Available Bandwidth Estimation Tools: Metrics, Approach and Performance

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Abstract: The estimation of the available bandwidth (av_bw) between two end nodes through the Internet, is an area that has motivated researchers around the world in the last twenty years, to have faster and more accurate tools; Due to the utility it has in various network applications; Such as routing management, intrusion detection systems and the performance of transport protocols. Different tools use different estimation techniques but generally only analyze the three most used metrics as av_bw, relative error and estimation time. This work expands the information regarding the evaluation literature of the current Available Bandwidth Estimation Tools (ABET’s), where they analyze the estimation techniques, metrics, different generation tools of cross-traffic and evaluation tested; Concentrating on the techniques and estimation methodologies used, as well as the challenges faced by open-source tools in high-performance networks of 10 Gbps or higher.

Keywords: Internet measurement tools, Available bandwidth estimation, Network throughput.

1. Introduction

The last years have brought a great change in the increase in the consumption of multi-content and it is becoming more frequent for the user to choose the moment, place and format to visualize information of his preference. This phenomenon implies, for example: The migration of traditional television to multimedia consumption on the Internet, among other changes of paradigms.

In the new century has seen an increasing and continuous number of Internet users and network applications. Internet users have grown more than 900% from 2000 to 2017 [1] and as well as the use of network applications such as e-mail, voice over IP (VoIP), Peer to Peer (P2P) and video Streaming. For some of these, information on available bandwidth can be used to monitor and improve performance. The concept of bandwidth is essential for digital communications, and specifically the data packet network, which refers to the amount of data that a route can support per link or which can transmit per unit time. For many applications with high data load, such as file transfer or multimedia streaming; Managing real-time av_bw can positively impact application performance as well as interactive performance, which are more sensitive to low latencies than to high network performance, which can benefit from lower end-to-end delays associated to high bandwidth links with low latencies of data transmission [2].

The correct estimation of av_bw as a metric is important for both users and providers. For the former, estimation techniques facilitate the optimization of end-to-end transmission behavior. For the latter is taken advantage of by the administration tools can accurately monitor the use of one or more links; Internet service providers, can monitor and verify levels of quality of service; Transport protocols can determine the best transmission rate according to the amount of bandwidth available in the network; Intrusion detection systems can generate alerts based on an unexpected increase in network utilization; Which has been studied widely [3], [4], [5], [6], [7], [8], [9]. These and other applications require an end-to-end estimate of the av_bw, because there is no control over the intermediate links through which the communication channel is established.

Table 1. ABET’s developed to date

<table>
<thead>
<tr>
<th>Year</th>
<th>Tool</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>NEXT-FT</td>
<td>Kumar, Tachibana and Hasegawa</td>
</tr>
<tr>
<td>2014</td>
<td>BEST-AP</td>
<td>Dely, Kassler, Chow, Bambos, Bayer and Einsiedler</td>
</tr>
<tr>
<td>2009</td>
<td>ASSOLO</td>
<td>Goldoni, Rossi and Torelli</td>
</tr>
<tr>
<td>2008</td>
<td>DCSPT</td>
<td>Erbgl, Grote, Luo, Raychaudhuri and Liu</td>
</tr>
<tr>
<td>2007</td>
<td>YAZ</td>
<td>Sommers, Barford and Willinge</td>
</tr>
<tr>
<td>2006</td>
<td>IntTCP</td>
<td>Mir, Hasegawa and Murata</td>
</tr>
<tr>
<td>2005</td>
<td>BET</td>
<td>Botta, D’Antonio, Pescapé, Ventre</td>
</tr>
<tr>
<td>2004</td>
<td>DietTopp</td>
<td>Johnsson, Melander and Björkman</td>
</tr>
<tr>
<td>2003</td>
<td>PTR</td>
<td>Hu and Steenkiste</td>
</tr>
<tr>
<td>2002</td>
<td>IGI - PTR</td>
<td>Ningning Hu</td>
</tr>
<tr>
<td>2001</td>
<td>Pathload</td>
<td>Jain and Dovrolis</td>
</tr>
<tr>
<td>2000</td>
<td>TOPP</td>
<td>Bob Melander</td>
</tr>
<tr>
<td>1997</td>
<td>Pathchar</td>
<td>Van Jacobson</td>
</tr>
<tr>
<td>1996</td>
<td>Cprobe</td>
<td>Carter and Crovelia</td>
</tr>
</tbody>
</table>

The main av_bw estimation tools developed so far, are based on the two approaches. The first one, called Probe Rate Model [10], whose most representative tools are Pathload [11], Pathchirp [12], BART - Bandwidth Available in Real-Time [13] and Yaz [14]. And the second one, Probe Gap Model [15], with Traceband [16], Spruce [17], Abing [18] and Initial Gap Increasing (IGI) and Packet Transmission Rate (PTR) [19].

Based on one or another approach, trying to improve the different authors have developed techniques and methods of...
Due to the number of techniques and tools in the current literature, in the area of av_bw estimation, there are many attempts by different authors to collect useful information, which serves in two ways. One is as general information about the area of estimation of estimation of av_bw and second as reference for specific specialized consultation od basic concepts, functionality of estimation approaches, characteristics of the techniques developed and performance of certain tools. In [23], [24], [25], [26], [27], [28], treats the basic concepts of the av_bw estimation area, such as capacity, availablebandwidth and the behavior of Internet traffic Self-similar and Burst traffic. Also authors in [29], [2], [17], broaden the previous basic concepts of the area of the estimation and measurement of av_bw, more used and important but concentrate on new elements like Narrow link, cross-traffic, tight link and add concepts like bulk transfer capacity (BTC), among others. Studies such as [30], [10], [31], [32], [33], [9], [34], [35], [36], [20], [37], [38], [39], [40], [41], concentrate on analyzing the techniques developed, because each author, based on one of the two approaches, creates a technique to optimize the variables of the av_bw metric, such as estimation time, prediction, and relative error. When developing a technique, it is implemented, evaluated and compared with studies such as [42], [11], [12], [43], [44], [45], [46], [47], [22], [48], [20], [49], [16], [50], [51], [13], [52], [53], [54], [55], show the comparative performance between two or more tools evaluated in simulated environments such as using NS-2 or NS-3, and in real network testbeds. Evaluate protocols, control certain network parameters, see Table 3.

All studies presented and reviewed, are important and at the time offered a relevant content according to the subject addressed, covering the needs of the area of the estimation of av_bw. This area is constantly changing, and information is growing rapidly. Due to this, our work will focus on a complete and updated summary of the av_bw concepts, metrics, variables, approaches, techniques and tools found in the current literature, concentrating on the analysis of the behavior of each estimation technique, and also; In the successes and failures offered by the most representative tools developed under these techniques.

The rest of the document is distributed as follows. In section II, we discuss the concepts of metrics related to the estimation of av_bw. Next in section II, a summary of all the estimation techniques used by the most representative tools of the area appears. In section IV, the main characteristics or differentiating elements of the av_bw estimation tools are discussed, which have been evaluated and compared by different authors. Finally, we find as conclusions, a summary and observations.

2. Metrics related to \( \text{av}_\text{bw} \)

This section introduces four metrics related to bandwidth: capacity, available bandwidth, One-Way Delay, and Bulk-Transfer Capacity (BTC). The first two are defined for both individual links and end-to-end links, while the BTC is generally defined only by an end-to-end path.

2.1 Capacity

The capacity of a link can be defined as the lowest bit rate that it is possible to transmit along the individual segments that are found in its route. The speed at which a network segment can transfer the data is usually the transmission rate or segment capacity. Thus, the link that determines the lowest capacity in the path is the one that will determine the capacity of the entire link [2], [11].

\[
C = \min_{i=1..L} C_i, \tag{1}
\]

On the other hand, in a segment or link, the link layer can transmit data at a constant rate, for example, the rate of a 10-Gigabit Ethernet segment, it can handle transfer rates up to 10Gbps or less. However, in the network layer (IP), this rate is always lower because of the number of headers that are introduced. If the transmission time for an IP packet is:

\[
T_{L3} = \frac{P_{L3} + O_{L2}}{C_{L2}}, \tag{2}
\]

where \(P_{L3}\) is the size of the IP packet, \(O_{L2}\) the size of the Layer 2 protocol header (Ethernet, PPP, among others) and \(C_{L3}\) is the capacity of the link. At the link level. If the capacity at level 3 is

\[
C_{L3} = \frac{P_{L3}}{T_{L3}} = \frac{P_{L3}}{P_{L3} + O_{L2}} = C_{L2} = \frac{1}{1 + \frac{O_{L2}}{P_{L3}}}, \tag{3}
\]
\[ C_{L3}C_{L2} = \frac{1}{1 + \frac{O}{L^2}} \]  

(4)

In this way, two protocols of the link layer can be compared, such as PPP and Ethernet. The PPP protocol has a header that occupies 8 bytes and the Ethernet header occupies 38 bytes.

It is important highlight that, there are other level 2 technologies that do not transmit at a constant rate, as is the case of networks that use IEEE 802.11n Wireless technology. In this case, transmissions are used between (54-300) Mbps, depending on the error rate found in said transmission. The first definition of capacity that was used in Equation 1 can be applied in these technologies as long as it is used in a time interval in which it is transmitting at a constant rate.

### 2.2 Available Bandwidth

The most important indicator in this study is an end-to-end link. The av_bw of a link refers to the unused part of the total capacity of the link for a certain period of time. Therefore, although it appears that the capacity of a connection depends on the transmission rate of the technology used and the propagation medium used, it furthermore depends on the traffic load on that link that will vary with time [17], [27], [29].

Since at any point in time a new connection may arise within the link, in order to correctly measure this indicator, bandwidth measurements must be made in a time interval over which an average can be calculated. This can be expressed by the following equation:

\[ \bar{u}_i(t, t + \tau) = \frac{1}{\tau} \int_{t}^{t+\tau} u_i(t) dt, \]

(5)

where \( u(x) \) is the av_bw at a given time instant \( x \).

It is possible to calculate av_bw in a segment, so that if \( C_i \) is the capacity of segment \( i \), \( u_i \) is the average utilization of that segment in a given time interval, the mean value of av_bw \( A_i \) can be expressed as follows:

\[ A_i = C_i (1 - u_i), \]

(6)

In the same way as capacity, av_bw will be the minimum found along a link or several segments:

\[ A = \min_{i=1,..,N} A_i. \]

(7)

### 2.3 TCP y Bulk transfer capacity (BTC)

TCP is the most important transport protocol that exists on the Internet, its use is almost 90% of traffic. Therefore, getting a measure of your performance would be of great interest to end users. Unfortunately, it is not easy to get the performance of a TCP connection. There are several factors that can influence TCP performance, such as the size of the transfers, the type of cross-traffic (UDP or TCP), the number of TCP connections that compete, the size of the initial window, etc. For example, transfers such as a typical web page depend mainly on the first congestion window, round trip time (RTT), and the TCP Slow-Start boot mechanism, instead of taking into account the bandwidth Of the route. In addition, TCP transfer performance can vary significantly when using different versions of TCP, even if the av_bw is the same [44], [56].

The BTC defines an indicator that represents the achievable performance for a TCP connection, ie, the BTC is when the maximum performance is obtained by a single TCP connection. In the connection, all TCP congestion control algorithms must be able to be applied as specified in RFC-2581. However, this RFC leaves some implementation details open, so a measure must also specify in detail other important parameters about the application (or emulation) of TCP. It should be noted that av_bw and BTC are different parameters. BTC is specific for a TCP connection, whereas the av_bw does not depend on a transport protocol. The BTC depends on how the bandwidth is shared with other TCP connections, while the av_bw assumes that the average traffic load is kept constant and estimates the available bandwidth on the link.

![Figure 1. Minimum av_bw in 3 different capacities network segments.](image)

### 3. Bandwidth Estimation Techniques

Within the active methods two groups can be distinguished. On the one hand those dedicated to the study of capacity and bandwidth available and on the other those that analyze the delay, its variation and the rate of packet loss. Within this group stand out the following set of techniques: Variable Packet Size Probing (VPS) estimates the ability of individual jumps. Packet Pair/Train Dispersion (PPTD) which estimates end-to-end capacity. Periodic Streams (SLOPS) which estimates the bandwidth available end-to-end. Trains Of Packet Pairs (TOPP) which estimates the end-to-end available bandwidth [29], [57].

#### 3.1 Variable Packet Size (VPS)

The VPS method is based on the single packet delay model; You can measure the capacity of each jump or section along a link. Typical tools that are based on the VPS technique include pathchar, cliik, pchar, etc. The key element of the VPS technique is to measure the RTT method from the source to each hop of the link depending on the size of the bundle \cite{Li2008}. Specifically, it is expected that the minimum RTT \( T_i(L) \) for a given packet of size \( L \) to the jump \( i \) is:

\[ T_i(L) = \alpha + \sum_{k=1}^{L} \frac{L}{C_k} + \alpha + \beta_i L, \]

(8)

where \( C_k \) is the capacity of the corresponding \( k \) jumps, \( \alpha \) is the delay of the packet up to the iS$\$ jump that does not depend on the size of the \( L \) polling package, and \( \beta_i \) is the slope of the minimum RTT until the jump \( i \) against the size of the poll package \( L \), given by

\[ \beta_i = \sum_{k=1}^{i} \frac{1}{C_k}, \]

(9)

Repeating the minimum RTT measurement for each jump \( i = 1,...,H \), and by linear interpolation, the estimate of the capacity at each jump \( i \) along the link is

\[ C_i = \frac{1}{\beta_i - \beta_{i-1}}, \]

(10)
3.2 Packet Pair/Train Dispersion (PPTD)

The PPTD technique consists of sending bursts of consecutive $k$ consecutive packets of constant size $(S)$ ($k \geq 2$) from source to destination. The dispersion (temporal separation between packets) measured at the destination, which these packets undergo, allows to estimate the maximum rate that can be reached in the traversed network. Therefore, capacity is estimated using the following equation:

$$C = \frac{(k-1) \cdot S}{t_k - t_1}, \quad (11)$$

where $t_i$ is the arrival time of the packet $i$, and $t_1$ is the arrival time of packet 1.

### Table 3. Analysis of available bandwidth studies

<table>
<thead>
<tr>
<th>Author</th>
<th>Estimated metric</th>
<th>Type of traffic</th>
<th>Utilized testbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downey [60]</td>
<td>Accuracy, Av_bw, latency</td>
<td>ICMP packets</td>
<td>Internet infrastructure</td>
</tr>
<tr>
<td>Zangrelli and Lowenkamp [61]</td>
<td>Av_bw, overhead, accuracy, estimation time, Latency</td>
<td>TCP and UDP packets</td>
<td>Real Testbed</td>
</tr>
<tr>
<td>Strauss et al. [77]</td>
<td>Accuracy, failure patterns, overhead.</td>
<td>UDP packets</td>
<td>Internet infrastructure</td>
</tr>
<tr>
<td>Prasad et al. [7]</td>
<td>Capacity, Av_bw, Bulk-Transfer Capacity</td>
<td>Variable Packet Size (VPS) probing, TCP and UDP packets.</td>
<td>Real tested</td>
</tr>
<tr>
<td>Jian and Devrois [21]</td>
<td>Relative Error, Accuracy, Estimation Time; Packet Size and Latency</td>
<td>Use TCP packets real cross traffic</td>
<td>Real tested</td>
</tr>
<tr>
<td>Hu and Streitkote [19]</td>
<td>Accuracy, Relative Error, Estimation Time, Av_bw</td>
<td>TCP and UDP packets</td>
<td>NS2</td>
</tr>
<tr>
<td>Shrivast et al. [62]</td>
<td>Accuracy, Overhead</td>
<td>Accuracy, Overhead</td>
<td>Real tested</td>
</tr>
<tr>
<td>Michant and Lepage [63]</td>
<td>OWL, Delay variation, RTT, Packet loss</td>
<td>TCP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Botti et al. [44]</td>
<td>Accuracy, Relative error, Av_bw</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Man et al. [46]</td>
<td>Capacity, RSS, bandwidth</td>
<td>Internet Traffic-TCP packets</td>
<td>NS2</td>
</tr>
<tr>
<td>Johnson et al. [64]</td>
<td>Packet Delay</td>
<td>Internet traffic</td>
<td>Real tested</td>
</tr>
<tr>
<td>Guerrero and Labrador [65]</td>
<td>Accuracy, overhead, relative error, convergence time</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Angnisit et al [66]</td>
<td>Capacity, Av_bw</td>
<td>UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Sommersen et al. [14]</td>
<td>Accuracy, overhead, Relative error, Av_bw</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Ali et al. [67]</td>
<td>Accuracy, overhead, response time</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Droz-Keller et al. [68]</td>
<td>Av_bw and time-stamp</td>
<td>Data set</td>
<td>Real tested</td>
</tr>
<tr>
<td>Mingue Li et al. [69]</td>
<td>Av_bw, relative error, overhead, cross traffic, Estimation time</td>
<td>Traffic generated by MGEn and sper flow</td>
<td>Real tested</td>
</tr>
<tr>
<td>Ergin et al. [70]</td>
<td>Av_bw, dispersion, packet delay, throughput</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
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<tr>
<td>Gupta et al. [71]</td>
<td>Data rate, number of hops, interference amount</td>
<td>Data set</td>
<td>Real tested</td>
</tr>
<tr>
<td>Cahana et al.[72]</td>
<td>Av_bw, accuracy</td>
<td>No describes</td>
<td>Real tested</td>
</tr>
<tr>
<td>Guerrero and Labrador [73]</td>
<td>Tight link capacity, cross traffic, cross traffic packet size, Av_bw, accuracy</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Goldoni and Schovi [74]</td>
<td>Estimation time, overhead and accuracy</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Botti et al. [6]</td>
<td>Accuracy, probing time, overhead, Av_bw</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Xiaod et al. [75]</td>
<td>Av_bw, accuracy, estimation time</td>
<td>TCP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Nguyen et al. [7]</td>
<td>Av_bw, cross traffic, RTT, packet loss rate</td>
<td>TCP and UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Low and Alias [76]</td>
<td>Bandwidth, RTT, packet loss rate</td>
<td>TCP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Hernandez and Johnson [77]</td>
<td>Av_bw, accuracy, estimation time</td>
<td>UDP packets</td>
<td>Real tested</td>
</tr>
<tr>
<td>Sukeito et. al [78]</td>
<td>Av_bw, overhead, relative error, estimation time</td>
<td>TCP and UDP packets and cross traffic</td>
<td>Real tested</td>
</tr>
</tbody>
</table>

However, if there is traffic from another source simultaneously with the test, there is an underestimation of the capacity as Consequence of the fact that the packages of another origin are intermingled with the ones of test increasing the dispersion of the latter. This effect is more pronounced as greater than $k$, since it increases the probability that traffic from another source that circulates through the network is introduced between the test packets.

3.3 Self-Loading of Periodic Streams (SLoPS)

SLoPS measures the available $\text{cite{Jain2003}}$ capacity of a network path. The source sends a number of packets of the same size $S$ (a periodic packet stream) to the receiver with a certain rate $r_s$ and with arrival rate $r$, the period between packets is $T=S/r_s$. This methodology considers variations in the monitoring of the delays in a sense $D$ one-way delay of the test packages. It assumes that if the flow rate $r_s$ is greater than the available bandwidth $\text{av}_bw$, the flow will cause a temporary overload in the queue of the more congested node, that is, of the link that Determines the available bandwidth on the $[59]$ path.

One-way delays $(\text{OWD})$ will continue to increase as each packet of the stream is queued at the lowest $\text{av}_bw$ (tight link) link. In the other case, if the flow rate $r$ is less than the available bandwidth $\text{av}_bw$, the test packets will go through the path without causing any accumulation or agglomeration on the lowest $\text{av}_bw$ and the delay will not increase. Based on this principle, an iterative algorithm is developed to measure and estimate $\text{av}_bw$. The source host $(\text{SND})$ sends a periodic stream $n$ with rate $r(n)$ and the receiver $(\text{RCV})$ analyzes the variations of delays to determine if $r(n) > av_bw$ or not and notifies the $\text{SND}$ to increase or decrease the $r(n)$ rate.

The source examines the trajectory with successive packet streams of different transmission rates, while the receiver notifies the source about the trend of delays in one direction of each stream. Available bandwidth estimated $\text{Av}_bw$ may fluctuate during the measurement. SLoPS identifies such variations it when detects the $\text{OWD}$ delays of a flow do not show a clear tendency to increase or decrease.

3.4 One-Way Delay (OWD)

In the Figure 1 can see how the last segment $A_l$ has the smallest $\text{av}_bw$ and this will be the bottleneck of the transmission at that instant of time.

It is important to note that on many occasions it is assumed that the traffic load is stationary all the way. This is only reasonable taking a short time interval since it is an indicator that varies rapidly with time. This fact is the main difference that exists with respect to the capacity, since it does not change as fast as there are no modifications in the routes or the links.

One-Way Delay (OWD) is defined as the delay experienced by the packet on the outgoing route, i.e the time a packet $k$ uses to reach its destination. This delay depends on the transmission time, latency and queue delay. The transmission time is the time the router uses to transmit a packet, which is a function of the packet size and the connection capacity. Queue latency is the time the signal uses to traverse the link, determined by the physical characteristics of the link. Queue delay is the time that a packet has to wait in the router due to cross-traffic. The first two terms are deterministic while the latter is random.

Therefore, the OWD can be expressed as:

$$\Delta_k = \sum_{s=0}^{i} (x_s + d_s + q_s) = \sum_{s=0}^{i} \left( \frac{P_s}{c_s} + d_s + q_s \right), \quad (12)$$

where $x_s$ is the transmission time of a packet of the size of $P_s$, $d_s$ is the queue latency and $q_s$ is the queue delay. To measure OWD, it is necessary to have timestamps, both at the origin and at the destination. For some applications, a single measure at the origin can be interesting using Round-Trip Time (RTT),
which is the time it takes to go and return a packet along the link. 

3.5 Trains Of Packet Pairs (TOPP)

The TOPP technique can estimate both the nominal capacity and the available capacity of several nodes in a network path [59]. The technique consists of two phases, the first consists of the technique of probing or sending trains of packet pairs, and the second, the analysis of the time stamps of the packet pairs. In the first step or probing stage, several packet streams are sent, whose transmission rate increases linearly to a maximum rate that is greater than the available capacity of the narrowest node in the trajectory (tight link). 

\[ r_1 = [r_1, r_2, r_3, \ldots, r_n] \]

where 

\[ r_1 = r_{\text{min}}, r_2 = r_1 + \Delta r, r_3 = r_2 + \Delta r, \ldots, r_n = r_{n-1} + \Delta r \]

The size of each probe packet is constant: \( S_1 = S_2 = \ldots = S_n \). Thus, there is a total set of packet streams that equals the number of transmission rate levels. In the second step, from each pair of measurements \((r, \Delta r)\), we estimate the capacity values \( C \) and \( \text{av_bw} \). If \( r \) is greater than the \( \text{av_bw} \), then TOPP assumes that the packet pair arrives at the receiver at the same rate it had at the time it left the source. There are similarities between the SLoPS and TOPP techniques, since both are based on the self-congestion of the lower capacity node, the main differences between the two techniques are related to the statistical processing of the measurement to estimate the \( \text{av_bw} \) [2].

Table 4. Evaluated tools frequency by researches

<table>
<thead>
<tr>
<th>Author</th>
<th>Tool</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>IGI</td>
<td>9</td>
</tr>
<tr>
<td>2002</td>
<td>Pathload</td>
<td>22</td>
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<td>2003</td>
<td>PTR</td>
<td>7</td>
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<td>2003</td>
<td>PathChirp</td>
<td>12</td>
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<tr>
<td>2003</td>
<td>Spruce</td>
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<td>2003</td>
<td>Abing</td>
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<td>2004</td>
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<td>YAZ</td>
<td>3</td>
</tr>
<tr>
<td>2009</td>
<td>ASSOLO</td>
<td>4</td>
</tr>
</tbody>
</table>

4. ABET’s performance analysis

At present, no complete comparative studies are included in the literature, which include the largest number of technical review and evaluation of estimation tools. In 2015 [77], introduced a complete state of the art of available bandwidth, however, this work is only focused on a few databases and there are about 18 papers focused on evaluation of estimation tools. For this review we analyze a little more than 30 works focused on the evaluation of tools of estimation of bandwidth, however, some works were discarded due to their present a greater publication boom for the years 2003-2007, where they are 14 of the 28 total documents. It should be noted that for the last 5 years the average number of tools evaluated per document is 6 tools, while for the other years. It is important to clarify that in most works the evaluations were carried out, given that the document presented a new tool, or a technique to improve the accuracy, speed or other metric of the measure. The most evaluated tools are IGI, Pathload, PTR, PathChirp, Spruce, Abing, DietTopp, YAZ and ASSOLO, the other tools were evaluated in less than three documents. Certainly, the most evaluated tool is Pathload, with a total of 22 documents in which it was taken for comparisons, followed by PathChirp with 12 documents and Spruce with 11, see Table 4.

In terms of the environment in which the tools were evaluated, about 75% i.e., about 20 documents made their measurements under a testbed test platform and a small percentage in a simulated environment, see Table 2 and Table 3. For traffic generation the most used packet generators are MGEN and D-ITG, mostly using synthetic Poisson and Bursty traffic with about 45% and 37% of the documents respectively.

The most evaluated metrics in the documents are capacity, available bandwidth, error, accuracy and estimation time, accounting for more than 75% of documents. In most works Pathload is considered as the tool that delivers the most successful results, that is to say with a minor error, but it is also considered one of the tools with the longest measurement and intrusive time. Likewise, contradictory results are presented between the performance of the tools, all of which are supported by the different measuring conditions and tests carried out, which vary considerably from one document to another.

5. Conclusions and perspectives

In the literature there were no papers focused on the revision of documentation of available bandwidth estimation tools, this being an initial work in the performance of a current evaluation work. This work is excepted to encourage more work in the area of available bandwidth to obtain greater developments in the area because in recent years the tools and techniques developed has been declining.

It was determined that the development of tools focused on the overhead caused in the estimation of available bandwidth are in an initial stage, the developments and characterizations realized in this work contribute to the generation of knowledge of later works focused on the estimation of \( \text{av_bw} \) of end-to-end path with zero overhead, which impacts on better packet transmission rates and traffic control, this makes telecommunication networks much more efficient which has been of great importance due to the great growth in their use given the new technologies.

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