Multi-hop Available Bandwidth Estimation Based on General Link in Wireless Mesh Network[1)]

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Abstract:
Available bandwidth is an important network performance metric, which can benefit a lot of network protocols and applications. Though many works have been done for the bandwidth estimation in wired network, it is still a challenge in wireless networks. In this paper, based on the shared medium nature of wireless networks, the concept of general link is introduced for the analysis and estimation of wireless path capacity and available bandwidth. The proposed method also combines both variable packet size and packet train approach. The simulation results show that the proposed method can estimate the available bandwidth successfully and efficiently.

1 Introduction

Wireless mesh network [1] is a communication network in which all nodes are organized in a mesh topology. Combined both the "wireless" and "ad hoc" technologies, wireless mesh network has gained great advantages of high bandwidth, reliability and scalability. The path capacity and available bandwidth [2] are important metrics for describing the status of a network path. They can benefit a lot of applications, protocols and services providing for making decisions concerning many issues, such as video streaming, load control, admission control, routing protocols and so on. The path capacity is the maximum achievable throughput at IP layer when there is no influence of competing traffic. The end-to-end available bandwidth of a path is the maximum achievable throughput without disrupting the current cross traffic.

The network path capacity and available bandwidth measurement have been received a lot of attentions [3, 4, 5]. Many methods have been proposed for both wired and wireless networks. However, the available bandwidth measurement issue in wireless networks is still a challenge due to the characteristic of wireless networks, such as sharing medium, cross-traffic interference and so on [6, 7]. Generally, there are two categories of estimation methods: (1) Passive mode: This type of methods estimate the bandwidth through using local information (such as channel utilization or history records), without injecting any extra load to the network. (2) Active

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probing: In this scheme, the source sends a pair or a train of probing packets into the network for estimation. Through measuring the changes of packets gap dispersion, the final probing packet rate or the round-trip time delays, the available bandwidth can be estimated.

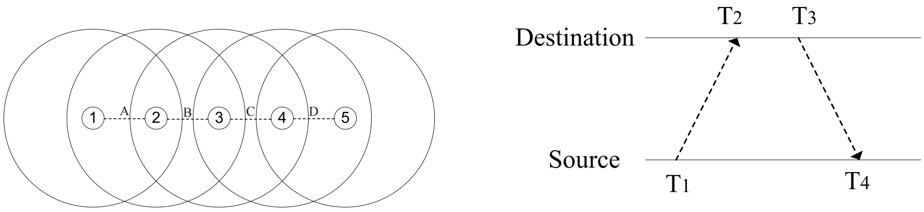
In this paper, we proposed MAB (Multi-hop Available Bandwidth) for estimating the path available bandwidth in wireless mesh networks. According to the shared medium nature of wireless network, we introduce the concept of general link to mitigate the influence of link interference, which makes the analysis of bandwidth for wireless network path much easier.

The organization of the rest of this paper is as follows. Section 2 provides some of the related research work on bandwidth estimation. The details of MAB are described in the Section 3. Section 4 is the evaluation of the proposed method. Finally, Section 5 is the conclusion.

2 Related Work

The variable packet size probing scheme, e.g. Clink [8], is one of the major methods for capacity estimation. The main idea is to measure the round trip time from the source to each hop, try to find the relationship with probing packet size, and usually use linear regression for estimation. In packet pair scheme, e.g. Nettimer [9], the source of the path sends several groups of back-to-back packets to the destination which replies with an acknowledgement. It is based on the fact that the dispersion between the back-to-back packets pairs is determined by the bottleneck link. The packet train scheme usually sends a train of probing packets from the source to the destination. Most of this kind of methods try to find out the turning point of the probing rate at the receiver side. For example, TOPP [10] sends many probing packet trains at a gradually increasing rate from the source to the destination. It assumes that if the probing rate is higher than the path available bandwidth, the measured probing rate at the destination will be lower than the initial offered rate. PathChirp[11] uses packet train with constant packet size, starting with probing rate that is increased exponentially. The basic idea is to induce congestion in the path until the point where a packet suffers from queue delay.

Paper [12] proposed WBest for estimating the capacity and available bandwidth, but it is only for the network path where the last hop is wireless. Paper [6] analyzed the performance of TOPP [10] and SLoPS [13] in terms of accuracy and probing time, and proposed SLOT. Combining the techniques of both TOPP and SLoPS, SLOT needs several iterations during estimation, which increase the load to the network. There also some passive methods for bandwidth estimation in wireless network, such as Admission Adaptive Control (AAC) [14] and Available Bandwidth Estimation (ABE) [7]. These methods mainly monitor the channel status and determine the 'busy' and 'idle' periods, using the channel level utilization for single-hop available bandwidth estimation. However, the sender and receiver may not be synchronized, i.e. their idle periods may not be perfect overlapped.



(a) Wireless Link Interference (b) End-to-End Delay Measurement

Figure 1: Multi-hop Wireless Path Available Bandwidth Estimation

3 Multi-hop Wireless Path Available Bandwidth Estimation

3.1 General Link Definitions

Suppose there are h hops on the path, and the ith link L_i can transmit data with rate C_i. In wired network, the bottleneck capacity is the link with minimum capacity: $C_{path} = \min_{i=1...h} C_i$. The available bandwidth is defined based on link utilization. Let $u_i(0 \leq u_i \leq 1)$ be the utilization of L_i during the time period of $[t, t+\tau]$. So the available bandwidth of link L_i is $A_i = C_i(1-u_i)$. The path available bandwidth is defined as the minimum available bandwidth among all links: $A_{path} = \min_{i=1...h} C_i(1-u_i)$. However, all these definitions for the wired network cannot be directly applied to wireless network due to its particular characteristics. Because of the shared medium characteristic, two wireless links cannot be used simultaneously if they are interfered with each other, i.e. the intended receiver of one of the senders is within the interference range of the other sender.

For simplicity, we assume that the transmission range and the interference range of all nodes are same. To solve the shared medium problem, we introduce the concept of **General Link**. A general link on a wireless network path is a subset of the links that belongs to the path. It contains those links that each link interferes with all the other links belonging to the same general link. There should be no more than one link in the same general link being used for data transmission simultaneously because of the nature of shared medium. In Fig. 1(a), there are five hops on this path in which nodes 1 through nodes 5, connected by links A through D. We suppose that each node can only communicate directly with its first hop neighbors and all the nodes use the same channel for transmission. Let G denote the set of all general links on this path. Totally there are three general links: $G = \{$(link A, link B), (link B, link C), (link C, link D)$\}$. Please note that, a single link may belong to several different general links.

3.2 Wireless Path Capacity Estimation

For each general link, we define the general link capacity. Suppose there are totally h' general links on a path, i.e. $G = (G_1, \ldots, G_{h'})$. And there are g_i wireless links in the ith general link

G_i. Let C_i denote the general capacity of G_i and $C_{i,j}$ denote the link capacity of the jth wireless link in general link G_i on the path. When a packet with size s travels through G_i, it will occupy each link in G_i for one time. So the total time needed for this packet to travel through G_i is $t_i = \sum_{j=1}^{g_i} \frac{s}{C_{i,j}}$. Thus the capacity of the general link G_i is $C_i = \frac{s}{t_i} = \frac{s}{\sum_{j=1}^{g_i} \frac{s}{C_{i,j}}} = \frac{1}{\sum_{j=1}^{g_i} \frac{1}{C_{i,j}}}$. Similar to the definition in wired network, the end-to-end path capacity is defined as the minimum general link capacity among all the general links G on the path:

$$C_{path} = \min_{i=1...h'} C_i = \min_{i=1...h'} \frac{1}{\sum_{j=1}^{g_i} \frac{1}{C_{i,j}}} \tag{1}$$

It is obvious that the definition in wired network is a special case of the definition in Equation (1), where $g_i = 1(i = 1, \ldots, h')$ for all general links. Consider the situation when cross traffic and probing traffic arrive at G_i at the same time. Let f_i denote the cross traffic rate and p_i the probing traffic rate, where $f_i < C_i$, $p_i < C_i$ and $f_i + p_i > C_i$. They share the same bandwidth of the general link G_i and will contend the general link equally. Similar to the link share principle [10], we define the **General Link Share Principle** based on general link:

$$p_{i+1} = \frac{p_i}{f_i + p_i} C_i \tag{2}$$

3.3 End-to-end Available Bandwidth Estimation

The fundamental idea of MAB is: the source node sends a train of probing packets with different packet size to the destination at rate p which is higher than the available bandwidth. The destination responses by replying an acknowledgement to the source for each of the receiving probing packet. Then the source can use the probing packets' round trip delay to estimate the end-to-end path available bandwidth.

In order to avoid the interference caused by the probing traffic itself, the destination shouldn't response immediately when the probing packets are received. It should wait until all the probing packets are received before replying them back. Thus, four time values will be recorded for each probing packets, as described in Fig. 1(b). So the measured end-to-end delay will be $d = \frac{(T_4 - T_1) - (T_3 - T_2)}{2}$. Please note that, the source and destination don't need to be synchronized.

According to the general link share principle, the general link utilization of G_i is defined as the ratio of the cross traffic rate before entering that general link to the general link capacity:

$$u_i = \begin{cases} f_i / C_i, & f_i \leq C_i \\ 1, & f_i > C_i \end{cases} \tag{3}$$

The available bandwidth of G_i is defined as $A_i = C_i(1 - u_i)$. The available bandwidth of a path is defined as the minimum available bandwidth among all the general links on the path:

$$A_{path} = \min_{i=1...h'} A_i = \min_{i=1...h'} C_i(1 - u_i) \tag{4}$$

Let the probing rate at the sender be p_1. When a probing packet travels through the general links, because of the effect of interference and cross traffic, the probing rate will be changed and p_i is considered to be different at each general link G_i. Let $x_i = f_i/p_i$, so x_i is non-negative. The end-to-end delay of the probing packet is:

$$d \approx \sum_{i=1}^{h'} (\frac{s}{p_i/(p_i + f_i)C_i} + v_i) = \sum_{i=1}^{h'} ((1 + \frac{f_i}{p_i})\frac{s}{C_i} + v_i) = \sum_{i=1}^{h'} ((1 + x_i)\frac{s}{C_i} + v_i) \quad (5)$$

where v_i is the processing delay on G_i. Suppose there are k probing packets in the probing train. So k end-to-end delays will be measured. The least square optimization method can be used to determine x_i. In order to derive all the value of x_i, k should not be too small. It is recommended that $k > h'$ to ensure that there is enough end-to-end delay samples for the bandwidth estimation. Let D_j be the delay of the jth probing packet with packet size s_j. Thus, $D_j = \sum_{i=1}^{h'} [(1 + x_i)\frac{s_j}{C_i} + v_i]$. Let d_j be the measured delay of the jth probing packet. So for this linear squares optimization problem, our objective is to achieve:

$$\min_x f(x_1, \ldots, x_{h'}) = \sum_{j=1}^{k} \{D_j - d_j\}^2 = \sum_{j=1}^{k} \{\sum_{i=1}^{h'} [(1 + x_i)\frac{s_j}{C_i}] - d_j\}^2 \quad (6)$$

where $x = [x_1, \ldots, x_{h'}]^T = [f_1/p_1, \ldots, f_{h'}/p_{h'}]^T$ and $x_i \geq 0, i = 1, \ldots, h'$.

Theorem 1. *If $k > h'$ probing packets are sent to the destination from the source, s_j is the size of the jth probing packet and q_i^j is the cross traffic load at general link G_i when s_j arrives. There is a solution for the optimization (6) and the solution is:* $x_i = \frac{\sum_{j=1}^{k} s_j q_i^j}{\sum_{j=1}^{k} s_j^2}$

The detailed proof is not presented here due to the limit of space. Since p_1 is already known, and the input rate on G_{i+1} is equal to the output rate of G_i. Once we calculate $x = [x_1, \ldots, x_{h'}]^T$, all the general link utilization can be got through iteration (7):

$$f_i = x_i \cdot p_i, \; p_{i+1} = \frac{p_i}{p_i + f_i} C_i, \; u_i = f_i/C_i, i = 1, \; \ldots, h' \quad (7)$$

After all the general link utilization are calculated, the available bandwidth of the path can be calculated according to the definition in Equation (4).

4 Evaluation

4.1 Experimental Model

In this section, we evaluate the performance of MAB in ns-2.34. The network involves up to 20 wireless nodes deployed randomly within a 2-dimensional network area of 2000 m×1500 m. For simplicity of evaluation and analysis, we choose a path with 6 nodes and 5 links in the network, where each link can only interfere with its adjacent links, as shown in Fig. 2.

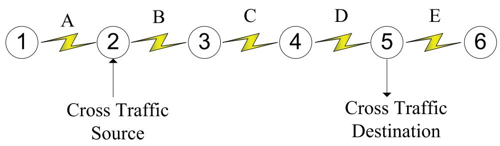


Figure 2: The Selected Path in the Simulation Topology

Table 1: Measured Wireless Link Capacity on the Selected Path

Links	A	B	C	D	E
Capacity (Mbps)	6.0439	6.2036	6.0872	6.1357	6.1886

All the other nodes are deployed randomly in the network area. To simulate the influence of background traffic, there are also some constant data traffic among these nodes. Some of these nodes are transmitting or forwarding data packets, some of them are idle. All these 20 nodes are static, so the network topology remains the same throughout the simulation, thus the interference and capacity of the selected path. We use 802.11 MAC protocol with the RTS/CTS mechanism being shut off to achieve higher throughput. The MAC layer data rates of all the nodes are set to 11Mbps. The simulation is running for 150 seconds. The cross traffic is generated between node 2 and node 5. It starts at 50s with the sending rate increasing from 1.5Mbps to 3Mbps until 100s. Then the rate of the cross traffic remains 3Mbps for 10 seconds until 110s when it is shut down. The initial rate of 1.5Mbps can be viewed as a burst cross traffic data to evaluate the performance of proposed method. For MAB, we choose $k = 6$. The probing packet size is varied from 1000 to 1460 bytes. We also simulated pathChirp [11] under the same scenario for comparison, and its default configuration is used during the simulation.

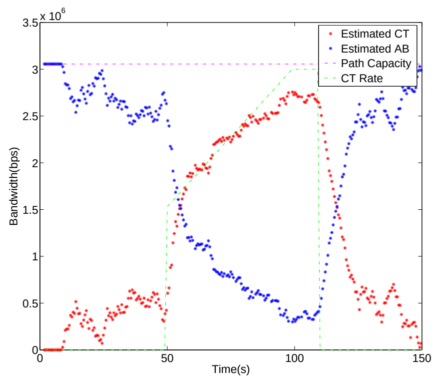
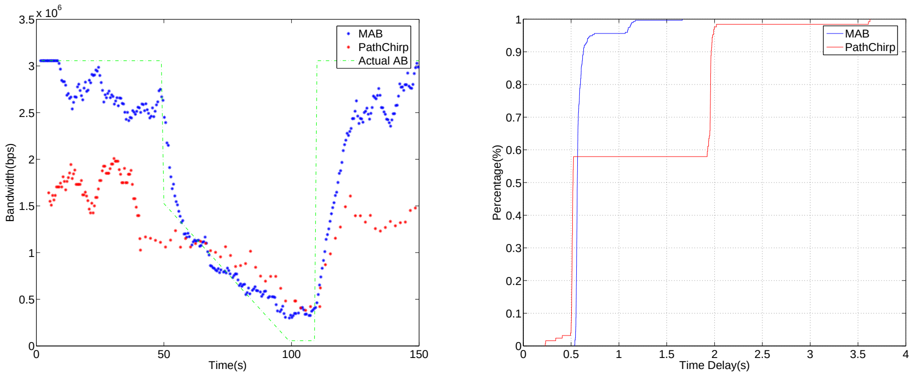


Figure 3: The Performance of MAB

4.2 Simulation Results and Analysis

The capacity of all the links on the selected path are calculated based on 100s running of transmitting probing packets from the source to the destination when there is no cross traffic on the selected path. The averaged results are shown in Table 1. Fig. 3 shows the estimated results of MAB. The capacity of the path is calculated through the measured link capacity in



(a) Estimation of Available Bandwidth (b) CDF of Estimation Time

Figure 4: Performance Comparison of MAB and pathChirp

Table 1 according to Equation (1). The data rate of Cross Traffic (CT) is the sending rate of data packets at node 2. Fig. 3 also shows both the estimated rate of Cross Traffic and Available Bandwidth (AB) by MAB. From the result we can see that MAB can estimate the available bandwidth most of the time, especially when there is cross traffic. We also notice that its performance degrades when there are no cross traffic on the path. At 110s, when the rate cross traffic drops from 3Mbps to 0Mbps, MAB shows a latency before the estimated result converged. This is because MAB uses smoothed delay for estimation, which needs some time to converge when the raw delay sample drops down suddenly from a very high value.

Fig. 4(a) shows the performance comparison of pathChirp and MAB. We have the same observation that when there is no cross traffic, pathChirp underestimates the available bandwidth. And MAB can estimate the available better than pathChirp. This is mainly because that the pathChirp doesn't consider the interference among the adjacent wireless links, while MAB estimate the bandwidth based on the general link and varied probing packet size. Fig. 4(b) shows the CDF of the estimation time, i.e. the period spent between two consecutive estimated results for both MAB and pathChirp. The estimation time is greatly dependent on the time taken for each probing train. The result shows that up to 95% of the probing trains of MAB are finished in 1 second, compared to 40% of the time is nearly 2 seconds for pathChirp.

5 Conclusion

The capacity and available bandwidth estimation in wired network has been deeply studied. However, their estimation in wireless mesh network is still a challenge due to the characteristics of wireless network, such as shared medium. In this paper, we introduce the concept of general link according to the interference in wireless network, which makes the analysis of bandwidth for wireless network path much easier. The probing procedure combines schemes of both varied packet size and packet train. The simulation results show that the proposed method can estimate the bandwidth with the presence of cross traffic. The evaluation of the proposed method in the real wireless mesh network will be our future work.

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