MultiLink-QuickAbw: A Multi-Congestion-Links-Oriented Fast Available Bandwidth Measurement Method

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ABSTRACT

In this research, we have implemented a fast available bandwidth measurement method for Multi-Congestion-Links in path, which is based on our previous method QuickAbw. QuickAbw is a fast available bandwidth measurement method which calculates the available bandwidth based on the link delay changes caused by probe packets. QuickAbw has the advantages of fast measurement speed and low intrusion, however it is not suitable for situations where there are multiple congested links in network path. In this study, we analyzed the link delay changes when there are multiple congested links in network path, based on the analysis of multi-link model, a universal improvement was made to QuickAbw, enabling it to measure the number of congested links and available bandwidth in the multi-links path.

CCS CONCEPTS

• **Computing methodologies** → Modeling and simulation; Model development and analysis.

KEYWORDS

Fast available bandwidth, measurement

ACM Reference Format:

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1 INTRODUCTION

Available bandwidth is a key indicator for measuring network service quality. Applications that rely on network service quality, such as streaming media and VOIP, use the available link bandwidth to adjust the audio and video stream bit rate to bring better user experience. In addition to the measurement accuracy of the available

bandwidth, these applications also have high requirements for measurement speed. Faster measurement speed brings faster functional response. In addition, reducing the intrusion of the user network during the measurement process also has important practical significance, such as Reduce the user's mobile data consumption.

In our previous work, we implemented QuickAbw[1], a fast available bandwidth measurement method for a single bottleneck link. This method makes measurements by sending only a small number of packets, which uses the relationship between the delay growth rate of the packets and the sending rate to calculate the bottleneck link bandwidth, however, this method does not support the measurement of the available bandwidth of multiple bottleneck links. In a complex network environment, there are multiple bottleneck links the path at the same time. For example, when two mobile users use VOIP in P2P mode, each user to the mobile base station is a bottleneck link. Based on the analysis of this study, measurement result of Quickabw in this case would be higher than the actual value.

In this study, a model of multiple bottleneck links was established. We proposed a method for identifying the number of congested links based on the model, and further proposed MultiLink-QuickAbw, a fast available bandwidth measurement method for Multi-Congestion-Links in the path.

The contents of this study are as follows: In section II we propose MultiLink-QuickAbw, a fast available bandwidth measurement method suitable for Multi-Congestion-Link in network path. In section III we verify our method through experiment, and analyze the factors leading to measurement error. The fourth section is related work, introducing the research progress of available bandwidth measurement.

2 IMPLEMENTATION OF MULTILINK-QUICKABW

In this section, we first introduced the relevant definitions and QuickAbw formula of our previous work. Then through mathematical modeling, it is concluded that if QuickAbw is directly used for multi-tight link measurement, the result will be higher than the actual available bandwidth value. In section B, we propose an algorithm to identify the number of tight links, and based on this algorithm, iterative-based MultiLink-QuickAbw is proposed. When MultiLink-QuickAbw finds that there are multiple tight links in the link, it reduces the sending rate in an iterative manner until the available bandwidth can be directly calculated using the QuickAbw formula.

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2.1 Definitions

Path $P_{a,b}$ connecting node a and node b is composed of multiple links $L_1, L_2, \dots, L_n$. Our purpose is to measure the path-available bandwidth between node a and node b. Node a is called the starting point of path $P_{a,b}$ and node b is called the endpoint. The link bandwidth is the highest data transmission rates the link can achieve which is expressed as C_i . The bottleneck bandwidth is the smallest-link bandwidth of the path which represents the maximum transmission rate of the path $P_{a,b}$. The bottleneck bandwidth is constant, unaffected by the traffic in the link, and it can be expressed as $C_{a,b} = \min(C_i), (i = 0, 1, \dots, n)$. The background traffic is expressed as s^m . The probing traffic is formed by actively sending probing packet sequence to obtain the available bandwidth and the bottleneck bandwidth, which is expressed as s^R . We assume the rate of the probing traffic in the starting point is expressed as R_0 . The receiving rate of the probing traffic in the link L_i is expressed as R_{s_i} and the sending rate is expressed as R_{r_i} . The sending rate of the link background traffic is expressed as M_{s_i} and the receiving rate is expressed as $M_{r_i} (i = 0, 1, \dots, n)$.

The link-available bandwidth is the remaining bandwidth in the link except for the background traffic, is expressed as A_i . The path-available bandwidth, the smallest available bandwidth among all links in the path, is expressed as $A_{a,b} = \min(A_i), (i = 0, 1, \dots, n)$. The tight link is the link with the smallest available bandwidth. We define that the sending rate of the total traffic in the link is Q_{s_i} and the receiving rate is Q_{r_i} . We also know that $Q_{s_i} = M_{s_i} + R_{s_i}$, $Q_{r_i} = M_{r_i} + R_{r_i}$. We assume that the nodes at both ends of the link L_i are N_{i-1} and N_i , of which the buffer size is B_{i-1} and B_i . The congestion link is the link of which the total traffic is greater than its bandwidth, and the congestion path is the path in which the congestion link exists.

We define K_i is the delay growth rate of link L_i . The definition of the delay growth rate is in our previous work [1]. When there is only one congestion link, $K = K_i^c$. If the two different nonzero delay increase rates of the path are K'' and K' , and the corresponding rates of the probing traffic in the starting point of the path are R''_0 and R'_0 , the path-available bandwidth A can be expressed as QuickAbw formula:

$$A = \frac{K''R'_0 - K'R''_0}{K'' - K'}$$

The capacity of the link is

$$C_i = \frac{R''_0 - R'_0}{K''_i - K'_i}$$

2.2 Qualitative analysis of Measurement error of QuickAbw under Multiple Congestion Links in Path

1) Relation Analysis between Path Delay Increase Rate and Rate of Probing Traffic During the measurement period, the background traffic in the network is presumed to be constant and the path delay increase rate K is only related to R_0 . K can be expressed as a function related to R_0 , $K = f(R_0)$.

Theorem 1 When there is a specific congestion link sequence $L_1^c, L_2^c, \dots, L_u^c$, the probing traffic in link L_i^c is $s_i^c R$ and the background traffic is s_i^c . The receiving rate of the probing traffic and the

background traffic is $mr(s_i^c R)$ and $mr(s_i^c m)$, which can be expressed as a function $f_{mr(s_i^c R)}(R_0)$ and $f_{mr(s_i^c m)}(R_0)$ about R_0 . When $R_0'' > R_0'$, $f_{mr(s_i^c R)}(R_0'') > f_{mr(s_i^c R)}(R_0')$ and $f_{mr(s_i^c m)}(R_0'') < f_{mr(s_i^c m)}(R_0')$.

Proof. When $i = 1$, L_1^c is congested firstly. The rate $m_1^c(s_1^c)$ of the sending end is constant. According to formulas (6) and (7), $f_{mr(s_1^c R)}(R_0'') > f_{mr(s_1^c R)}(R_0')$, $f_{mr(s_1^c m)}(R_0'') < f_{mr(s_1^c m)}(R_0')$.

When $i \neq 1$, we assume that $f_{mr(s_i^c R)}(R_0'') > f_{mr(s_i^c R)}(R_0')$, $f_{mr(s_i^c m)}(R_0'') < f_{mr(s_i^c m)}(R_0')$. According to the steady flow model assumption, for arbitrary R_0 , $f_{mr(s_i^c output)}(R_0) = \gamma f_{mr(s_i^c m)}(R_0)$, $0 \leq \gamma \leq 1$, γ is constant. Therefore, $f_{mr(s_i^c output)}(R_0'') < f_{mr(s_i^c output)}(R_0')$.

Case 1. $L_i^{c+1} = L_{i+1}^c$.

$f_{ms(s_{i+1}^c cross)}(R_0'') + f_{ms(s_{i+1}^c input)}(R_0'') < f_{ms(s_{i+1}^c cross)}(R_0') + f_{ms(s_{i+1}^c input)}(R_0')$. However, $ms(s_{i+1}^c inter)$ and $ms(s_{i+1}^c intra)$, keeping constant, are unrelated to R_0 . Therefore, when is L_{i+1}^c congested, $f_{ms(s_{i+1}^c m)}(R_0'') < f_{ms(s_{i+1}^c m)}(R_0')$.

According to formulas (6) and (7) and the assumption of the link up one level, $f_{mr(s_{i+1}^c R)}(R_0'') > f_{mr(s_{i+1}^c R)}(R_0')$, $f_{mr(s_{i+1}^c m)}(R_0'') < f_{mr(s_{i+1}^c m)}(R_0')$.

Case 2. The higher level link of L_{i+1}^c is not L_i^c , i.e., $L_i^{c+1} \neq L_{i+1}^c$. The part of the traffic $s_i^c output$ sent to link L_{i+1}^c is s' , and the rate of traffic s' in the sending end of L_{i+1}^c is $ms(s')$. At the moment,

$$ms(s') = \delta mr(s_i^c output), 0 \leq \delta \leq 1$$

where δ is constant. It is easy to see that $f_{ms(s')}(R_0'') \leq f_{ms(s')}(R_0')$. When they are equal, δ is zero.

At the moment, the rest of the data traffic in the traffic s_{i+1}^c is unrelated to R_0 , except s' . Therefore, $f_{ms(s_{i+1}^c m)}(R_0'') \leq f_{ms(s_{i+1}^c m)}(R_0')$. According to formula (6), $f_{mr(s_{i+1}^c m)}(R_0'') < f_{mr(s_{i+1}^c m)}(R_0')$.

In conclusion, Theorem 1 is proved.

Theorem 2 $f(R_0)$ is a continuous function of $R_0 \in [0, +\infty)$.

Proof. First, we prove the continuity of specific congestion link $f(R_0)$. When $R_0 \in [r_1, r_2]$, we can get the congestion links $L_1^c, L_2^c, \dots, L_u^c$ and $f(R_0) = \sum_{i=1}^u g_i^c(R_0)$. Therefore, we only need to

prove that for any i , $g_i^c(R_0)$ is continuous on $[r_1, r_2]$. Further, we can prove for any $f_i^c(R_0)$, it is continuous on $[r_1, r_2]$.

For any link L_i^c , $f_i^c(R_0)$ can be expressed as

$$f_i^c(R_0) = \frac{f_{ms(s_i^c R)}(R_0) + f_{ms(s_i^c m)}(R_0) - C_i}{C_i}$$

We use the induction method to prove it.

Since $L_1^c, ms(s_1^c m)$ and R_0 are independent and $f_{ms(s_1^c R)}(R_0) = R_0$ is continuous on $[r_1, r_2]$, we can get the following equation:

$$f_1^c(R_0) = \frac{R_0 + ms(s_1^c m) - C_1^c}{C_1^c}$$

At this time, $f_1^c(R_0)$ is monotonously increased about R_0 and continuous on $[r_1, r_2]$.

According to formula (8), we can get the two following equations:

$$f_{mr(s_i^{c_m})}(R_0) = \frac{f_{ms(s_i^{c_m})}(R_0)}{f_{ms(s_i^{c_R})}(R_0) + f_{ms(s_i^{c_m})}(R_0)} C_i^c$$

$$f_{mr(s_i^{c_R})}(R_0) = \frac{f_{ms(s_i^{c_R})}(R_0)}{f_{ms(s_i^{c_R})}(R_0) + f_{ms(s_i^{c_m})}(R_0)} C_i^c$$

For link L_i^c , if $f_{ms(s_i^{c_R})}(R_0)$ and $f_{ms(s_i^{c_m})}(R_0)$ are continuous, $f_{mr(s_i^{c_m})}(R_0)$ and $f_{mr(s_i^{c_R})}(R_0)$ are also continuous. According to formula (8), $f_{ms(s_i^{c_R})}(R_0) = f_{mr(s_i^{c_R})}(R_0)$. Therefore, $f_{ms(s_i^{c_R})}(R_0)$ are continuous on $[r_1, r_2]$.

In s_{i+1}^c , we can set s' as the probing traffic that passes through L_i^c , and s'' as the probing traffic that does not pass through L_i^c . There is $ms(s_{i+1}^c) = ms(s') + ms(s'')$. Because $ms(s'')$ and R_0 are independent, $ms(s')$ can be expressed as

$$f_{ms(s')}(R_0) = \rho f_{mr(s_i^{c_{output}})}(R_0), 0 \leq \rho \leq 1$$

According to the constant traffic hypothesis,

$$f_{mr(s_i^{c_{output}})}(R_0) = \varphi f_{mr(s_i^{c_m})}(R_0), 0 \leq \varphi \leq 1$$

When $f_{mr(s_i^{c_m})}(R_0)$ is a continuous function, $f_{mr(s_i^{c_{output}})}(R_0)$ is also a continuous function. Therefore, $f_{i+1}^c(R_0)$ is a continuous function.

At this time, we come to the conclusion that when there is a specific congestion link, $f(R_0)$ is a continuous function. In conclusion, Theorem 1 is proved.

Theorem 3 $f(R_0)$ has a linear relation with R_0 when congestion links in a particular sequence exist in the path.

Proof. We assume that congestion links in a particular sequence that exist in the path are $L_1^c, L_2^c \dots L_u^c$.

$$f(R_0) = \frac{T + \Delta d}{T} - 1 = \frac{ms(s_1^{c_R})}{mr(s_u^{c_R})} - 1.$$

We need only to prove that $\frac{ms(s_1^{c_R})}{mr(s_u^{c_R})}$ has a linear relation with R_0 .

For the first congestion link, $\frac{ms(s_1^{c_R})}{mr(s_1^{c_R})} = \frac{R_0}{c} + \frac{ms(s_i^{c_m})}{c}$, $ms(s_i^{c_m})$ has nothing to do with R_0 , and $\frac{ms(s_1^{c_R})}{mr(s_1^{c_R})}$ has a linear relation with R_0 .

If $\frac{ms(s_1^{c_R})}{mr(s_i^{c_R})}$ has a linear relation with R_0 , we assume that $\frac{ms(s_1^{c_R})}{mr(s_i^{c_R})} = aR_0 + b$. Therefore,

$$mr(s_{i+1}^{c_R}) = \frac{\frac{C_i^c ms(s_1^{c_R})}{ms(s_i^{c_R}) + ms(s_i^{c_m})}}{\frac{ms(s_i^{c_R}) + C_i^c}{ms(s_i^{c_R}) + ms(s_i^{c_m})} + \frac{\gamma ms(s_i^{c_m}) + C_i^c}{ms(s_i^{c_R}) + ms(s_i^{c_m})} + ms(s_i^{intra}) + ms(s_i^{inter}))}$$

C_{i+1}^c is the percentage of s_i^c in the background traffic sent from L_i^c to L_{i+1}^c . Now,

$$\frac{ms(s_{i+1}^{c_R})}{mr(s_{i+1}^{c_R})} = \frac{R_0}{C_{i+1}^c} + \left(\frac{ms(s_i^{c_m})(ms(s_i^{intra}) + ms(s_i^{inter}))}{C_{i+1}^c C_i^c} + \frac{\gamma ms(s_i^{c_m})}{C_{i+1}^c} \right)$$

$$(aR_0 + b) + \frac{ms(s_i^{intra}) + ms(s_i^{inter})}{C_{i+1}^c C_i^c}$$

$\frac{ms(s_{i+1}^{c_R})}{mr(s_{i+1}^{c_R})}$ has a linear relation with R_0 , therefore, $\frac{ms(s_1^{c_R})}{mr(s_u^{c_R})}$ has a linear relation with R_0 .

In conclusion, Theorem 3 is proved.

Theorem 4 $f(R_0)$ generates congestion sequences $L_1^c, L_2^c \dots L_u^c$ in the domain of $[r_1, r_2]$. If we add one congestion link to the sequences, $f(R_0)$ will get bigger on the condition that R_0 remains unchanged.

Proof. We assume that the congestion link at the last is L_u^c , after

adding a congestion link L_i^c and $f(R_0)' = \frac{ms(s_1^{c_R})}{mr(s_u^{c_R})} - 1$. If L_i^c is the last congestion link, it is obvious that $f(R_0)' > f(R_0)$. If L_i^c is added to other locations, it is easy to prove that $mr(s_u^{c_R}) > mr(s_u^{c_R})$ through the inductive method. At the moment, $f(R_0)' > f(R_0)$. In conclusion, Theorem 4 is proved.

2) Measuring Error Analysis We assume that the rates of the probing traffic are R''_0 and R'_0 ($R''_0 > R'_0$), and the corresponding path delay increase rates actually measured are K and K' . The available bandwidth is calculated to be A^m . The delay increase rates measured in the tight link on both sides according to R''_0 and R'_0 are $K^{e''}$ and $K^{e'}$, and the actual available bandwidth is supposed to be A^e .

$K^{e''} = \frac{(R''_0 - A)}{C_i}$, $K^{e'} = \frac{(R'_0 - A)}{C_i}$. Therefore, the error d can be expressed as

$$d = A^m - A^e = \frac{K^m(R''_0 - R'_0) - K^{m'}(R''_0 - R'_0)}{K^{m''} - K^{m'}} - \frac{K^{e''}(R''_0 - R'_0) - K^{e'}(R''_0 - R'_0)}{K^{e''} - K^{e'}}$$

We suppose that $\eta(R''_0, R'_0) = d$, and the measuring error can be expressed as

$$\eta(R''_0, R'_0) = \frac{f(R''_0)R'_0 - f(R'_0)R''_0}{f(R''_0) - f(R'_0)} - \frac{\sigma(R''_0)R'_0 - \sigma(R'_0)R''_0}{\sigma(R''_0) - \sigma(R'_0)}$$

where $f = \sigma$ when $R_0 < A$. Therefore, $\eta(R''_0, R'_0) = 0$ to random $A > R''_0 > R'_0$. When there is only one congestion link in the path, the path delay increase rate K measured is the delay increase rate of the tight link and $f(R_0) = \sigma(R_0)$, $\eta(R''_0, R'_0) = 0$. There is no error in theory using formula (21) to get the path-available bandwidth.

According to Theorems 2 and 3, we know that $f(R_0)$ has a piecewise linear relation with R_0 , and the slope of $f(R_0)$ increases gradually with the increase of the congestion link caused by the increase of R_0 . According to the related approximate triangle theorem, it is easy to prove that the path-available bandwidth will be bigger than actual if it is calculated using K and corresponding R_0 is measured when there are multiple congestion links.

2.3 Identify the number of congested links in the path

1) Relation Analysis between Path Delay Increase Rate and Time Recognizing the number of congestion links is key to getting the correct available bandwidth.

The following analysis shows that the one-way delay increase K has a piecewise linear relation with the time t under a fixed rate of the probing traffic when the buffer of the node in the path is limited.

We suppose that the congestion links are $L_1^c, L_2^c \dots L_u^c$ and the rate of the data traffic beyond the bandwidth of one link L_i^c is

$$Es_i^c = Rs_i^c + Ms_i^c - C_i^c$$

According to the law of “little,” the occupied capacity of the buffer of the node is $O_{i-1}^c = Ms_i^c * Delay_{i-1}^c$ before sending the probing traffic. The buffer size of node N_{i-1}^c on the sending end of L_i^c is B_{i-1}^c . $Delay_{i-1}^c$ is the sum of the queuing delay and the TX delay of node N_{i-1}^c , and the remaining buffer size is $B_{i-1}' = B_{i-1}^c - O_{i-1}^c$. The overflow time of node N_{i-1}^c is $t_i^c = \frac{B_{i-1}'}{E_i^c}$. It begins to lose part of the new package after a buffer overflow and the time interval between the time of the packages that are not be discarded entering the queue and the time of the packages sent is $d_i^c = B_{i-1}' / C_i^c$, which is constant obviously. The delay increase is zero at the moment, i.e., $\Delta d_i^c = 0$, and the delay increase rate of link L_i^c is zero, $K_i^c = 0$. We sort the links $L_1^c, L_2^c \dots L_u^c$ in ascending order according to the length of overflow time, and we get the links $L_1^c, L_2^c \dots L_u^c$, whose corresponding overflow time and delay increase rate is $t_1^c, t_2^c \dots t_u^c$ and $K_1^c, K_2^c \dots K_u^c$. The path-delay increase rate K can be expressed as a function $\omega(t)$ about the time t .

$$\omega(t) = \begin{cases} K, & t \leq t_1^c \\ \sum_{i=1}^u H_i^c, & \text{when } L_p^c = L_i^c, i < j, t_{j-1}^c < t \leq t_j^c, \text{exist } K_p^c = 0 \\ 0, & t > t_u^c \end{cases}$$

In a particular case, $t_1^c = t_i^c = t_u^c, 1 < i < u$, and

$$\omega(t) = \begin{cases} K, & t \leq t_1^c \\ 0, & t > t_1^c \end{cases}.$$

Therefore, $\omega(t)$ is a constant function about t .

We can get the numbers of congestion links by getting the segments of the function $\omega(t)$ through identify technology of the segments of line segment.

2) Algorithm of Getting Segments of Straight Lines We assume that the numerical sequence measured is $\omega(t_1), \omega(t_2) \dots \omega(t_N)$, which we need pre-process. We accumulate the numerical sequence to get the numerical sequence $w(t_1), w(t_2) \dots w(t_N)$ as data of the y axis and make the time as the x axis. Then we can clearly watch out the tendency of the delay. The slope of a point in the linear fitting curve is the delay increase rate.

The key to recognizing whether there are multiple congestion links is to observe the segments of the linear fitting curve. If the segments are larger than two, there is more than one congestion link in the link.

Algorithm 1 Optimal partitioning algorithm of the set

The algorithm can be expressed as the best fitting of a set of data points and the segments T , i.e., the smallest sum of the distance between the data points and the fitting curve.

First of all, we make the difference of the data points in the set processed. We extract a point from each N point, and the point should satisfy the median of the N point, which can reduce the amount of computations to form a point set for the following steps. We divide the set of points in segments to get a non-empty subset sum and all partitions.

We calculate the imitative straight line of each subset and process the points in the subset with a linear least squares fit. The error of the subset sum is the sum of the squares of the distance between all points in the set and the imitative straight line. We calculate the error and record the quadratic sum and the variance of the error

mean. In addition, we calculate the sum of errors in all sets to get the partition with smallest sum of errors.

The minimum variance, found from dividing the origin points into an m subsets sum, is expressed as $F_m(i, j)$, whose recursion formula is

$$F_m(i, j) = \text{Min}\{F_1(i, k) + F_{m-1}(k, j)\}.$$

The time complexity of Algorithm 1 is $O(N^4)$ and the space complexity of the algorithm is $O(N * N * n)$.

Algorithm 2 Piecewise combination algorithm

The optimal partitioning set can be obtained from Algorithm 1, including T sub-collections

$$\text{best\_set} = \{\text{sque}_1, \text{sque}_2, \dots, \text{sque}_T\}$$

The algorithm assumes that the error of the subset and the midpoint to the fitting straight line is in accordance with normal distribution, and it uses the hypothesis testing based on normal distribution to merge them.

According to the 3σ principle of normal distribution, we can calculate the mean error of the point in set sque_i to the fitting straight line corresponding to set sque_{i+1} , with the fitting straight line corresponding to set $\text{sque}_{i+1} \cdot \mu'$.

If $\text{sque}_{i+1} \cdot \mu' \in [\text{sque}_i \cdot \mu - 3 * \text{sque}_i \cdot \sigma, \text{sque}_i \cdot \mu + 3 * \text{sque}_i \cdot \sigma]$, when the confidence coefficient is 99.7%, set sque_{i+1} is considered as a sample of the same normal distribution as set sque_i , and set sque_{i+1} is combined with set sque_i .

Traverse best_set and combine to give a final number of subset x . The time complexity of Algorithm 2 is $O(n)$.

Based on the above analysis, when the input time of probing traffic is long enough, the value of x is at least 2.

In the experiment, in order to enhance the recognition rate of Algorithm 2, the segments shorter than $1/10$ of the average length after combination are discarded.

Furthermore, the MultiLink-QuickAbw algorithm can even identify the overflow of the sending nodes on the congested links. Algorithm 3 decides whether to terminate the probing traffic.

Algorithm 3 Algorithm of judgment on the termination of probing traffic

The number of data packages we receive is M at the receiving end, and we make the accumulated value of the delay increase and the time of arrival a point.

Running Algorithm 1 with these points as parameters and setting the segments T to 1, we can get the linear fitting equation $y = ax + b$, average error μ , and the error variance σ^2 . In addition, we calculate the average error μ' between these points and the straight line $y = b$, and still test μ' using the hypothesis of normal distribution. If , the delay increase rate of these packages is zero and the sending nodes of all congestion links are overflowed, which shows we should stop sending the probing traffic.

We require preprocessing before executing Algorithm 1. If the delay increase rate is zero, the number of points whose delay increase rate is zero should be extended to of the total numbers along the time axis (x axis) to lower the error of Algorithm 1.

2.4 MultiLink-QuickAbw Algorithm

Algorithm 4 We set the initial rate of probing traffic as .
Loop,

We send probing traffic and calculate the output rate when each receives M probe packets at the receiving end. If is equal to , there is no congestion link. is the rate we need to increase. Then we set , GOTO NEXT.

If is not equal to , we execute Algorithm 3 with the data to judge whether we should send probing traffic or not. The sending time is . If we need to continue to send probing traffic, GOTO NEXT.

After we stop sending probing traffic, we accumulate the relative delay of the receiving packages at the receiving end and get . We set the number of links in the network to plus one as the number of segments. Executing Algorithms 1 and 2, we can get x , which is the number of segments. If x is equal to 1, the overflow time is too short. Then we set $M = M * p$, ($1 < p < 2$), GOTO NEXT.

If x is bigger than 2, there is more than one congestion link. Then we set , GOTO NEXT.

If x is equal to 2, there is only one congestion link. We can calculate the available bandwidth A with the delay increase rate K . If not assigned, we set GOTO NEXT. If is assigned, we set and . Substituting them into Equation 2-21, we can calculate the available bandwidth A , then we end the loop.

Next,

Sleep a length of , the length of must be long enough to make the buffer in the node congestion disappear. According to the law of “little,” the limit of is . Because the available bandwidth is unknown, we would consider the congestion link as gone if we cannot receive the probing packages.

GOTO LOOP

END.

In the case where Algorithm 3 has achieved two K whose segment number is 2, we can continue the iteration and widen the distance between the two K values, which is helpful for the accuracy of the calculation.

When Algorithm 3 is run second, in order to further decrease the probing time, the probing traffic rate can be set to the corresponding probing traffic rate when the last measured first number of segments is 2. In practice, in order to reduce the error we can make several iterations and calculate the average of the available bandwidths. When QuickAbw algorithm first finds that there is only one congested link, record the number of packets before the buffer overflows as L . When the probing traffic is sent again, the number of packages should not exceed L . In this way, the measuring time and the network measurements are reduced.

3 EXPERIMENT

3.1 Verify Probing Traffic Input-Output Curve Characteristics

As shown in Figure 1, nodes $N1, N2, \dots, N6$ are connected by links $L1, L2, \dots, L5$. The capacity of these links are $C(L1)=200\text{Mb/s}, C(L2)=155\text{Mb/s}, C(L3)=34\text{Mb/s}, C(L4)=10\text{Mb/s}$, and $C(L5)=200\text{Mb/s}$, and the background traffic rates are :

. The corresponding available bandwidths are $A(L1)=200\text{Mb/s}, A(L2)=3\text{Mb/s}, A(L3)=5\text{Mb/s}, A(L4)=3\text{Mb/s}$, and $A(L5)=200\text{Mb/s}$.

Sending probing traffic from $N1$ to $N6$, the rate rises from 0 Mb/s to 9 Mb/s with the step of 10Kb/s. According to the simulation in MATLAB, we can get the relationship between delay increase rate K and .

Figure 1: Network topology for experiment

Figure 2: Delay rate theoretical curve (black line) and the corresponding simulation curve (red asterisk), when the probing traffic rate increased from 0 to 9000kb/s

We get simulation data from the NS2 platform in this way: the same network environment is constructed in the NS2 environment, the probing traffic rises from 0 KB/s up to 9000 KB/s, setting the step size to 100 KB/s. The size of the packet is set to 1000 bytes. We can only collect the delay increase rate before the probing traffic loses packet.

As can be seen in Figure 2 the first congestion link happens when the rate reaches 3000kb/s, the second happens when 5050kb/s, and the third at 7750. From the results of the simulation we find that the curve acquired from NS2 fits the curve of the theoretical derivation.

3.2 Path Delay Rate and Time Curve

We use the network topology in Figure 1 and set $C(L1)=200\text{Mb/s}, C(L2)=20\text{Mb/s}, C(L3)=100\text{Mb/s}, C(L4)=10\text{Mb/s}$, and $C(L5)=200\text{Mb/s}$. We set the network background flow to , then the available bandwidth will be $A(L1)=200\text{Mb/s}, A(L2)=7\text{Mb/s}, A(L3)=3\text{Mb/s}, A(L4)=9\text{Mb/s}$, and $A(L5)=200\text{Mb/s}$.

We set the probing traffic rate at 8Mb/s, the number of packets as 700, and the size as 1000 bytes. The measured results are shown in Figure 3, where the x-axis represents the time and the y-axis the time delay. We can see from the figure that the algorithm detects flow changes at the receiving end, but the change trend of the delay cannot be observed.

We can observe the trend of detect flow delay by cumulating the delay variation. Make Arithmetic 2.1 and Arithmetic 2.2 piecewise fitting, and set the maximum number of segments to 5 (number of link), as shown in Figure 4

Figure 3: Corresponding variation of packet delay, when the injection rate is 8Mb/s and the number of pack is 700, measuring sustained 0.8S

Figure 4: Curve fitting after segmentation

The curve consisting of black points is the result after we adopt Arithmetics 1 and 2 with piecewise fitting. Algorithm 2 finds the section number is 3, which indicates there are two congestion links. The packet loss rate of the curve in the time interval is shown in Figure 5

The piecewise linear curve fit is shown in Figure 4, and the slope of each section shows the time delay corresponding to the growth rate. In Figures 4 and 5, we can see packet loss, and the delay rate decreases in 0.13 seconds with the congestion link sending node overflows. In 0.52 seconds all the congestion link send node overflows, delay growth rate to zero, the number of link congestion occurred to 2, Algorithm 1 and Algorithm 2 identify the number of curve segment is 3.

When the detecting flow injection rate is 5 MB/s, the number of package for 700, the delay variation at the receiving ends is as shown in Figure 6

Accumulating the delay changes, the corresponding delay change curve is as shown in Figure 7

Figure 5: Packet loss rate curve when the probing traffic is 8Mb/s

Figure 6: Correspond variation of packet delay, when the injection rate is 5Mb/s and the number of pack is 700, measuring sustained 1.12S

Figure 7: Curve fitting after segmentation when the probing traffic is 5Mb/s

Figure 8: Corresponding cumulative curve delay variation when probing traffic rate is 60Mb/s

Figure 7 shows that the link congestion link exists in one place, and Algorithms 1 and 2 to identify the number of curve segments as 2. Algorithms 1 and 2 under these two input rates more accurately identify the number of piecewise curves, but in some cases the cumulative delay change curve segment number is not easy to identify, such as detection of flow rate is 60 MB/s, its cumulative delay change curve as shown in Figure 8

When the detecting flow injection rate reaches 60 MB/s, the corresponding cumulative delay change curve slope of change is not obvious, and after the delay rate reaches 0 the jitter is larger; in 0.052 s, 0.078 s, and 0.12 s are sending node spilling. In this case it is difficult for Algorithms 1 and 2.2 to identify the path of the congestion link number: 0.078 s overflow in the test case failed to recognize and identify the congestion link number as 2, and the actual congestion link number was 3. But as long as it can correctly identify that the congestion link is greater than 1 it will not affect the iterations of the algorithm.

3.3 Measuring Error of Validation under Numbers of Congestion Links

The network structure is constructed in the same way as done in III.A, and the initial rate is set to 15 MB/s. We can get the acquisition delay rate and the corresponding rate, therefore, there are two congestion links, at the initial iteration to obtain and corresponding sending rate to calculate the available bandwidth. Figure 9 shows different transmission speeds of the available bandwidth.

Starting the iteration with 15M/s at the sending end until the sending rate reaches 3972.98Kb/s, we find that it has conducted 50 seconds and 74 times. We calculate the available bandwidth using the rate of sending end as and the corresponding delay increase rate as

The results show that the available bandwidth measured is larger than the actual bandwidth available, despite the fact that there is only one congestion link.

Figure 9 shows that, in the two data collected for calculating the available bandwidth, as long as there exists more than one congested link when collecting data, the measured result is larger than the actual value. This is consistent with the derivation of Section II.B.

Figure 9: Measurement error when there are two congested links

Figure 10: Cure of available bandwidth when the initial rate is 7Mb/s

3.4 Measuring Example of CBR Background Traffic

Set the background traffic is CBR, sending rate is constant, and the packet size is 1500B. M in Arithmetic 2.3 is set to 100, which means each received 100 package judged whether the entire sending node congested links are overflow. We consider that the probe packets disappear from a path after 0.2s when the last probe packet has been received at the receiving end. The probing package size is set to 1000B. The initial rate is set to 20MB/s. Each iterations until all nodes overflow. The measurement process is shown in Table 1

In Table 1, seven iterations took 5.5 seconds. Using the fifth iteration rate for, the corresponding delay growth as, the sixth iterative calculation of the available bandwidth is 2.7527 Mb/s. From the seventh time using the correspond data we know that the available bandwidth is 3.04872Mb/s, which has a very small error from the actual value.

3.5 Factors that Affect Measuring Precision

We use the same environment as the previous section, starting the iteration at 7Mb/s to obtain the corresponding data and, and then calculate the available bandwidth. Figure 10 shows the calculation results.

Table 1: Measurement process under initial probing rate 20Mb/s

#Iterations	Sending rate (Mb/s)	Receiving rate (Mb/s)	Number of congestion links	Measured results (Mb/s)
1	20.00	9.30	3	-
2	9.30	7.90	2	-
3	7.90	7.23	2	-
4	7.23	6.92	2	-
5	6.92	6.76	1	-
6	6.76	6.51	1	2.75
7	6.51	6.35	1	3.04

Figure 11: Cure of available bandwidth when the initial rate is 5Mb/s

From Figure 10 it can be seen that, along with the iteration, the sending end rate reduces more and more slowly, and eventually stops (3975.35 Kb/s). At this time, the available bandwidth calculated is no longer change at 3069.14 (Kb/s). From Figure 3-10 we cannot conclude that the bigger the rate difference of the two probing traffics, the more accurate the result is. Before the iteration speed is constant, the available bandwidth measured and the difference between the two detecting flow rates has no significant regularity. The average result is 2910.26 Kb/s, lower than the actual value, and the variance is 18746. In the measurement, the maximum error is 404.21Kb/s. Due to the fact that the gap between two probing traffics rate is at least 537Kb/s, we need further experiments for when the probing traffic rate gap is small. Therefore, we set the initial rate at 5Mb/s and 4.3Mb/s, and the corresponding measurement curves of available bandwidth are as shown as Figures 11 and 12

Figure 11 Shows that when the initial rate of the probing package is 5.0Mb/s, variance of the measured results increases obviously. When the difference between the two probing packages is 700 KB/s or less, the measurements jitter seriously and the error is large. Figure 12 shows that the sending rate in the sender become less, when the initial rate is 4.3Mb/s. The low initial rate affects the accuracy of the results because it will lead to small differences between two measurements. In the above experiment, the average of multiple measurements is very close to the real available bandwidth; therefore, it can be measured by taking the average of multiple iterations to achieve higher accuracy.

Figure 12: Cure of available bandwidth when the initial rate is 4.3Mb/s **Figure 13: Measurements at different intervals to detect the flow rate and the flow rate of the first probe traffic**

To further analyze the influence of rate interval of the probing traffic and rate on the accuracy, we set the rate interval of the probing traffic to 50Kb/s, 100Kb/s, 200Kb/s, 400Kb/s, 600Kb/s, 800Kb/s, 1200Kb/s, and 1600Kb/s, and the calculation interval as 500Kb/s from 6.9Mb/s to 3.9Mb/s. The results are shown in Figure 13. Figure 13 shows that the rate difference is small (50Kb/s, 100Kb/s), the measurement error is large, and the jitter serious, especially with the high initial rate. Initial probing traffic rate, the closer it gets to the available bandwidth, the greater the difference between the two probing traffic rates, calculate the more accurately available bandwidth. When the difference between the probing traffic rates increased, the high initial probing traffic rate had a reduced impact on the measurement results. But in the actual cases, the lower initial

rate will make it smaller that the sending each iterative reduced (as shown in Figure 12), so it is not conducive to achieve result accurately.

4 RELATED WORK

Available bandwidth measurement can be divided into active measurement and passive measurement. Passive measurement is less invasive and has little impact on the network, but due to environmental constraints, active measurement methods are often required. Active measurement typically sends probe packets from the sending node to the receiving node, and then we can get delay variation and packet loss rate of the packet in the receiving node to calculate the available bandwidth. Active measurement can be divided into probe gap model (PGM) and probe rate model (PRM). The available bandwidth measurement tools IGI [2] and Spruce [3] using the PGM model estimate the available bandwidth by using the input and output interval dispersion of the probe packet pairs. PRM mode which includes measurement tools Pathload [4], Pathchirp [5], Yaz [6], Assalo [7], Topp [8], etc., calculates available bandwidth by calculating the trend of one-way delay change of detected packets. These active measurement algorithms have a common feature that they need to adjust the transmission rate of the probe packet at the sending end until it is equal to the transmission rate at the receiving end, which eventually leads to a long measurement time. To achieve high accuracy, the PGM model algorithm uses multiple repeated measurements to calculate the mean value. Due to the long measurement time, PRM model algorithm will pour a large number of detection messages into the network, affecting the normal work of the network.

In recent years, with the rapid growth of network bandwidth and the popularization of 5G network, the research on the measurement of available bandwidth is still continuing. For example, [9] [10] [11] [12] involves the study of available bandwidth. Wireless networks. Minprobe [13] uses a low-cost intermediate box to measure the available bandwidth on a 10Ge network. [14] proposes an ABW estimation method with less overhead than existing methods. The above classification method is suitable for most new measurement methods.

With the emergence of these new methods, some studies such as [15] [16] [17] have focused on the evaluation of ABW tools. These studies try to find the key factors that affect the measurement results of available bandwidth, such as network load conditions and the characteristics of the injected probe packet. The study in literature [17] shows that the measurement accuracy of available bandwidth is proportional to the detection volume. While improving the measurement accuracy, it is difficult to reduce the number of detection packets sent.

In our previous work[1], we implemented the QuickAbw method. Both simulations and contrast test in real network environment show that QuickAbw has higher measurement accuracy and shorter measurement time than other compared tools in a network with single bottleneck-link under a variety of common background traffic, it outperforms comparison tools under most network loads, however, QuickAbw is only suitable for single congested links in the path.

5 CONCLUSIONS

This research further expands our previous research, enabling QuickAbw to measure bandwidth under a more complex Multi-Congestion-Links path. In addition to measuring the large amount available, the algorithm can also be used to measure the number of congested links. In the experiment, we analyzed the key factors that affect the measurement error. In actual online applications, these factors can be referenced to set appropriate values to obtain a compromise between measurement accuracy, measurement speed, and network intrusion.

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