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Analysis of minimal backlogging-based available bandwidth estimation mechanism

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ABSTRACT

This paper analyzes the minimal backlogging-based available bandwidth estimation mechanism to strengthen the theory behind the mechanism. The *minimal backlogging method* estimates the available bandwidth using the statistic of the probing traffic service rate. We show that the statistic of the probing traffic service rate is a consistent estimator of the available bandwidth for a $G/G/1$ queueing system under minimal backlogging condition to support the minimal backlogging method theoretically. In order to emulate the minimal backlogging method in a real multi-hop network, we detect the minimal backlogging condition or closeness of the probing rate to the available bandwidth based on the busy period length, and change the probing rate adaptively to maintain the minimal backlogging condition. We explain that the minimal backlogging condition or available bandwidth might be detected more accurately by the busy period of probing packets than by the gap response curve or rate response curve, and enhance the minimal backlogging method further by introducing a new initial probing rate estimation mechanism. A reasonable range of available bandwidth for a short time interval can be obtained using the mean and variance of the estimated available bandwidth, since the proposed mechanism can estimate the available bandwidth quickly and track it adaptively. The proposed mechanism is implemented in a Linux environment. The performance of our scheme is compared to those of conventional available bandwidth estimation mechanisms through experiments on a test-bed with single-hop or multiple-hop topologies.

1. Introduction

The reliable estimation of *available bandwidth* for a network path is crucial for high utilization of network resources, as well as QoS guarantee for real-time flows. If the available bandwidth (AB) for a specific network path is known to a traffic source node, the source node might avoid congested paths [1] or the information about AB can be used for capacity provisioning, network troubleshooting, traffic engineering (TE), admission control, and end-to-end QoS provisioning [2–5]. Thus, reliable AB monitoring is crucial to exploit network resource efficiently.

For a network path $\mathcal{P}$ between a node pair consisting of H serially connected links, AB C_a for the path is usually defined as

$$C_a = \min_{1 \leqslant i \leqslant H} C_i(1 - u_i),$$

where C_i and u_i are the link rate and the utilization of the ith link, respectively. The link with the least unused bandwidth of C_a is referred to as the *tight link*. The link with the minimum link rate is referred to as the *narrow link*.

Many schemes have been proposed to estimate the end-to-end available bandwidth [6–13]. The underlying principles of most of these methods can be classified into two categories: probe gap model (PGM) and probe rate model (PRM). In the probe gap model, a probe packet pair is usually sent to the destination node. When Δ_{in} and Δ_{out} are the inter-packet gaps just before and at the tight link, respectively, if we know the link rate of the tight link C, then the rate of cross-traffic is $C(\Delta_{out} - \Delta_{in})/\Delta_{in}$, and the available bandwidth is

$$C_a = C\left(1 - \frac{\Delta_{out} - \Delta_{in}}{\Delta_{in}}\right). \tag{1}$$

Spruce [12], Delphi [7], and IGI [11] are based on this PGM. However, this result is justified only under the fluid cross-traffic model [14,15].

Melander et al. [8] investigated the relationship between the input probing rate (r_I) and the output probing rate (r_O) of a single node and showed the following relationship under the First-In First-Out (FIFO) fluid model:

$$r_O = \begin{cases} r_I, & r_I < C - \lambda, \\ C\frac{r_I}{r_I+\lambda}, & r_I \geqslant C - \lambda, \end{cases} \tag{2}$$

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where C and λ are the link rate and the cross-traffic rate, respectively. On the multiple hop path, the relationship between r_I and r_O is maintained if r_I is less than the second smallest available bandwidth on the path under the same fluid model. Thus, if we find the value of r_I above which the ratio of r_I/r_O is greater than 1, that value of r_I corresponds to the available bandwidth by the model of (2). This available bandwidth detection principle is called PRM, and TOPP [8], PTR [11], pathload [9], and pathchirp [10] are based on this idea. TOPP and PTR search the point where the value of r_I/r_O diverges from 1 using the concept of linear search. Pathload finds the range of the available bandwidth using the binary search concept. Although other PRM methods use packet pairs or equally spaced packet trains, pathchirp uses packet trains with exponentially decreasing inter-packet spacing and calculates the available bandwidth based on the queueing pattern of the arriving packets. Liebeherr et al. [16] analyzed pathload and pathchirp by interpreting available bandwidth estimation as a problem in min-plus linear systems under the idealized fluid-flow traffic assumption.

Thus, most existing methods are based on either PGM or PRM. In this paper, we investigate a different available bandwidth estimation methodology, termed the minimal backlogging method. We proposed the minimal backlogging method to estimate the end-to-end available bandwidth in [13]. The mechanism of [13] estimates the available bandwidth using the statistic of the probing traffic service rate when the probing packets are sent according to the minimal backlogging method. However, the convergence of the statistic was not proved in [13]. Thus, to strengthen the theory for the minimal backlogging method, we show that the statistic of probing traffic service rate is a consistent estimator of the available bandwidth for a $G/G/1$ queueing system under the minimal backlogging condition. Another issue related to the original version of the minimal backlogging method is the convergence time might be increased if the gap between the initial probing rate and the available bandwidth is large. We propose a new initial probing rate estimation scheme to reduce the gap between the initial probing rate and the available bandwidth. The enhanced version of the minimal backlogging method is implemented in a Linux environment and compared to conventional available bandwidth estimation tools. We also investigate the advantage of busy period length-based minimal backlogging condition detection over available bandwidth detection based on the gap or rate response curve used in PGM or PRM. Thus, the contributions of this paper can be summarized as follows:

- We show that the statistic of the probing traffic service rate under minimal-backlogging condition is a consistent estimator of the available bandwidth for a $G/G/1$ queueing system.
- We show that the minimal backlogging condition can be checked based on the busy period length through analysis and simulation.
- We show that the minimal backlogging-based available bandwidth estimation mechanism has higher accuracy than conventional available bandwidth mechanisms, especially when the cross traffic load changes dynamically on a multi-hop path due to the busy period length-based minimal backlogging condition detection and a new initial probing rate estimation scheme.

The remainder of this paper is organized as follows. We first discuss related work in Section 2. In Section 3, we explain the minimal backlogging method and the statistic, probing traffic service rate, used to estimate the available bandwidth of a queueing system. We show that the above statistic is a consistent estimator of the available bandwidth for a $G/G/1$ queueing system under the condition that the probing packets are sent by the minimal backlogging method. In Section 4, we explain how the minimal backlogging method is adapted in a realistic environment and the advantage of detecting the minimal backlogging condition based on busy period length is described. In Section 5, we introduce a simplified path model for multiple hop paths. The approach for a single server is extended to multiple hop paths using the simplified path model, and we also propose a new initial probing rate estimation scheme. In Section 6, the performance of the proposed available bandwidth estimation mechanism is evaluated by experiments on a test-bed with a single-hop or multiple-hop network topology. Finally, conclusions are presented in Section 7.

2. Related work

C-probe [6] was the first attempt to measure available bandwidth. C-probe estimates the available bandwidth from the dispersion of trains of eight packets. A similar approach was taken in *pipechar* [17]. They assumed that the dispersion of long packet trains is inversely proportional to the available bandwidth. However, Dovrolis et al. [18] showed that this is not true. The dispersion of long packet trains does not measure the available bandwidth in a path, but measures a different throughput metric that is referred to as *Asymptotic Dispersion Rate* (ADR).

Most existing available bandwidth mechanisms are based on PGM or PRM explained through Eqs. (1) and (2). However, Eqs. (1) and (2) are justified when the cross traffic is modeled as a fluid. Thus, they may not be accurate for the real packet-version cross traffic. Liu et al. investigated the validity of the fluid assumption under a single-hop environment [14,15] and a multiple-hop environment [19,20]. They investigate the effect of non-fluidness of cross traffic through gap response curve and rate response curve, and show that the discrepancy in the gap/rate response curve due to non-fluidness can be overcome by long packet trains for PRM in case of single-hop probing. For the multi-hop probing case, they compare three curves: simplified version of single-hop fluid response curve $\mathcal{S}$, fluid response curve $\mathcal{F}$ with no single-hop simplification, and packet-version response curve $\mathcal{Z}$. They show that the real response curve $\mathcal{Z}$ and the curve $\mathcal{S}$ obtained under single-hop simplification and fluid assumption for cross-traffic can converge, especially when r_I is not higher than the second smallest available bandwidth on the path if the packet train length can be increased sufficiently.

However, even for a single hop case the probing bias exists when the probing train length is limited, and this probing bias usually degrades the accuracy of the available bandwidth estimation mechanisms that are based on the gap or rate response curve. The proposed scheme attempts to improve the estimation accuracy by detecting the available bandwidth based on a new metric, busy period length, while avoiding the use of the gap/rate response curve.

3. Estimation of available bandwidth for a single server

Before considering the AB estimation problem for multiple hop routes, we introduce some concepts and theory for a single server. We consider a queueing system with a First-Come-First-Served (FCFS) service policy. Fig. 1 shows a queueing system of interest. The service rate is C (bits per second), and the arrival rate of packets, except probing packets, is λ (packets per second). Suppose that the service time of a packet is given by the packet size divided by the service rate C of the system. Let L' denote the average length of the packets, except probing packets. Then, for the queueing system, available bandwidth C_a is defined as

$$C_a = C(1-\rho),$$

where $\rho = \lambda L'/C$ is the traffic load to the system. If the parameters C, λ and L' representing a queueing system are unknown, this system