2.9 Mbps the independence peak has almost vanished in the upper right histogram. The mirror patterns is now overwhelmingly conspicuous. As in the previous experiment no chain patterns can be seen.

The two lower histograms show the same thing as in experiment 1 in Section VI-A, the chain (which creates a rate peak, the leftmost peak in both histograms) and quantification patterns divided in three regions. These patterns are still very clear, despite interfering cross traffic at two hops, since the chain and quantification patterns are recreated when the probe packets enter a new B-hop.

VII. Conclusions

In this paper we use a multihop model that describes the delay variation of adjacent packets in general. This model has been used to describe and analyze how packet trains are affected by interfering cross traffic when traversing a network path.

Three major cross traffic effects on packet trains was identified and described. They are: chain, quantification and mirror patterns. It is important to understand the influence of these patterns when developing packet-train techniques for measurements of bandwidth properties, since the patterns - as we have argued - can bias the dispersion averages (and other metrics) when doing calculations of bandwidth properties.

It should also be noted that these patterns on packet trains also affect other packet flows, such as MPEG streams. However, whether these patterns can be exploited in some way to gain better streaming media is left to future work.

We have performed testbed measurements to verify the occurrence of all three packet train patterns. The outcome of these measurements are a set of histograms where different kinds of signatures are visible. The signatures originates from one or several of the three patterns.

In the future it is our hope to develop new packet-train based techniques that compensate for, or in some way use the information embedded within an affected packet train using new, more accurate analysis methods.

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