Estimation of Statistical Bandwidth through Backlog Measurement

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Abstract. Bandwidth estimation in wireless networks is difficult due to the intrinsic randomness of the wireless links. In this paper, we propose a network calculus based method for statistical bandwidth estimation in wireless networks with random service, where the bandwidth is expressed in terms of a statistical service curve with a violation probability. By injecting probing packet trains, the statistical bandwidth can be estimated through the measurement of backlogs in the system.

1 Introduction

Network calculus is a theory for service guarantee analysis of computer and communication networks. Recently, it has been developed for estimating available bandwidth based on traffic measurements [1] [2]. In [1], Liebeherr et. al proposed a systematic approach for available service estimation of time-invariant systems through the measurement of deterministic backlog. In [2], the authors extended the method to networks with random traffic load or link capacities. The bandwidth is estimated through the measurement of time stamps of probing packet trains.

In this paper, we extended the work in [1] [2] and developed a network calculus based method for bandwidth estimation of system with random service, where the bandwidth is estimated through the measurement of statistical backlog based on probing packet trains. The bandwidth is expressed by statistical service curves that are allowed to violate a service guarantee with a certain probability [3]. Our method is exempt from the same timing reference for the nodes in the network compared with the time stamp based estimation methods.

2 Statistical Bandwidth Estimation

Consider a system with the arrival process, service process, and departure process denoted by $R(t)$, $S(t)$, and $D(t)$ respectively. Let $\tilde{S}(t)$ represent the statistical service curve which is defined as follows:

Definition: Statistical service curve Consider a non-decreasing function $\tilde{S}(t)$. It is a statistical service curve of the system if the following equality holds [3],

$$Pr\left\{D(t) \geq R \otimes \tilde{S}(t)\right\} > 1 - \xi \tag{1}$$

where$R \otimes \tilde{S}(t) = \inf_\tau \left[R(\tau) + \tilde{S}(t-\tau)\right]$ denotes the min-plus convolution. And ξ denotes the violation probability, which satisfies $0 < \xi < 1$.

The objective of bandwidth estimation is to derive the statistical service curve $\tilde{S}(t)$ from $B(t)$, $R(t)$ and $D(t)$, where $R(t)$ is the arrival process, $B(t)$ and $D(t)$ are backlog and output, respectively. We adopt the *rate scanning* probe scheme proposed in [1], where the packet trains are transmitted with increasing rates. The arrival process can be expressed as $R(t) = rt$, where r is the transmission rate.

Since it is very difficult to derive the exact service process $S(t)$, we try to estimate the statistical service curve $\tilde{S}(t)$. Their relations is defined by the following lemma. The proof of this lemma can be found in [2].

Lemma: Consider a system with service process $S(t)$. Any $\tilde{S}(t)$ that satisfies,

$$Pr\left\{S(t) \geq \tilde{S}(t)\right\} > 1 - \xi \tag{2}$$

for $t \geq 0$, is a statistical service curve of the system.

The input of the system consists of constant rate packet trains, so the arrival process can be expressed by $R(t) = rt$, where r is the arrival rate of the probing trains. We define the *statistical steady-state backlog* $B^\epsilon(r)$ as ,

$$Pr\left\{B(r) \leq B^\epsilon(r)\right\} > 1 - \epsilon \tag{3}$$

where $B(r)$ denotes the steady-state backlog when the probing rate is r. In practice, the statistical backlog bound can be obtained based on the percentiles.

We formalize the process of deriving statistic service curve through the measurement of backlog by the following theorem.

Theorem: Consider a system with probing packet trains constrained by the arrival curve $R(t) = rt$. Based on the measurement of the statistical steady-state backlog $B^\epsilon(r)$, the statistical service curve of the system can be derived by,

$$\tilde{S}(t) = \sup_r \left\{rt - B^\epsilon(r)\right\} \tag{4}$$

where the violation probability of the statistical service curve is $\xi = \sum_r \epsilon$.

The detailed proof of this theorem can be found in [6]. The theorem relates the statistical backlog bound with the statistical service curve based on the Legendre transform. It is able to estimate service curve for random wireless channels using probe packet trains transmitted at different rates. To estimate the bandwidth, tens or hundreds of different probe rates may be applied for the estimation. However, in the calculation of $\sum_r \epsilon$, we only need to consider the probe rates that contribute to the derivation of $\tilde{S}(t)$.

3 Results and Conclusions

Simulations are conducted to validate the proposed estimation method. The system consists of one sender and one receiver. Packet trains are periodically injected to the buffers of the sender. A packet train contains 1000 packets, and the arrival interval between two adjacent packets is 10 ms. The link between the sender and receiver is time-variant with capacity uniformly randomly varying in the range $(20\ kbps, 200\ kbps)$. Assume the link status does not change during the transmission of a packet. The length of a packet changes from 300 bit to 3000 bit with an increment of 50 bit in each step. Hence, the corresponding probing data rate varies from 30 $kbps$ to 300 $kbps$ with an increment of 5 $kbps$. For each probing rate, the simulation runs 1000 times. The values of backlog are recorded every millisecond until the last packet has been sent.

In simulations, the statistical service curve and backlog can be obtained from their percentiles. Fig. 1 shows the percentiles of link capacity and their corresponding statistical service curves. The deterministic service curve is the upper bound of the service curve we generated in the simulation. The left part of Fig. 2 shows the statistical results of the measured backlogs with varying probing rates. From these backlog values, the statistical service curve can be derived according to the theorem. In the right part of Fig. 2, we compare the statistical service curve estimated by our method with the actual statistical service curve. As we can see, when the violation probability is smaller, the difference between these two is smaller. It means that our method can accurately estimate the service capacity with a small violation probability. In our future work, we will study which parameters impact the estimation accuracy.

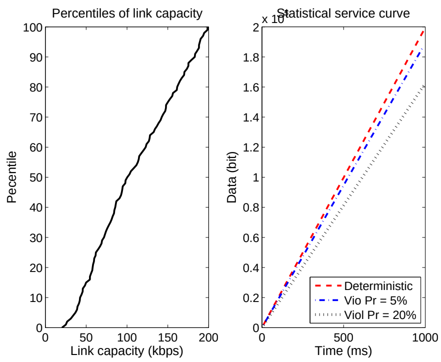

Fig. 1. Left: Percentiles of random link capacity ; Right: the statistical service curve of the random link.

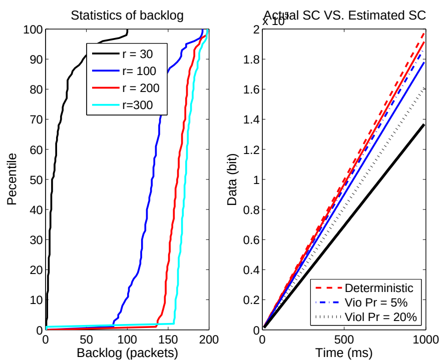

Fig. 2. Left: Statistical backlog measurements; Right: Comparison between the reference service curve and the estimated service curve (The solid line denotes the estimated service curve and the dashed line denotes the reference service curve).

In this paper, we proposed a network calculus based method of statistical bandwidth estimation for networks with random service. The statistical bandwidth is estimated from the measurement of statistical steady-state backlog with probing packet trains. Our method does not rely on the same timing reference for the sender and receiver.

References

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