What do packet dispersion techniques measure?

According to "the packet pair technique" the capacity of a path is estimated by the dispersion of two back-to-back packets sent with a space, from the source to the sink. However, the path capacity is not always the global mode due to cross traffic so it cannot be estimated using standard statistical procedures. In this report a methodology is presented, that takes cross traffic into consideration for the capacity estimation and has been implemented in a tool called path rate.

1. Introduction

Bandwidth monitoring has arisen to be a crucial operation in the past years, both for the providers and the users of the internet. The method we will discuss relies on end-to-end bandwidth monitoring as it is the only way to estimate capacity in a path that crosses several networks. The metrics studied in a network path are:

1. **the capacity** - the maximum IP-layer throughput that the path can provide to a flow, when there is no competing traffic load and,
2. **the available bandwidth** - the maximum IP-layer throughput that the path can provide to a flow, given the path's current cross traffic load

The packet pair technique is a well-known procedure to measure the capacity of a path. When a packet is transmitted in a link, it encounters a transmission or serialization delay due to the physical bandwidth limitations of the link and the hardware constraints of the transmitting equipment. A packet pair experiment consists of two packets sent with a spacing that is as short as possible, from the source to the sink. Without any cross traffic in the path, the packet pair will reach the receiver dispersed (spaced) by the transmission delay in the narrow link. The main problem is that there is cross traffic in the path that distorts the packet pair dispersion, increasing or decreasing the capacity estimates. So, a new methodology is presented which is robust to cross traffic effects.

2. Previous Work

When the concept of the packet dispersion method was first described the cross traffic was not taken into consideration, but later it was studied by several scientists, focusing on robust statistical filtering techniques. Paxson was the first to observe that the distribution of bandwidth measurements is multimodal, and he elaborated on the identification and final selection of a capacity estimate from these modes. Dispersion techniques using packet trains instead of packet pairs have also been proposed for the estimation of the available bandwidth in a path.
3. Packet Pair Dispersion

The dispersion of a packet pair is the interval from the instant the last bit of the first packet is received at a certain path point to the instant the last bit of the second packet is received at that point. Since the distribution varies in general, if we repeat the experiment many times, the values will form a certain distribution B. Our goal, then, is to infer a final path capacity estimate C from the distribution B.

It is understood that when there is no cross traffic, all the bandwidth estimates are equal to the capacity. However, the probing packets can experience additional queuing delays due to cross traffic that can cause a dispersion at the receiver that is lower than the dispersion at the narrow link. The additional hops after the narrow link are called post-narrow links. Consequently the capacity of the path cannot be estimated simply from the minimum measured dispersion, as that value could have resulted from a post-narrow link.

In order to examine the properties of the distribution in a controllable and repeatable manner we used simulations, which allow us to investigate the cross traffic effects in packet pair dispersion. The results of two such simulations for two different path loads is shown in Figure 1.

![Figure 1. The B distribution in two different path loads](image)

When the path is lightly loaded (\( \approx 20\% \)) the capacity value of 40 Mbps is prevalent in B, forming the Capacity Mode (CM), which in this case is the global mode of the distribution. Bandwidth estimates that are lower than the CM are caused by CT packets that interfere with the packet pair, and they define the Sub-Capacity Dispersion Range (SCDR). Bandwidth estimates that are higher than the CM are caused in the post-narrow links when the first probing packet is delayed more than the second; these estimates are referred to as Post-Narrow Capacity Modes (PNCMs). In heavy load conditions (\( \approx 80\% \)) the global mode is in the SCDR, which...
now dominates the bandwidth measurements, so the path capacity cannot be always correctly estimated by statistical techniques that extract the most common bandwidth value or range.

4. Packet Train Dispersion

Extending the packet pair technique, the source can send N>2 back-to-back packets of size L to the sink; we refer to these packets as a packet train of length N. Measuring the capacity of a path using packet trains is required when the narrow link is multi-channeled or to measure the sustainable rate of a traffic shaper. Packet trains are not robust to measurement noise as many believe. Although the dispersion becomes larger as N increases, so does the ‘noise’ in the measured values, since it becomes more likely that CT packets will interfere in the packet train. From simulation results (Figure 2) illustrating the effect of N in the bandwidth distribution we make some general observations about this relation.

![Figure 2. The effect of the packet train length](image)

1. As the length N of the train increases, the CM and PCNMs become weaker and the SCDR prevails in the bandwidth distribution. This means that the best value of for generating a strong capacity mode is =2, i.e., to use packet pairs; anything longer than packet pairs is more likely to get additional dispersion due to cross traffic.

2. As N increases, the dispersion becomes uni-modal. This means that the dispersion of packet trains by CT packets is determined by the aggregate amount of CT interfering with the packet train.

3. The range of the distribution, which is related to the measurement variance, decreases as N increases. This implies that the variance in the amount of
cross traffic interfering with the packet train decreases, as the length of the packet train increases.

4. When $N$ is sufficiently large, the center of the (unique) mode (a.k.a. Asymptotic Dispersion Rate) is independent on $N$.

5. The Size of Probing Packets

Although it was believed that is that the optimal $L$ is the maximum non-fragmented packet size, taking cross traffic into consideration it is now obvious that a larger packet size leads to a wider time interval in which a CT packet can interfere with the packet pair. The larger the $L$, the higher the likelihood of an interfering CT arrival, and thus the SCDR becomes more prevalent in the bandwidth distribution.

A minimum sized packet, however, is not optimal either. As $L$ decreases, the dispersion decreases proportionally, and thus, it becomes more susceptible to distortion at the post-narrow links. In other words, when $L$ is small, the formation of PNCMs becomes more likely and the CM becomes weaker as shown in Figure 3.

![Figure 3. Small versus large packet size in packet pair probing.](image)

Given the previous trade-off in the selection of the packet size, a value of $L$ somewhere in the middle of the range is preferred. The empirical conclusion from Internet experiments is that a packet size around 800 bytes leads to the stronger CM in heavily loaded paths.
6. A Capacity Estimation Methodology

In this chapter we discuss a methodology based on the insight developed so far and has been implemented in a tool called pathrate. It is a two end-point methodology and is divided in two phases.

Phase I: Packet pair probing. In this phase a large number of packet pair experiments is used to ‘uncover’ all the local modes of the bandwidth distribution $B$, expecting that one of them is the CM. From the resulting distribution of bandwidth measurements $B$, we obtain all the local modes and the sequence of local modes, in increasing order, is denoted as $M = \{m_1, m_2, ..., m_M\}$. If the distribution $B$ is unimodal, which happens in very lightly loaded paths, the measurement process terminates and the capacity estimate is the unique mode.

Phase II: Packet train probing. In this phase the Asymptotic Dispersion Rate $R$ is found and a heuristic rule is used to estimate the capacity mode. The heuristic is based on the following reasoning. First, when $N$ is sufficiently large for $B(N)$ to be unimodal, almost all packet trains have encountered dispersion due to cross traffic. Second, because $N$ is the minimum packet train length that generates a unimodal $B(N)$, the range of the unique mode is still sufficiently wide to cover all the local modes in the SCDR of $B$ between $R$ and the capacity estimate $C$.

In order to evaluate the accuracy of the presented heuristic, we simulated the pathrate methodology in a number of different path and traffic configurations, comparing the actual capacity with the capacity estimate. The methodology is quite accurate as long as the path capacity is lower than about 40 Mbps.

For higher path capacities the capacity estimate is lower than the actual capacity, in some cases by almost a factor of two. This mainly occurs in paths with heavy load (more than 80%) in the narrow or pre-narrow links. When the specified bin width is 1 Mbps for lower capacity paths (< 40 Mbps), and 2 Mbps for higher capacity paths (> 40 Mbps), the estimates are more accurate. In other words, the resolution has to be chosen based on a rough estimate of the path’s capacity.
7. Conclusions
In this report we studied the dispersion of packet pairs and packet trains, focusing on the effects of the cross traffic. As an application of this study we described a capacity estimation methodology. The insight gained, though, can probably be also applied to congestion control mechanisms, server selection algorithms, as well as quality of service monitoring.