Licentiate thesis proposal
Investigation of dispersion-based measurements in wired and wireless networks

Andreas Johnsson
The Department of Computer Science and Engineering
Mälardalen University, Sweden
Andreas.Johnsson@mdh.se

April 16, 2004

Abstract

This is a proposed time plan that describes work that has been done and work that is to be completed before my licentiate thesis defense. It describes the area of active end-to-end measurements of network path characteristics. Especially it studies link capacity and available bandwidth measurement methods. Further, my research contributions are presented, followed by published and planned papers, and ends with future work, beyond my licentiate thesis defense.

1 Background and motivation

End-to-end measurement of network path characteristics, such as link capacity and available bandwidth, is important in best-effort networks where resource reservations can not be made. In the past years, research efforts have been made to study and develop methods to measure such characteristics.

A variety of tools exist today. However, they all suffer from different problems. For example, applications that use the metrics provided by the measurement tools may have time constraints. Today, most end-to-end measurement methods are slow. Another problem is that heavy loads are injected into the network by most probing methods. This load affects other traffic - hence, measurement traffic must be kept to a minimum especially in networks with low bandwidth. Yet another problem is accuracy. The traffic in networks, in the Internet for example, is far from static. Since all end-to-end measurements run within a time interval the estimates will vary depending on how dynamic the traffic is. Traffic burstiness is usually removed from measurement results by mean filtering, even if such information is important to the application.

Since many Internet applications require a certain amount of available bandwidth to be useful, it is important to be able to measure it in a fast and accurate way. Applications that would benefit from having such metrics are for example streaming video, IP telephony, router decision algorithms, error detection et cetera.

Because of time constraints and accuracy problems of todays bandwidth measurement tools there is a need for more research in the area.

2 Definitions and related work

This section defines the most important concepts in the active end-to-end dispersion-based measurement area. First a high level definition of the metrics are presented. Further, techniques for obtaining estimates of e.g. available bandwidth is described. This section ends with a brief survey of tools available today.

2.1 What to measure

A set of hosts are connected by a network, for example the Internet. Between two hosts there is a number of links (see Figure 1) with different link capacities. The network traffic on each link varies (the gray portion of each link in Figure 1). In end-to-end measurements the link with the least available bandwidth is the important one, since that link limits the traffic throughput.

Below, the most important definitions in the area of bandwidth estimations are described. The definitions has also been described in [1, 2].

The link capacity L_i is by definition the bit rate of a link (i.e. the number of bits that can be transfered during time τ). In Figure 1 the link capacity is visualized by the width C of each link.

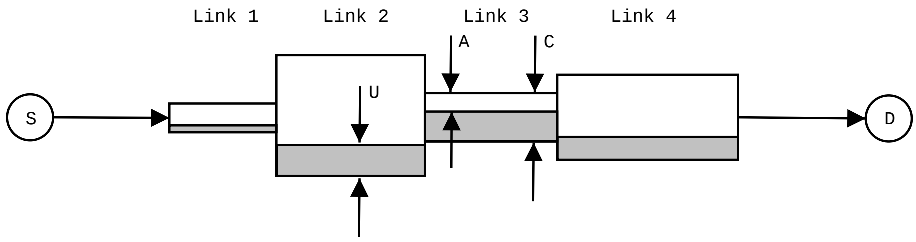

Figure 1: Network path

Further, the path capacity is the least link capacity on a given path consisting of several links. It is defined as follow

$$C = \min_{i=1..H}(C_i) \tag{1}$$

where i is the link index and H is the number of links in the network path. The path capacity is limited by the *narrow link* which is the link with the least capacity. The path capacity in Figure 1 is the capacity of link 1, since that link has the least capacity in the path between the source (S) and the destination (D).

Empty links are not very common in networks, hence a definition of the link utilization is needed. The utilization of a link is by definition the number of bits transfered during time τ divided by the link capacity. That is, the utilization is a measure within the interval $[0, 1]$. The utilization is seen as the gray area of each link in Figure 1, respectively.

The definition of available bandwidth on one single link is (link capacity) * (1 - link utilization) during time τ (i.e. the non-utilized capacity). The link available bandwidth is represented by the unfilled portion of each link in Figure 1.

Further, the definition of end-to-end available bandwidth is

$$A = \min_{i=1..H}(C_i * (1 - u_i)), \tag{2}$$

where u_i is the utilization of link i. As stated above, the link available bandwidth is the unfilled portion of each link in Figure 1. The end-to-end available bandwidth is the least link available bandwidth in the path. In the figure the end-to-end available bandwidth is limited due to link 3.

2.2 Dispersion-based probing schemes

The previous subsection defined end-to-end available bandwidth, but how do we measure it without knowledge about the network? So called active end-to-end measurements are based on the injection of *probe packets* into the network. The probe packets are sent out with a predefined separation (hereafter called dispersion) from the source S in Figure 1. When the probe packets traverse the network, this dispersion will change due to other packets in the path (called cross traffic packets) or due to limited link capacity on one or several links [3, 4]. Limited link capacity will increase the probe packet dispersion while packet interaction will either decrease or increase the dispersion.

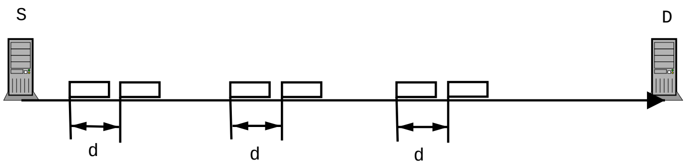

Figure 2: Packet-pair probing schemes.

The injection of probe packets can broadly be grouped into two schemes. The first scheme is to inject probe packets in pairs [1, 5, 6, 7, 8]. That is, a pair of probe packets traverse the network together. Successive probe pairs are separated enough to not interact with each other. The dispersion between the two probe packets in each pair is used for obtaining an estimate of the measured metric. The packet-pair probing scheme is visualized in Figure 2. The sender S is sending three probe packet pairs to the destination D. Using this setup 3 dispersion values are obtained.

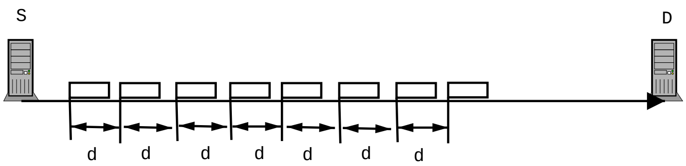

Figure 3: Packet-train probing schemes.

The other scheme of probe packet injection is to send probe packets in trains [9, 10]. A number of probe packets (at least 3) are sent from the source with a predefined dispersion. Now, every probe packet is used for two dispersion values (except for the first and the last probe packet in the train). The packet-train probing scheme is shown in Figure 3. The sender S sends 8 probe packets to the destination D. When using packet-trains in this example 7 dispersion values are obtained. The dispersion of the probe packets are measured at the destination D.

2.3 Analysis

The analysis phase uses some algorithm typically involving statistical operations on the dispersion values gathered using either packet-pair or packet-train probing schemes, described in subsection 2.2. Contemporary tools use either packet-pair or packet-train probing schemes, but differ in the analysis phase.

Many methods uses the mean of dispersion values obtained from using a probing scheme to filter out noise and short traffic bursts. The calculated metric is then used in the analysis.

To get an idea of how an analysis is performed an simplified example will be discussed. The example is based on Pathload [10].

When injecting probe packets into the network, the dispersion between the probe packets will change as they traverse the network. However, the mean of the obtained dispersion values will approximately be equal to the mean of the dispersion values when injected into the network, if the network is underloaded. Pathload sends probe packet trains and measure the dispersion between packets. If the mean of the gathered dispersion values are greater than the initial dispersion, according to a set of rules defined by Pathload, the analysis assumes that the probe rate (i.e. the probe packet dispersion) is higher than the available bandwidth of the network path. That is, the network is overloaded. The probe packet dispersion is then increased to reduce the probe rate. If the dispersion mean obtained on the receiver side is the same as the initial dispersion, Pathload assumes that the rate is less than the available bandwidth and the probe rate is increased. That is, the network path is underloaded. Using an iterative algorithm Pathload *zooms* in, or converges to the available bandwidth.

Hence, Pathload initializes a probing scheme (i.e. the dispersion between probe packets). It transmits the probe packets to the receiver. The receiver measures the dispersion of the probe packets and produces data. Statistical operations (the mean in this case) are used to filter out noise and in the end the filtered values are analyzed. If necessary, a new probing scheme is initialized, transmitted and analyzed as described.

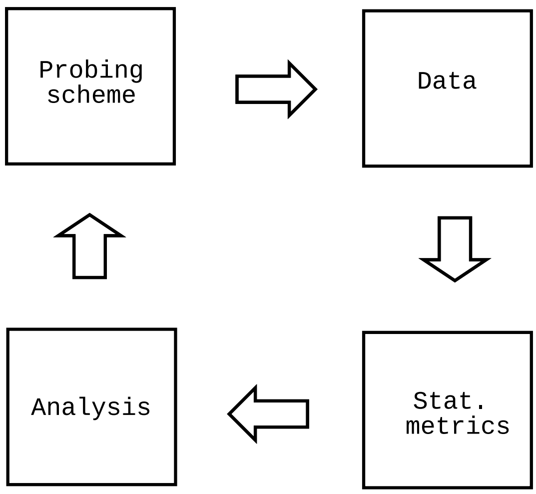

Figure 4: The four states in a dispersion-based measurement

Most probing methods can in abstract terms be divided into four steps [11] as seen in Figure 4. The first step is to initialize the *probing scheme*. The second step is to *collect data* (i.e. dispersion values). This is done at the probe packet receiver. These two steps are defined as the data collection phase. The third step is to use, for example, mean filtering on the obtained dispersion values. The filtered values are then used in an analysis. Depending on the analysis, these four steps are iterated until the requested accuracy is achieved.

2.4 Related work

A lot of work has been done in the area of available bandwidth measurements. Several tools exist today that measure available bandwidth as well as link capacity. Depending on whether the network is a high-speed network, or if it is a wireless network, or a sensor network different aspects must be considered.

Tools and methods available today for measurements of end-to-end characteristics are for example Pathload [10], Pathrate [1, 12], Tracerate [13], TOPP [9] and TPTEST [14, 15] which all have their strengths and weaknesses. As illustrated in Table 1 each tool measures different characteristics of the network path using either packet pair/packet train or throughput probing schemes. (There exists a lot of other tools in the research community.)

It should be noted that TPTEST is not a dispersion-based measurement tool. Instead, it uses raw TCP-throughput. However, this tool is interesting to study since it is used by the common public, and it is not constructed by the research community. Further, TPTEST is able to run on ordinary operating systems such as Windows XP. This is not the case for the other measurement tools (which requires a non-multitasking system). We have studied TPTEST as a case study.

	A.B.	L.C.	Probing scheme
Pathload	X	-	Packet train
Pathchirp	X	-	Packet train variant
TOPP	X	X	Packet pair/train
TPTEST	X	-	TCP throughput
Pathrate	-	X	Packet pair
Tracerate	-	X	Packet pair

Table 1: Network characteristics measured by different tools. A.B. = available bandwidth, L.C. = link capacity.

Other, more theoretical work has also been done. In [1] an investigation of dispersion-based techniques is made. It describes what such techniques really measure when applied to best effort networks, such as the Internet.

In [16] a theoretical investigation of probe-pair probing schemes is made. It describes how the probe packet delay variation changes when the packets traverse a network path. Further, it identifies histogram signatures that can be used to identify so called secondary bottlenecks.

Most of the previous work has best effort networks, such as the Internet, in mind. Thus, it is not clear that they are applicable in more demanding networks such as wireless and sensor networks. Yet, there has not been much work done using dispersion-based methods in wireless ad-hoc networks. In [17] initial findings are presented and [18] presents an investigation of how to measure the available bandwidth in VPN and MobileIP networks.

3 My research activities

We have developed methods to understand how dispersion-based probing is affected by cross traffic when traversing a network path. We study probe packet and cross-traffic packet interaction at the discrete packet level. We also study how different statistical metrics (mean, median and variance) are affected by cross traffic.

Further, we intend to study if current dispersion-based methods and tools to estimate available bandwidth can be used, possibly with modifications, in wireless ad-hoc networks. Within this work we also intend to describe the differences between probing in wired and wireless networks from a dispersion-based probing measurement point of view.

In this section we describe our contribution to the field in more detail. Planned and published papers are reviewed and the time plan to the licentiate thesis is marked out.

3.1 The approach

The approach to our research findings is to use experimental setups and analyze data obtained from measurements. From the data we derive models that explain the behavior. The experiments are performed both in simulations (ns-2 [19]) and in testbeds. We have not performed any measurements in networks that are actually in use, such as the Internet. This is mainly due to the fact that it is very difficult to know all the network characteristics and hence there is no possibility to validate the results. However, many conferences and workshops require that measurements are done in real networks. Because of this, we will perform such measurements in the future.

3.2 Contribution

The main contributions of the work accomplished so far, and the work to be done is summarized below

- *Packet interaction framework.* We have developed a framework that describes, at the discrete packet level, how probe packets and cross-traffic packets interact with each other when traversing a network path. Within this work we have also compared two common probing schemes (packet-pair and packet-train schemes) and showed that they are fundamentally different from each other. This is important when developing new techniques to measure the available bandwidth using dispersion-based methods.

- *Study of other metrics than the mean.* Usually, the analysis of values obtained from dispersion-based probing uses mean filtering of probe packet dispersions to give an estimate of a network characteristic. We have studied the median and we have found that it give hints of packet interactions that mean filtering hides. Exactly how to use this in the context of dispersion-based measurements is a subject of further research.

- *Dispersion-based probing in wireless networks* We will study how the existing tools for obtaining an estimate of the available bandwidth reacts when executed in a wireless network (ad-hoc). Within this work we will also point out the differences between wired and wireless networks from a dispersion-based probing scheme point of view.

- *Implementation.* We have implemented a probing tool that gives raw packet-dispersion data to be analyzed in, for example, Matlab. This tool is important when trying different analysis methods on the same data from the data collection phase.

- *TPTEST.* We have studied TPTEST and the experiences from using it. This work has been presented for an international audience.

3.3 Papers

This subsection is a review of planned and published papers within my research at Mälardalen University. First, four papers are described that are all are intended to be a part of my licentiate thesis. The other papers are not intended to be part of my thesis.

- *Paper 1.* "Modeling of Packet Interactions in Dispersion-Based Network Probing Schemes". This paper describes the interaction between probe and cross-traffic packets when traversing a network path. It shows the difference between packet-pair and packet-train probing schemes. All measurements are done in ns-2. This paper is submitted to the International Workshop on Quality-of-Service.

- *Paper 2.* "On the Analysis of Packet-Train Probing Schemes". This paper studies histogram signatures obtained from packet-train probing schemes. It is also an initial study of the median filtering operation. All measurements in this paper has been done in a testbed at Ericsson Research using a measurement tool developed by myself and Bob Melander, Mälardalen University. This paper is submitted to the International Conference on Modeling, Simulation and Visualization Methods. Special session on Network Simulation and Performance Analysis: Practice and Theory. (MSV'04)

- *Paper 3.* "A Study of Dispersion-based Measurement Methods in IEEE 802.11 Ad-hoc Networks". This paper is a position paper and an initial study of how dispersion-based measurement methods handle wireless ad-hoc environments. It is submitted to MSV'04.

- *Paper 4.* The fourth paper will be a comparison and investigation of dispersion-based probing tools in wireless ad-hoc networks. The paper will also address difficulties when measuring the available bandwidth in ad-hoc wireless networks. The study will rely on ns-2 simulations and testbed measurements. The testbed is currently under construction at Mälardalen University and will consist of 8-10 nodes. The ns-2 simulation framework is completed. This paper will be submitted to the Local Computer Network conference, May 21:st.

During my time as a Ph.D. student at Mälardalen University I have also completed one short paper, one paper abstract and one technical report.

The short paper ("On the Comparison of Packet-pair and Packet-train Measurements" [20]) was presented as a poster on the Swedish National Computer Networking Workshop at Arlandastad (September 2003).

The paper abstract was presented at the Bandwidth Estimation Workshop in San Diego (December 2004). The abstract/presentation described the TPTEST measurement tool and infrastructure [15] and the experiences from using it.

The technical report was published within MRTC at Mälardalen University. The title is "Analyzing Cross Traffic Effects on Packet Trains using a Generic Multihop Model" [21].

4 Thesis outline

My licentiate thesis will consist of two parts. The first part is the description of my research area (i.e. definitions and concepts) and where my contributions fit in. It will cover related work such as dispersion-based measurement methods and other theoretical work. The second part will consist of the four papers that I intend to publish.

5 Time plan

This section presents the time plan toward my licentiate thesis defense. However, this time plan is not very precise, but it still gives the overview.

February 20	Paper 1 submitted to the International Workshop on Quality-of-Service
Mars 15	Paper 2 and 3 are submitted to MSV'04
Mars 24	Licentiate thesis proposal is presented
May 21	Paper 4 is going to be submitted to the Local Computer Network Conference

I have earned 20 course credits[1]. The courses I have completed so far are shown in Table 2. To be able to receive a licentiate degree in computer science at Mälardalen University I need 10 more credits. Currently I take a reading course in computer communications [22]. It will be completed this spring and award me with 5 credits. During the fall I will attend courses awarding me at least 5 credits within the ARTES++ programme [23].

Name	Level	Credit	University
Distributed Systems MN1	D-level	5	UU
Computer Communications MN2	D-level	5	UU
Computer Architecture MN2	D-level	5	UU
Secure Computer Systems	C-level	5	UU

Table 2: Courses taken, the level, the credits and from which University. UU stands for Uppsala University.

The actual licentiate thesis will be written during the fall, 2004. It will be defended in December 2004. That is, approximately two years after I started my Ph.D. studies at Mälardalen University.

6 Future work

My research activities after my licentiate degree will be oriented toward two main areas. The first area is a continuation of my previous work. That is, the study of dispersion-based probing schemes in wireless ad-hoc environments and the median filtering on obtained dispersion values. This work aims at the development of a new tool to estimate end-to-end available bandwidth in wireless ad-hoc environments.

The second area of interest is to study large scale available bandwidth methods in the Internet. For example, we want to study if an end-to-end measurement between two end hosts can be divided into several parts - to gain more

[1] 1 credit corresponds to 1 week of full time study.

accuracy but also to increase the speed of the measurement. Within this area it is also important to study how we can combine different (but concurrent) end-to-end measurements to create a picture of bottlenecks in a network at a given time. Using that knowledge we might be able to predict network bottlenecks - and then be able to avoid the route through them.

We also intend to interact more with the TPTEST development team, to be able to study user behavior when using TPTEST. We also want to see if we can try our own methods in the ordinary PC environment.

References

[1] Constantinos Dovrolis, Parameswaran Ramanathan, and David Moore, "What do packet dispersion techniques measure?," in *Proceedings of IEEE INFOCOM*, Anchorage, AK, USA, Apr. 2001, pp. 905–914.

[2] Constantinos Dovrolis, "Bandwidth metrics: definitions and terminology," Bandwidth Estimation Workshop, La Jolla, CA, 2003.

[3] Van Jacobson, "Congestion avoidance and control," in *Proceedings of ACM SIGCOMM*, Stanford, CA, USA, Aug. 1988, pp. 314–329.

[4] Bob Melander, Mats Björkman, and Per Gunningberg, "First-come-first-served packet dispersion and implications for tcp," in *Proceedings of IEEE GLOBECOM'02*, Taipei, Taiwan, November 2002.

[5] Robert Carter and Mark Crovella, "Measuring bottleneck link speed in packet-switched networks," Tech. Rep. 1996-006, Boston University Computer Science Department, Boston, MA, USA, Mar. 1996.

[6] Srinivasan Keshav, "A control-theoretic approach to flow control," in *Proceedings of ACM SIGCOMM*, Zürich, Switzerland, Sept. 1991, pp. 3–15.

[7] Kevin Lai and Mary Baker, "Measuring bandwidth," in *Proceedings of IEEE INFOCOM*, New York, NY, USA, Mar. 1999, pp. 235–245.

[8] Jiri Navratil and R. Les. Cottrell, "ABwE: A practical approach to available bandwidth estimation," in *Passive and Active Measurement (PAM) Workshop 2003 Proceedings*, La Jolla, CA, USA, Apr. 2003.

[9] Bob Melander, Mats Björkman, and Per Gunningberg, "Regression-based available bandwidth measurements," in *Proceedings of the 2002 International Symposium on Performance Evaluation of Computer and Telecommunications Systems*, San Diego, CA, USA, July 2002.

[10] Manish Jain and Constantinos Dovrolis, "Pathload: a measurement tool for end-to-end available bandwidth," in *Passive and Active Measurement (PAM) Workshop 2002 Proceedings*, Ft Collins, Co, USA, Mar. 2002, pp. 14–25.

[11] Attila Pásztor, "On evaluating a new class of available bandwidth methods," Bandwidth Estimation Workshop, La Jolla, CA, 2003.

[12] Constantinos Dovrolis, Manish Jain, and Ravi Prasad, "Pathrate," www.pathrate.org.

[13] Mathieu Goutelle and Pascale Primet, "tracerate: A non-intrusive method for measuring the hop-by-hop capacity of a path," Bandwidth Estimation Workshop, La Jolla, CA, 2003.

[14] Gatorhole AB, "tptest," http://www.gatorhole.se.

[15] Mats Björkman, Andreas Johnsson, and Bob Melander, "Bandwidth measurements from a consumer perspective - a measurement infrastructure in sweden," Bandwidth Estimation Workshop, La Jolla, CA, 2003.

[16] Attila Pásztor and Darryl Veitch, "The packet size dependence of packet pair like methods," in *Tenth International Workshop on Quality of Service (IWQoS 2002)*, Miami Beach, USA, May 2002.

[17] Samarth Shah, "Available bandwidth estimation in ieee 802.11-based wireless networks," Bandwidth Estimation Workshop, La Jolla, CA, 2003.

[18] Takamichi Tateoka, Yukihiro Kurita, and Koki Abe, "A bandwidth measurement technique for mobile computers," http://almond.cs.uec.ac.jp/paper_pdf/2002/tate_kurita-iwmst.pdf.

[19] "The network simulator - ns-2," http://www.isi.edu/nsman/ns/.

[20] Andreas Johnsson, "On the comparison of packet-pair and packet-train measurements," Swedish National Computer Networking Workshop, Arlandastad, September 2003.

[21] Andreas Johnsson, Bob Melander, and Mats Björkman, "Analyzing cross traffic effects on packet trains using a generic multi-hop model," MRTC Report, Mälardalen University, November 2003.

[22] Reading course, "Computer communications," http://www.idt.mdh.se/˜ajn12/index.phtml/?choise=rg.

[23] ARTES++, "Graduate school in real-time and embedded systems," http://www.artes.uu.se/++/.