Computer Communications 47 (2014) 34–50

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Estimation of available bandwidth share by tracking unknown cross-traffic with adaptive extended Kalman filter

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ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 5 April 2014
Accepted 12 April 2014
Available online 21 April 2014

Keywords:
Available bandwidth share estimation
Adaptive extended Kalman filter
Unknown inputs
Congestion
Network policy

ABSTRACT

We propose a nonlinear network model to estimate the available bandwidth share of a source by tracking the unknown cross-traffic. Especially sudden changes in cross-traffic behavior are challenging to adapt since measurement or process models of the existing algorithms generally do not include the cross-traffic in the model. As a novel approach, combined cross-traffic behavior, generally considered as additive noise, is modeled as an unknown source enabling tracking of both the cross-traffic and network behavior. Adaptive Extended Kalman Filter with Unknown Inputs (EKF-UI) is used for the estimation of available bandwidth share. This approach works recursively and is suitable for real-time applications. Moreover, the measurements are based on passive monitoring. Hence, no probe traffic is induced to the network. It is also shown with multiple simulations that this model is robust against variable network conditions.
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1. Introduction

It is desirable to use the resources as efficiently as possible for both the benefit of network and source. Multimedia applications are an important part of total network traffic. In the case of congestion, overuse of unresponsive UDP traffic for multimedia transmission may cause unexpected traffic load for which responsive TCP flows may suffer in terms of bandwidth share. On the network side, there have been studies such as Choke [1] to penalize especially unresponsive flows rather than treating them equally as in RED [2]. On the source site, rate-distortion (RD) algorithms try to allocate sufficient amount of bits for digitized media for best rate-distortion performance. Hence, real-time compression, transmission or congestion control strategies need accurate available bandwidth share estimation for better performance. It is desirable to obtain a robust estimate for various network conditions. Fast adaptation and stability is especially important for many areas of networking, including but not limited to adaptive rate adjusting algorithms, routing protocols, flow controls, forward error correction (FEC), and RD algorithms. Some nodes in the network may differentiate services based on priority levels, service provider agreements, flow types or networking policy. With this kind of a structure and under varying cross-traffic characteristics, network conditions may change both in long-term and short-term durations. It is challenging to determine network's end-to-end behavior or cross-traffic load in each node during the transmission. Therefore, many researchers have worked on the estimation of bandwidth share without the exact knowledge of other traffic sources and their behavior. It is important, at this point, to properly define the *available bandwidth share* before going any further.

1.1. Available bandwidth share

Bottleneck bandwidth generally remains unchanged unless something unexpected, such as a broken link, occurs in the network. We assume for the rest of this study the bottleneck bandwidth is known and constant. Under this assumption, we combine two separate concepts in this definition: *The available bandwidth* and *the bandwidth share*. Available bandwidth is defined as the remaining bandwidth after all existing traffic gets its bandwidth share when there is no congestion. On the other hand, bandwidth share is defined as the fair share that can be allocated to the source. This definition gets meaningful when there is congestion. If network is not congested, that is, if there is unused bandwidth, then the bandwidth share of a source is same as the available bandwidth. Based on these, we define the *available bandwidth share* for a source as "unused (available) bandwidth if network is not congested, and the fair network share of the source if network is congested". We use the word *fair* loosely in this definition due to the fact that network policies may not always be designed based on the best-effort service where the fair share is allocated. Based

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http://dx.doi.org/10.1016/j.comcom.2014.04.008
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on this definition, Eq. (1) represents the available bandwidth share estimation of a user.

$$Available\ bandwidth\ share = \begin{cases} b\frac{r}{r+c}, & \text{if congested} \\ b-c, & \text{if no congestion} \end{cases} \quad (1)$$

where b, r, and c are the bottleneck bandwidth, the user's traffic rate and cross-traffic rate, respectively. Our definition for *available bandwidth share* is actually the same as the definition of available bandwidth of [3] for congestion free situation. However, bandwidth share estimation is also included in the definition for congested case as an important contribution. Hence, appropriate definition is provided.

2. Related work

Studies in this area are mainly focused on estimating either the available bandwidth or the fair bandwidth share. Mainly two techniques are used for available bandwidth estimation: active probing and passive monitoring.

Active probing techniques send properly sized packets into a network and measure the variations in the serving times for these packets. They give an estimation of bandwidth share after evaluating the measurements. Various active probing techniques such as variable packet size probing (VPS), packet pair/train dispersion probing, self-loading periodic streams, trains of packet pairs have been proposed to make an estimation by analyzing different features of the network [4]. Among these VPS aims to measure the capacity of each hop along a path by forcing probing packets to expire at a particular hop [5]. Packet pair/train dispersion probing is used to measure the end-to-end capacity of a path by using the dispersion of two equal-sized or train of probing packets sent back to back [6]. Self-Loading Periodic Streams (SLoPS) measures end-to-end available bandwidth by transmitting a periodic packet stream and measuring variations in one way delay [7]. Trains of packet pairs is another measurement methodology. It sends consecutive packet pairs with exponentially decreasing spacing to estimate the available bandwidth of a network path more efficiently [8]. The authors of [9] also use active probing for available bandwidth estimation with the use of modeling through a G/G/1 queue. One issue with all these methods is that the network is assumed to be stationary during the measurements. Actually, the network is highly dynamic and requires a dynamic model. Authors of [10] indicates that none of the earlier active probing bandwidth estimation studies have been found to be applicable to real network environments due to highly variable statistical nature of network traffic and they provide a stochastic approach to this problem. However, the other issue is that active probing creates additional traffic and causes congestion for measurements since it requires injection of certain amount of packets to the network. Finally, these methods are designed for providing only the available bandwidth but not the bandwidth share.

Passive monitoring techniques, on the other hand, capture the activity in the network and determine the share of an active user rather than the available bandwidth based on the long term observations. But it is essential to capture the short term behaviors with dynamic models as well. Hence, end-to-end delay and loss estimation of networks have been studied in [11,12]. In [12] it is stated that end-to-end delay dependency of packets in each train tends to get bigger if congestion level increases, and a time series analysis is provided for estimating the delay. However, if behavior of cross-traffic is not stationary, it is difficult to appropriately model the network with fixed-parameter time series models. In order to solve this issue, adaptive bandwidth estimation in TCP Westwood [13] proposes a bandwidth estimation method which adapts to network condition by tuning the filter and sampling parameters. In [13] the estimation algorithm is primarily based on exponentially weighted moving average with nicely placed tuning parameters.

Network conditions may show considerable variations especially when there are rapid changes in the cross-traffic. These variations become very important for many applications such as congestion control, adaptive rate or adaptive routing algorithms since they need to follow rapidly varying network conditions, and adapt their transmission rates or routes accordingly. It is also essential not to cause contention of resources while performing measurement tasks. While passive monitoring techniques cause using only extra computational power, active probing techniques use an additional bandwidth which may affect the original communication performance of the network. The authors of [14] proposed task scheduling for efficient use of resources. Once information about bandwidth is obtained then this information can be used for various purposes. For example, in [15] the researchers use the available bandwidth estimation for determining the routing. Some applications may have certain requirements for quality of service (QoS). It is essential to know the behavior of the network for these types of algorithms in order to dynamically arrange their rates, coding schemes and/or traffic behavior. The work in [13] actually provides a congestion preventive tool for these dynamic network conditions. The authors in [16] adopts the same idea and propose an available bandwidth estimator based on time sliding window for TCP-Jersey and its variant is introduced as TCP-New Jersey in [17] based on time stamped available bandwidth estimation. These are really effective and fast algorithms. However, these algorithms rely only on the measurements. Many mechanisms such as congestion control [18], QoS based admission control [19], TCP-friendly congestion control for the fair streaming of scalable video [20] based on bandwidth estimation techniques are proposed recently. If a dynamic model can be constructed it might be possible to efficiently capture the dynamic behavior of the network. Based on this idea, an end-to end bandwidth estimation method using Kalman filtering is introduced in [3]. A dynamic model is constructed for the network and non-linarites stemming from switching of the algorithm are handled within Kalman filtering framework. However, this algorithm relies on active probing. Besides, the behavior of unknown cross-traffic is not included in the model. Sudden changes on the cross-traffic have an adverse effect on the algorithm. Since it is unrealistic to model the changes in the network traffic as noise we include the cross-traffic itself as an unknown state in the dynamic model we propose in this study. Tracking this unknown input is challenging. Thankfully, an excellent study is proposed for the application of extended Kalman filter in the presence of unknown inputs named as Extended Kalman Filter with Unknown Inputs (EKF-UI) in [21]. This method has been originated from structural engineering applications and applied to power systems [22].

In network analysis, it is crucial to know the behavior of cross-traffic for better modeling. Models with constant cross-traffic behavior and additive Gaussian noise can provide an optimal estimation, but they may not be applicable to real-life network conditions.

In this study we treat the cross-traffic as an unknown input and use the approach defined in [21]. Hence, we propose available bandwidth share estimation with EKF-UI algorithm.

3. Material and methods

3.1. Proposed algorithm

We propose a network model with nonlinear state equations and utilize EKF-UI framework to estimate the available bandwidth

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