# Modeling of Packet Interactions in Dispersion-Based Network Probing Schemes

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*Abstract*— **Measurements of end-to-end available bandwidth is getting increasingly important in the Internet. Many measurement methods are based on analysis of the dispersion of probe packets that have traversed the network according to some probing scheme.**

**In this paper we present a theoretical framework to model interactions, at the discrete packet level, between probe packets and cross-traffic packets for dispersion-based probing schemes. We believe that an understanding of packet interactions is crucial to develop accurate and efficient measurement methods as well as to evaluate trade-offs between different probing schemes.**

**Using the framework, we show that for statistical metrics such as the mean there are significant differences between using packet-pair and packet-train probing schemes when subject to cross traffic. Hence, these two probing schemes should not be used interchangabely.**

**We show that the differences between packet-pair and packet-train probing schemes are due to correlations of dispersion values obtained from packet train probing. These correlations do not arise in packet-pair probing. The correlations are manifested as three characteristic patterns. The correlations and their corresponding patterns are identified and analyzed within our framework.**

## I. Introduction and Motivation

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

Active end-to-end measurements of available bandwidth are usually divided into two phases. The first phase is the data collection phase where a probe generator injects probe packets along the path to be measured (i.e. the probe generator *probes* the path). The probing scheme (i.e. the times or dispersions between successive probe packets) is predefined by the sender. The initial dispersion changes when the probe packets traverse the network path. It changes either due to limited link capacity or due to interaction with other packets using the same path (such packets are referred to as cross traffic packets).

Probe packets are time stamped when received by the probe receiver. The time stamps are used to calculate the dispersion between successive probe packets at the receiver side.

Two common types of probing schemes are probing using packet pairs [1], [2], [3], [4], [5], or probing using longer sequences (or *trains*) of probe packets [1], [6], [7], [8], [9].

The second phase in the measurement is the analysis phase. The analysis uses the dispersion values obtained by the data collection phase to produce an estimate of the available bandwidth. Most measurement methods are based on one of two probing schemes above but differ in the analysis phase.

In this paper, we present a theoretical framework to model and quantify, at the packet level, differences between packet-pair and packet-train probing schemes used in the probing phase of end-to-end available bandwidth measurements. Hence, our results are relevant to most measurement methods explained above.

### *Packet-pair vs. packet-train probing schemes*

Probing using packet trains is considered an appealing alternative to packet pairs, especially for high-speed networks, because of the higher resilience to errors in time resolution introduced by, for example, clock granularity or measurement inaccuracies.

Most often, packet-train schemes are considered to be optimizations of packet-pair schemes. In packet-train schemes every packet between the first and the last is used for obtaining two dispersion values. This means that the number of packets needed to obtain $N$ dispersion values is cut by half, from $2N$ packets to $N + 1$ packets. In this paper we show that there is a significant difference in the results using packet-pair and packet-train schemes. Further, we show that every interfering cross-traffic packet will affect (at least) two dispersion values obtained from a packet train. That is, there will be correlations between adjacent dispersion values. Such correlations do not exist when using packet-pair probing schemes.

Applying the same analysis to dispersion values obtained from packet-pair or packet-train probing may thus lead to erroneous results.

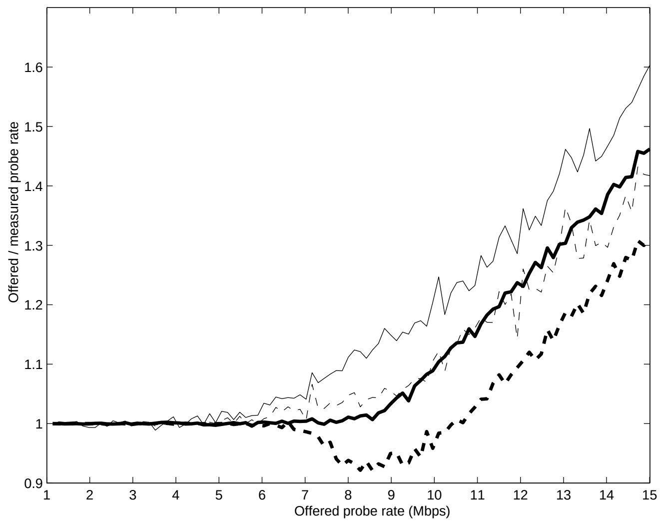


Fig. 1. Comparison of offered / measured mean rates (solid lines) and median rates (dashed lines) from packet trains (thick lines) and packet pairs (thin lines). Results from an ns-2 simulation, bottleneck bandwidth is 9 Mbps on a 15 Mbps link. The ns-2 setup is described in Section IV.

Examples of how these correlations affect bandwidth measurement results are shown in Figure 1. In the figure, the offered probe rates in ns simulations are compared to the measured probe rates. For clarity, the offered / measured ratio is shown on the y-axis. Mean values (solid lines) and median values (dashed lines) are plotted, as measured using packet-pair probing (thin lines) and packet-train probing (thick lines), respectively. As can be seen, there are significant differences between packet-pair and packet-train measurements, both for mean and median values. As will be explained in this paper, the reasons for these differences are found in the inherent differences between packet-pair and packet-train probing schemes. We will also explain the somewhat surprising behavior (ratio dropping below 1) of the packet-train median values around the point of saturation (9 Mbps).

In the following sections, we present quantitive methods that explain the differences between packet-pair and packet-train schemes, thereby giving developers of probing-based tools for network performance measurements, methods to overcome and use these inherent differences between measurement schemes.

We use a multi-hop model developed in [10] that describes how cross-traffic packets affect probe packets in general and consequently how they impact dispersion values. We extend this model and show that the effect of cross-traffic packets on dispersion values obtained from probe packet trains is significantly different to the effect exhibited on a sequence of probe packet pairs.

The rest of this paper is organized as follows: Section II describes the multi-hop delay variation model that we use and extend for the analysis of the patterns. It is followed by Section III that describes patterns within packet-train and packet-pair probing schemes. Section IV gives a comparative discussion between packet-train and packet-pair probing schemes. It also describe the ns-2 setup used for the measurements presented in this paper. The paper ends with conclusions in Section V.

## II. USING A GENERIC MULTIPLE-HOP MODEL FOR ROUTE DELAY VARIATION

To give a solid understanding on how probe packet dispersion if affected by cross traffic, we use a generic multiple-hop model presented in [10]. This section describes the concepts of that model, while we extend it in Section III.

In what follows, the definition of a *hop* is one router, its in-queue, and the outgoing link used by the packets. Hence, the arrival time of an arbitrary packet to hop $h+1$ is equal to the departure time from the previous hop $h$.

A packet $P_i$ arrives to a hop $h$ at time $\tau_i$. After a queuing time $w_i \geq 0$ the packet begins its service time $x_i > 0$. Packet $P_i$ leaves the hop at time $\tau_i^*$. Thus, the one-hop delay for packet $P_i$ is

$$d_i \equiv \tau_i^* - \tau_i = w_i + x_i + D, \tag{1}$$

where $D$ is the link propagation delay, which is equal for all equally-sized packets traveling on the same link.

From Equation (1), a set of equivalences to compare two adjacent packets are derived:

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

The waiting time of a packet within an infinite FIFO buffer is described by Lindley's equation

$$w_i = max(0, w_{i-1} + x_i - t_i) + c_i, \tag{2}$$

$c_i$ corresponds to the waiting time caused by cross traffic entering the hop between $\tau_{i-1}$ and $\tau_i$.

A router queue can in principle operate in two states - busy and idle state. The busy state implies that the router is constantly forwarding packets from its in-queue, while in the idle state the in-queue is empty.

Probe packets (i.e. packets used for obtaining dispersion values) can consequently be divided into two categories, **I**nitial and **B**usy probe packets (adapting to the notation in [10]). The first packet of a busy period is by definition an initial probe packet. That is, an **I** probe packet is never queued behind another probe packet (i.e. $w_i$ of Equation (2) is equal to $0 + c_i$). **B** probe packets are packets that *are* queued behind other probe packets.

With this categorization of probe packets, the delay variation $\delta_i$ is defined with respect to whether a probe packet $P_i$ is **I** or **B**. From [10] we have

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

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

where Equation (4) is derived from Equations (2) and (3).

Equations (3) and (4) are extended in [10] to describe multiple hops. These extensions are based on the following statements: if a probe packet is **I** or **B** at hop $j$ and **B** at hop $j+1$, $\delta_i$ is overwritten and replaced by $\delta_i$ from Equation (4). On the other hand, if the probe packet is **I** at hop $j+1$, the right hand side of Equation (3) is added to the existing $\delta_i$.

Hence, a probe packet that traverses an H-hop path, being **I** at every hop, has a delay variation

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

If a probe packet is **B** on at least one hop, it will be **B** for the last time at some hop in the path. Denote this hop $s_i$. The delay variation for such a probe packet is

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

## III. CROSS-TRAFFIC EFFECTS ON DISPERSION BASED PROBING

As stated in the Introduction, active probing schemes that is used to measure network path properties are typically divided into two types. Either a sequence of packet pairs or a number of packet trains are injected into the network. In packet-pair schemes, a change of the probe packet dispersion caused by cross traffic only affects the dispersion values from the particular probe-packet pair.

However, using packet-train probing, cross-traffic effects are more complex. Cross traffic can induce dispersion changes that are propagated along several successive packets in the probe train. For example, the displacement of one probe packet $P_i$ in the train will at least modify the delay variations $\delta_i$ and $\delta_{i+1}$. Hence, one cross-traffic packet will change at least two dispersion values. That is, dependencies will arise between adjacent delay variation values from a packet train, not found in packet-pair probing.

In this paper, three patterns in delay variation values obtained from packet train probing are identified and examined using the definitions and terminology described in Section II. We refer to these as *mirror*, *chain* and *quantification* patterns, respectively. They are described in the subsections III-A.1 to III-A.3. In Section III-B we show, by discussion, that delay variation values from packet pair probing can not form these patterns, with the exception of quantification patterns.

In our presentation of the patterns, the following assumptions are made. The routers use a simple FIFO queue and operate on packets in a store-and-forward fashion. The dispersion of adjacent probe packets within a packet train is constant, when leaving the probe packet generator (i.e. the rate within a probe-packet train is fixed). We also assume that the probe packet size is fixed, so that the service time $x_i$ for all probe packets are equal.

### *A. Probe trains*

#### A.1 Mirror patterns

In the following we will describe the characteristics of the mirror pattern. Hence, consider a probe packet train, containing at least three probe packets $P_{i-1}, P_i$ and $P_{i+1}$ that are all **I** at hop $h$. Further, assume that $P_{i-1}$ and $P_{i+1}$ are unaffected by cross traffic (i.e. $w_{i-1} = w_{i+1} = 0$). Then, if $P_i$ is delayed, $w_i > 0$, its delay variation $\delta_i > 0$. Hence, $P_i$ will have a delay variation $\delta_i = (x_i - x_{i-1}) + (w_i - w_{i-1}) = (w_i - w_{i-1})$, under the assumption of fix size probe packets.

Since both $P_{i-1}$ and $P_{i+1}$ are unaffected by cross traffic, the following holds

$$\begin{aligned} \delta_{i+1} &= w_{i+1} - w_i \\ &= -w_i \\ \delta_i &= w_i - w_{i-1} \\ &= w_i \\ &\Longrightarrow \\ \delta_{i+1} &= -\delta_i, \end{aligned} \tag{7}$$

which we define as a *perfect mirror pattern*. An example of this phenomenon is shown in Figure 2. The vertical packets above the time line shows when in time a probe packet (white box) or a cross-traffic packet (shaded box) arrives to the hop. The arc indicates when in time all bits of the packet have been received to the router. When all bits have been received, the router transmit the packet on the outgoing link, if it is not delayed by another packet. The transmission from the router is shown below the time line in the same manner as above the time line. The horizontal packets describe the packet pattern on the out-going link. Probe packet $P_i$ is delayed $w_i$ time units, visualized by the horizontal arrow next to $P_i$ in Figure 2. Since $P_{i-1}$ and $P_{i+1}$ are unaffected by cross traffic Equation (7) holds and we have a perfect mirror pattern.

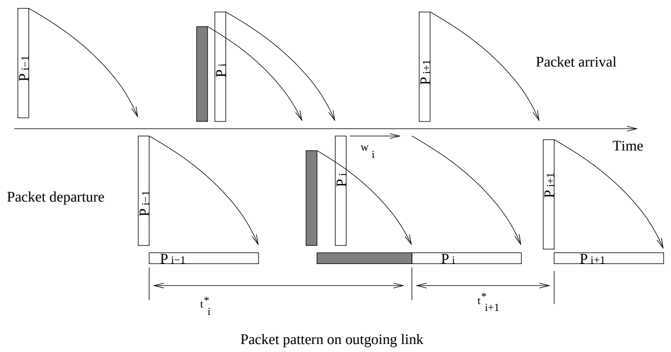


Fig. 2. Arrival and departure times for cross traffi c (shaded boxes) and probe packets (white boxes) entering a hop. All probe packets are assumed to be I, before and after the hop. The cross-traffi c packet delays probe $P_i$ in such a way that a *mirror pattern* arises.

In addition to the fact that probe packet $P_i$ can be delayed, there is a possibility that one, or both of $P_{i-1}$ and $P_{i+1}$ are affected by cross traffic. This will cause changes to the mirror pattern as described below. It is obvious that this possibility grows with increasing cross traffic and/or increasing probe rate.

Assume, for instance, that both $P_i$ and $P_{i+1}$ are delayed by cross traffic, while $P_{i-1}$ and $P_{i+2}$ are unaffected. Then the mirror pattern is *divided* in a predictable way. That is,

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

since $w_{i+1} > 0$. Now, the next packet in the train, $P_{i+2}$, will have a delay variation

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

since $P_{i+2}$ has a waiting time $w_{i+2} = 0$. Hence, $-\delta_i = \delta_{i+2} + \delta_{i+1}$.

To generalize, assume that $P_i$ and the following $(n-1)$ probe packets are delayed by cross traffic (not necessarily at the same hop), then we have a chain of divided mirror patterns. Their delay variations relate to each other in the following way:

$$\begin{aligned} \delta_{i+n} + \ldots + \delta_{i+1} &= (w_{i+n} - w_{i+(n-1)}) + \ldots + \\ &\quad (w_{i+2} - w_{i+1}) + (w_{i+1} - w_i) \\ &= -w_i \\ &= -\delta_i \end{aligned} \tag{8}$$

$$\Longrightarrow$$

$$\sum_{a=i}^{i+n} \delta_a = 0 \tag{9}$$

since $w_{i+n} = 0$. That is, cross-traffic effects on packet trains will cancel out, to a certain degree, and hence not affect the mean value of the packet dispersion values (nor $\delta$-values) obtained from the probe-packet train.

In Figure 1, the effect of mirror patterns can be seen as a difference in the mean values obtained from packet-pair and packet-train probing. Because of the mirror pattern correlation described above, the offered mean / measured mean values (thick solid line) will remain around 1 for higher probe rates than the uncorrelated offered mean / measured mean values (thin solid line) obtained from packet-pair probing.

Mirror patterns are erased if probe packets in the packet train are transformed from **I** to **B**, as described by Equations (5) and (6).

When a probe packet train traverses an H-hop path, the delay variation of every probe packet is described by Equation (5) or (6) depending on whether the probe packets ever become **B**. We have extended the model presented in [10] to describe the relation between delay variation values obtained from packet-train probing.

### A.2 Chain patterns

In this section we will describe the chain pattern. If a cross-traffic packet delays a probe packet, $P_{i-1}$, in such a way that at least $P_i$ and $P_{i+1}$ are transformed from **I** to **B**, and makes the involved probe packets $P_{i-1}$, $P_i$ and $P_{i+1}$ back-to-back after the hop, a chain pattern is visible.

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-A.3.

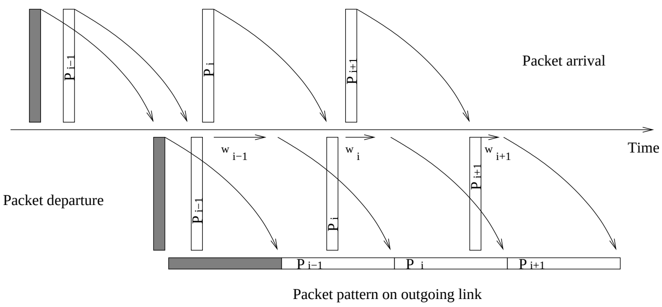


Fig. 3. Arrival and departure times for cross traffic (shaded boxes) and probe packets (white boxes) entering a hop. All probe packets are assumed to be I, before the hop. The cross-traffic packet delays $P_{i-1}$ in such a way that a *chain pattern* arises.

An example of a chain pattern is shown in Figure 3, which is similar to Figure 2. When $P_{i-1}$ is received, it must wait for the cross-traffic packet to complete its departure. The waiting time of $P_{i-1}$ is $w_{i-1}$, shown in Figure 3. $P_{i-1}$ is transmitted back-to-back behind the cross-traffic packet. $P_{i-1}$ is in this example by definition **I** since it does not have to queue behind any other probe packet.

During the waiting time of $P_{i-1}$, the next probe packet $P_i$ enters the router. $P_i$ has to wait $w_i$ time units in the queue for $P_{i-1}$ to complete its departure, and is therefore **B**. After the waiting time, $P_i$ is sent back-to-back behind $P_{i-1}$. The same procedure is repeated for $P_{i+1}$.

After the service time of $P_{i+1}$ has elapsed, $P_{i-1}$, $P_i$ and $P_{i+1}$ travel back-to-back after each other on the link. Also, $P_i$ and $P_{i+1}$ have been transformed from **I** to **B** since both packets had to queue behind other probe packets. Hence, a chain pattern is visible after the hop.

The relation between delay variation values from probe packets involved in a chain pattern can be described by Equation (8), similarly to mirror patterns. The difference is that the mirror pattern involves **I** probe packets while the chain pattern involves probe packets that change from **I** to **B**.

In Figure 1, chain patterns can be seen affecting the offered median / measured median plot obtained from packet-train probing (thick dashed line). Starting around one-half of the link bandwidth, the plot will dip because of the chain patterns described above. Since chain patterns cause a number of probe packets to be **B** and back-to-back, this will lower the median value of the dispersion times, thus lower the offered / measured median ratio.

Chain patterns are preserved to some degree in an H-hop path if the hop where the patterns arise is the last hop where the probe packets are **B**. Of course, this pattern is blurred by mirror and quantification patterns if there are hops downstream hop $s_i$ with cross-traffic. This is described by Equations (5) and (6).

### A.3 Quantification patterns

The last pattern identified in this paper is the quantification pattern. This pattern is described below.

Let us assume that the probe packet generator is sending probe packets at a high rate (i.e. the probe packet dispersion is less than the service time $x_{CT}$ of a large cross-traffic packet). When a cross-traffic packet enters the router queue between the arrival time of two probe packets the probe packets will become separated by the service time $x_{CT}$ of that cross-traffic packet. Hence there is no idle time gap in the router between the probe packets. This separation is hereafter referred to as a *quantification pattern*. The term quantification is used since the traffic consists of discrete transmissions, rather than a continuous flow of bits.

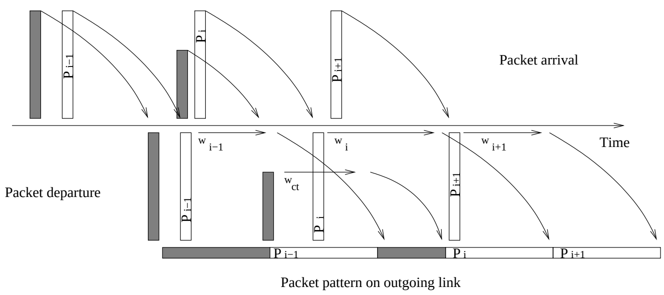


Fig. 4. Arrival and departure times of cross traffic (shaded boxes) and probe packets (white boxes) entering a router. The upper left cross-traffic packet causes a chain pattern. The smaller cross-traffic packet causes a *quantification pattern*.

An example of the quantification pattern is shown in Figure 4, which is similar to Figure 2. In this example we see that the leftmost cross-traffic packet creates a chain pattern (equivalent to Figure 3). The second cross-traffic packet entering the hop between probe packet $P_{i-1}$ and $P_i$ will be sent directly after

$P_{i-1}$, while $P_i$ is sent back-to-back with the second cross-traffic packet. Hence, $P_{i-1}$ has to wait $w_{i-1}$ time units (stemming from the large cross-traffic packet), while $P_i$ has to wait $w_i$ time units (corresponding to the small cross-traffic packet and a portion of the the big cross-traffic packet). That is, a quantification pattern has arisen.

The delay variation relation of values obtained from probe packets involved in a quantification pattern can be described by Equation (8), similarly to mirror patterns.

In Figure 1, quantification patterns cause all curves to rise, especially evident above the saturation point of 9 Mbps. When a router is trying to send packets above the outgoing link capacity its in-queue will be filled up by probe packets and cross-traffic packets. The order of the packets depends on their arrival times. Hence, the quantification pattern effect will eventually dominate over all other patterns described in this paper. Since the effect is similar when using packet pair and packet-train probing, all curves will have similar slopes at high probe rates.

Quantification patterns are preserved to some degree in an H-hop path if the hop where the pattern arise is the last hop where the probe packets are **B**. This pattern is blurred if there are hops downstream hop $s_i$ with cross-traffic noise. This is described by Equations (5) and (6).

### B. *Packet-pair probing*

In packet-pair probing schemes, two probe packets are sent out as a pair on the network. The dispersion between the two probe packets are used to form a bandwidth estimate using an analysis method. The pairs are sent separated enough to avoid any interaction between successive pairs (i.e. one probe packet pair can be seen as a packet train containing two probe packets). Cross-traffic-induced delay of any of the two probe packets in the pair either increases or decreases the probe packet dispersion for that particular pair. That is, there is no correlation between successive dispersion values obtained from different probe pairs.

Neither mirror nor chain patterns can occur since they require at least 3 successive probe packets. However, quantification patterns will appear, since two probe packets can be separated by one or several cross-traffic packets at a hop. Quantification patterns have the same properties independent on whether packet-pair or packet-train probing schemes is used. The details of these properties were discussed in subsection III-A.3.

## IV. Comparison

As we have shown above, the characteristic patterns identified in this paper will have implications on metrics derived from active end-to-end measurements using packet-pair and packet-train probing schemes. Independent of the analysis phase of the end-to-end measurement, the patterns will have impact on the probe packet dispersion median and mean values.

We have made simulations in ns-2 to support our framework of patterns. All curves in this paper originate from simulations with the setup shown in Figure 5. We will describe it below. In the figure there is one probe packet sender (PS) and one receiver (PR). The probe packets traverse a path consisting of 7 routers (R1-R7). To simulate cross traffic in the path we have a set of cross traffic generators (CT-in 1 to CT-in 6 in the figure). They

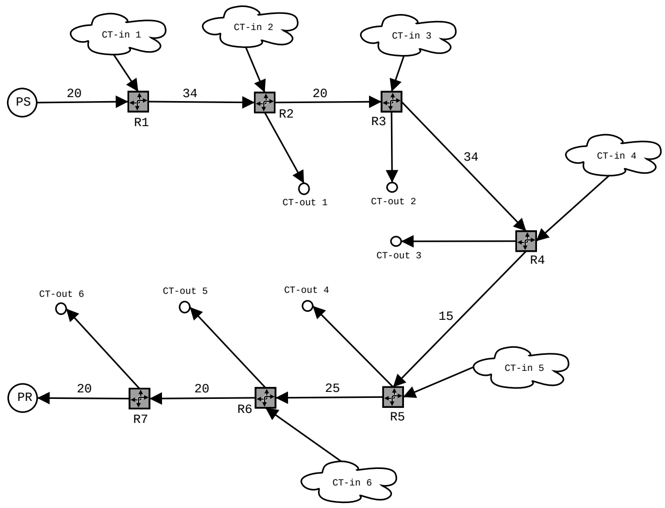


Fig. 5. Ns-2 testbed setup. PS = probe sender, PR = probe receiver, R1-R7 are routers, CT-in 1 to CT-in 6 are cross-traffic generators (8 cross-traffic generators in each cloud) and CT-out 1 to CT-out 6 are cross-traffic sinks. Link bandwidth is shown next to each link.

are connected to router R1 to R6, respectively. The traffic generators (CT-in 1 to CT-in 6) contains 8 independent cross-traffic sending engines each. The traffic generators are able to generate Pareto distributed or uniformly distributed cross traffic. Routers R2 to R7 are connected to cross traffic sinks (CT-out 1 to CT-out 6). The cross traffic generators use 4 different packet sizes (49, 148, 472 and 1477 bytes, originate from findings in [11]).

At low probe rates chain patterns nor quantification patterns arise in values obtained from packet-train and packet-pair probing. That is, the difference between packet-train and packet-pair probing is due to mirror patterns. Equation (8) shows the dependencies of successive dispersion values obtained from packet-train probing. Equation (9) shows that the changes in dispersion values due to mirror patterns sums to 0. This will cause the mean value to level out *despite the fact that the probe packets are delayed by cross traffic*. For example, the packet-pair plot starts to rise at 4.5 Mbps while the packet-train plot rises at approximately 8.5 Mbps where quantification and chain patterns start to dominate (see Figure 1).

At probe rates where quantification and chain patterns arise the median is different when comparing values from the two probing schemes. The median of the probe packet dispersions will be smaller when using packet trains compared to the median from packet-pair probing. This is due to chain patterns (i.e. the packet dispersion is small). This is also visible in Figure 1 where the thick dashed line dips after about 7.5 Mbps.

For both mean and median values, more and more quantification patters will cause a rise of both the packet-train and packet-pair plots, when the probe packet rate is increased.

For clarity, we have used a uniform cross-traffic distribution in Figure 1. In Figure 6 we compare the offered and the measured mean values for on-off Pareto distributed cross traffic (on time = 500 ms, off time = 500 ms and the shape parameter is 1.5). The available bandwidth is again 9 Mbps and the link bandwidth at the bottleneck is 15 Mbps. Cross traffic is present on several upstream and downstream links relative to the bottleneck link according to Figure 6. As can be seen, the thin

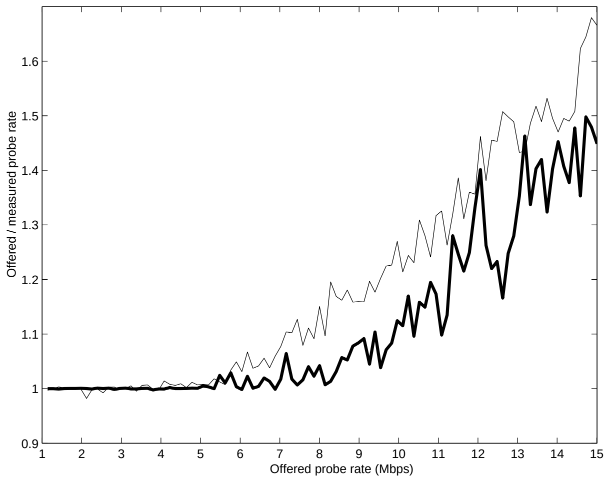


Fig. 6. Comparison of offered mean / measured mean probe rates obtained from packet train probing (thick line) and packet pair probing (thin line). The plot originates from an ns-2 simulation described in Section IV. The bottleneck bandwidth is 9 Mbps on a 15 Mbps link.

solid line diverges from $y = 1$ before the thick solid line, due to Equations (8) and (9). Also, the slope of the two curves are quite the same after the saturation point (9 Mbps), due to the quantification patterns that affects the two probing schemes in a similar way. The curves however show more variation, due to the effects of the bursty Pareto distributed cross traffic.

## V. CONCLUSIONS

In this paper, we have shown that packet-pair and packet-train probing schemes produce significantly different dispersion values. This will affect the analysis phase and thus the available bandwidth estimate.

We have extended a multi-hop delay variation model to develop a modeling framework. Using this framework we have described packet dispersion correlations within probe packet trains that do not exist using packet-pair probing schemes. These dispersion correlations affect statistical metrics and will bias for example the mean and median. Since the analysis phase depends on the dispersion values obtained during the data collection phase (i.e. either packet-pair or packet-train probing) it is very important to understand these differences.

The dispersion correlations form characteristic patterns in the dispersion values from packet train probing. These patterns have been identified and analyzed. They are: *mirror*, *chain*, and *quantification* patterns. Packet pairs can only form quantification patterns. That is, the two schemes are fundamentally different, which we have shown in theoretical discussions and in illustrative simulation examples.

We believe it is important to understand the low-level packet interactions (manifested by the identified patterns) when developing active dispersion-based end-to-end measurement methods.

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