Evaluation of backbone links in hybrid networks using GNU-Linux-based tools

Evaluación de enlaces troncales en redes híbridas usando herramientas basadas en GNU-Linux

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Carlos Molina
Universidad del Sinú. Montería, (Colombia)
carlosmolina@unisinu.edu.co

Yair Rivera
Universidad Americana. Barranquilla, (Colombia)
yrivera@americanaca.edu.co

Juan Manuel Torres
Universidad del Sinú. Montería, (Colombia)
juannavarro@unisinu.edu.co

Angel Pinto Mangones
Universidad del Sinú. Montería, (Colombia)
angelpinto@unisinu.edu.co

Cristian Revueltas
Universidad Cooperativa de Colombia Sinú. Montería, (Colombia)
cristian.revueltas@campusucc.edu.co

Nelson Pérez-García
Universidad del Sinú. Montería, (Córdoba)
perezn@ula.ve

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Abstract

The Internet today is a platform that must maintain optimal levels of quality service to meet customer demand. At the same time, the telecommunications infrastructures that support the applications require more rigorous and efficient management in heterogeneous networks. Consequently, this research uses the Available Bandwidth (Abdisp) evaluation tools in hybrid network backbone links, where Abdisp estimation tools such as Pathload and Traceband will be evaluated experimentally in a real network testbed, using synthetic Cross Traffic (CT). This work found that due to the performance of the metrics (Estimation Time, Relative Error) of the evaluated tools, they can be used with high confidence to know the performance of heterogeneous networks, which can be used with a confidence of up to 95% in the management of telecommunication systems.

Keywords: hybrid networks, Pathload, Quality of Service, Pathload, Quality of Service

Resumen

Internet hoy en día es una plataforma que necesita mantener niveles óptimos de calidad de servicio, para poder satisfacer la demanda de los clientes. Al mismo ritmo, las infraestructuras de telecomunicaciones que soportan las aplicaciones exigen una administración con mayor rigor y eficiencia en redes heterogéneas. En consecuencia, esta investigación utiliza las herramientas de evaluación de Ancho de Banda Disponible (Abdisp) en enlaces troncales de redes hibridas; donde se utilizarán herramientas de estimación Abdisp como Pathload y Traceband, que fueron evaluadas de manera experimental en un tesbed de red real, utilizando Tráfico Cruzado (TC) sintético. Este trabajo encontró que debido al rendimiento de las métricas (Tiempo de estimación, Error relativo) de las herramientas evaluadas, pueden ser utilizadas con alta confianza para conocer el desempeño de redes heterogéneas, que pueden ser usadas con una confianza de hasta un 95% en la administración de sistemas de telecomunicaciones.

Palabras clave: Ancho de Banda Disponible, Traceband, redes híbridas, Pathload, Calidad de Servicio

I. INTRODUCTION

One of the most important changes that humanity has experienced is the need to be connected 24/7/365. Consequently, the Internet is the scenario where all these interactions and transactions take place, which highlights the demand increases as video on demand, upload/download data, and computing in the cloud [1]. Thus, to maintain optimal Quality of Service (QoS) and Quality of Experience (QoE) levels, telecommunications services require more from the network infrastructures that support them. Every day, telecommunications services increase the demand for higher data transfer speeds exponentially, which today reaches an average minimum of 300 Mbps [2].

On the other hand, supervisory network links of these networks are mandatory in the new role of the Internet to humanity (also IoT platform) [3], [4], [5]. To supervise the telecommunication platform, the main technique is analyzing the packet flow, where the metrics such as Capacity, av_bw, among others, av_bw being the main one for this work [6], [7].

Av_bw is considered the more important metric in network monitoring. Thus, av_bw of a link is the unused capacity of the total link bandwidth during a period. The av_bw depends on the transfer rate, the type of medium used in the transmission packets, and the amount of cross-traffic into the network connection, which will vary over time [8], [9].

To accurately quantify this indicator in scenarios where new connections may dynamically emerge within the link, bandwidth must be measured over a specified time interval, allowing the computation of an average. This relationship is defined:

$$u_i(t, t+\tau) = \frac{1}{\tau}\int_t^{t+\tau} u_i(t)dt \quad (1)$$

To compute the av_bw on a segment time, if C_i represents the transmission rate i, and u_i show the transmission rate average over each slot time, then the available bandwidth average A_i is:

$$A_i = C_i(1 - u_i) \quad (2)$$

Similar to capacity, the comprising multiple network links is determined by the minimum value found across those segments:

$$A = \min_{i=1\ldots H} A_i \quad (3)$$

Av_bw estimation studies are important to researchers worldwide. Various studies have proposed techniques and explored key concepts related to bandwidth estimation [10], [11]. Other works have conducted comparative analyses of different estimation tools, evaluating their performance across diverse telecommunication environments and under varying types of CT [12]. However, works focus on other performance metrics, and not on the behavior of network links using protocols other than wired (e.g. IEEE 802.11) [13], [14], [15]; where physical transmission capacity, TCP segment losses, av_bw, and delays can be evaluated.

Despite existing research, there remains a need for studies that reveal the actual packet traffic behavior in hybrid telecommunications platforms (wired segments interconnected with wireless links), commonly referred to as trunks. In response, we present an analysis of the av_bw estimation tools in hybrid telecommunications platforms. It also includes a throughput link, aimed at network resources administration, while enhancing both the QoS for network applications and QoE for end users [16].

Accordingly, a total of 360 experiments were conducted in this study using a specialized real-network testbed. CT was generated using the MGEN tool [17]. The next section reviews Related works and outlines the motivation behind this study, along with the current state of the art in available bandwidth (av_bw) estimation research. Subsequent sections describe the Methodology, Results, and Conclusions are presented.

II. RELATED WORKS

The use of Internet-based services and the increasing demand for enhanced service performance have highlighted the importance of optimizing network resource management.

Among the various metrics used for this purpose, the estimation of av_bw has become particularly relevant, as it plays a critical role in ensuring QoS, especially in Global telecommunications platforms. This relevance justifies the ongoing global efforts by researchers to improve estimation techniques and analyze the performance of av_bw evaluation tools, as discussed in [18], [19], [20].

However, researchers in QoS of Internet-based services focus their research on wired networks, mainly on the analysis of the av_bw metric, because av_bw is used by administrators for the maintenance and optimization of telecommunication services: traffic analysis, real-time network link management, hardening, among others [21]. This work reveals that literature does not show an analysis of the effects on network performance, concerning the transmission speed of the communication trunk, lost frames, delays, and av_bw [22].

Among the notable studies is [23], which proposes a solution to mitigate the new issues in Wi-Fi deployments on av_bw estimation tools. It also assesses how 802.1Xx MAC layer factors affect the accuracy of four estimation tools. Similarly, [24] introduces and evaluates a novel estimation method, which employs a packet group train as a probing mechanism for av_bw estimation; that was tested using a commercial FDD-LTE system. Additionally, [14] presents an enhanced av_bw estimation technique, referred to as NEXT, which utilizes a parameter-independent curve fitting approach to interpret one-way tail delay signatures. This technique is evaluated in a real-world test conducted over a radio interface within a 4G/LTE mobile communications network [25].

In [26], a novel protocol approach is proposed for testing active available bandwidth (av_bw) estimation tools within wireless network environments. Additionally, [13], presents a methodology for accurately assessing the performance of 4G WiMAX data networks in real-world wireless settings from the end-user perspective. The study proposes an intelligent monitoring system, incorporating tools like OOKLA [27], which not only measures current performance but also predicts future performance based on historical data. Lastly, [28] introduces BEST-AP, a mechanism for selecting the optimal access point based on a novel av_bw estimation scheme. The av_bw offered by an access point is primarily influenced by signal quality and wireless channel load. By leveraging these av_bw estimates, the system dynamically maintains longer connections with higher-performing access points, while intermittently polling lower-performing ones to update bandwidth estimates.

The above highlights several aspects that distinguish this work from previous studies. First, it evaluates four av_bw estimation tools within a purely wired network scenario. Second, it extends the evaluation to a heterogeneous network environment, featuring a wireless link that acts as a backbone between two wired segments. Finally, the study presents a comparative analysis of both scenarios, focusing on latency and av_bw measurements.

III. METHODOLOGY

The work was carried out in several tasks. The first task was to select the Ab_disp estimation tools to be evaluated. Then, the network testbed was designed and configured for evaluating the chosen tools. Finally, the experiments were designed and executed.

Av_bw estimation tools evaluated

In the reviewed literature, av_bw estimation tools are considered active and intrusive [29], [30]. In [6] these tools were technically analyzed from their functionality and performance impact on their most important metrics. In total, this work is characterized by 26 tools. Therefore, taking that study as a reference, two tools using a different approach and technique were selected.

Consequently, two tools were chosen that are the most representative of each approach. On the PRM (Probe Rate Model) side is Pathload, which is the most evaluated and the most accurate in all the literature [31], [32]. The PGM (Probe Gap Model) approach is used by Traceband. Traceband is one of the least intrusive, the most accurate when the link has no traffic, and the fastest in delivering the estimation results [33], [34], [35].

Testbed de red

A. Hardware

The first testbed (see Figure 1) configured is fully controlled and configurable in terms of packet size and latency. The testbed contains: four computers (hosts), to access the network services and develop the experiments, equipped with a minimum CPU of 4.5 GHz, running operating systems based on open-source platforms (Linux-Mint).

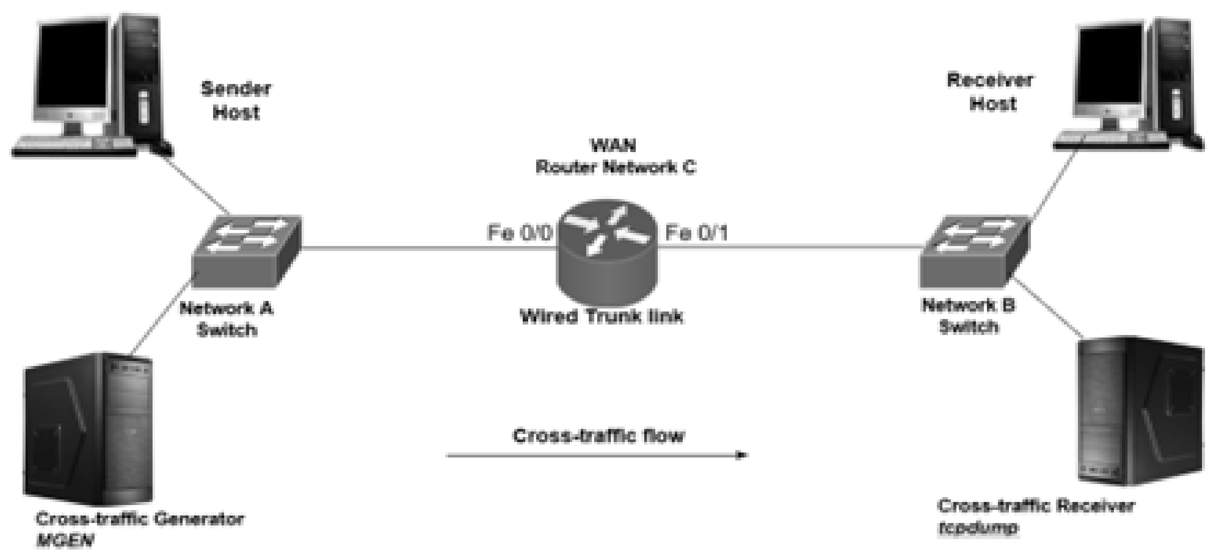

Figure 1. Wired network Testbed

Also, for each host for interconnection, the testbed at each end of the network has a Switch, which can transfer between 100 Mbps and 1000 Mbps. To join the two networks at each end, the testbed inserts a router that can operate up to 1000 Mbps. The joining of each network is done using the interfaces of the switches, connected to each LAN interface of the router, creating a WAN link, which becomes the C-network.

The second testbed presents some differences from the previous testbed, because it presents a change in the C network, which is constituted by a trunk based on wireless IEEE 802.11, which are joined through a HomeRouter (Wireless), creating the wireless trunk, see Figure 2.

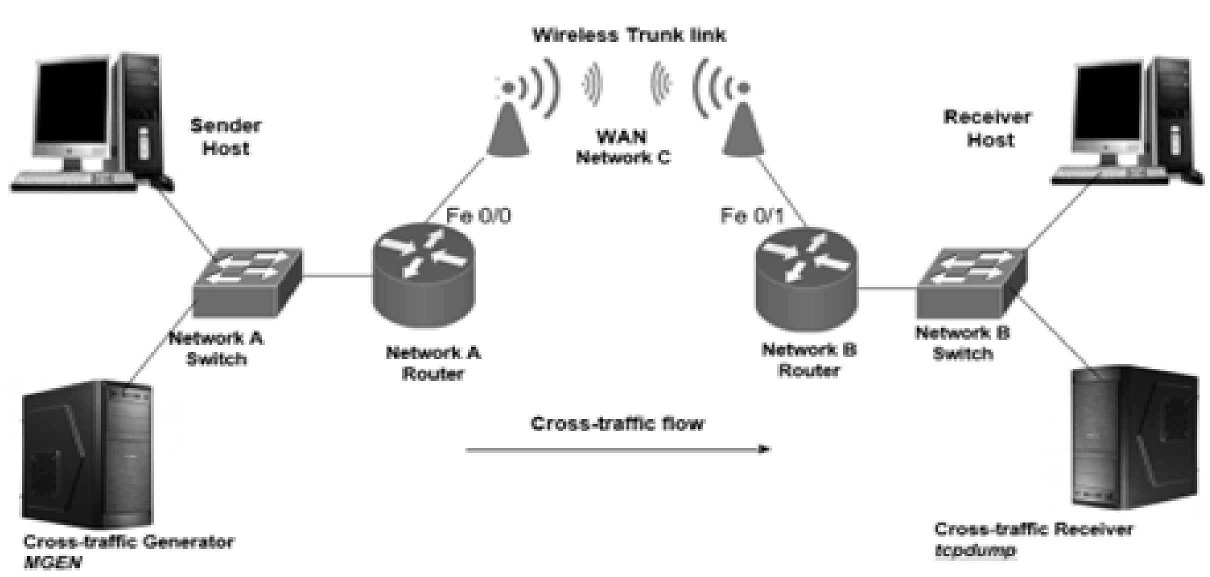

Figure 2. Wireless network testbed

B. Software

Two software components are the most important. First, the av_bw estimation tools selected for evaluation were configured at each end of the network (Network A and Network B).

In their evaluations, the researchers have been forced to emulate links to determine link behaviors and performance. To create such a scenario, they use synthetic traffic generators for estimation. Thus, to generate synthetic traffic, the MGEN tool was selected because it is easy to implement and use; it has a wide range of parameters (Protocol, Sender Host, Receiver Host, Events (CLONE), type of traffic (POISSON or BURST), traffic transmission (0% to 50%), among others).

Experiments

Experimental scenarios incorporating different traffic load levels were designed using the tcpreplay tool's trace scaling capability. This scaling was performed by parameterizing the

Mbps value, which allows insertion in the link with a controlled CT, with a temporal time-gap up to 1 µs.

Three evaluation scenarios were defined depending on the volume of injected traffic: no CT, 0%, and 50% cross-traffic. For each of these scenarios, 30 experimental runs per tool were carried out, resulting in 30 measurements per scenario. In total, 180 experiments were carried out per stage, thus reaching an overall total of 360 experiments.

Finally, latency and av_bw were the metrics selected for evaluating link and network performance since they allow quantifying the links' performance in direct relation to this study's objectives.

IV. RESULTS AND ANALYSIS

This work evaluates the tools using a 100 Mbps wired link and a 54 Mbps wireless link. The experiment computed the estimated av_bw of two tools (Traceband and Pathload)

Wired backbone link

When analyzing the average results obtained from the wired backbone link (see Figure 1), it was observed that, under 0% CT, both tools exhibited low performance during the first 10 experiments, significantly underestimating the av_bw compared to the actual value. However, from experiment 12 onward, their performance improved, though the estimated av_bw remained around 28% of the expected value.

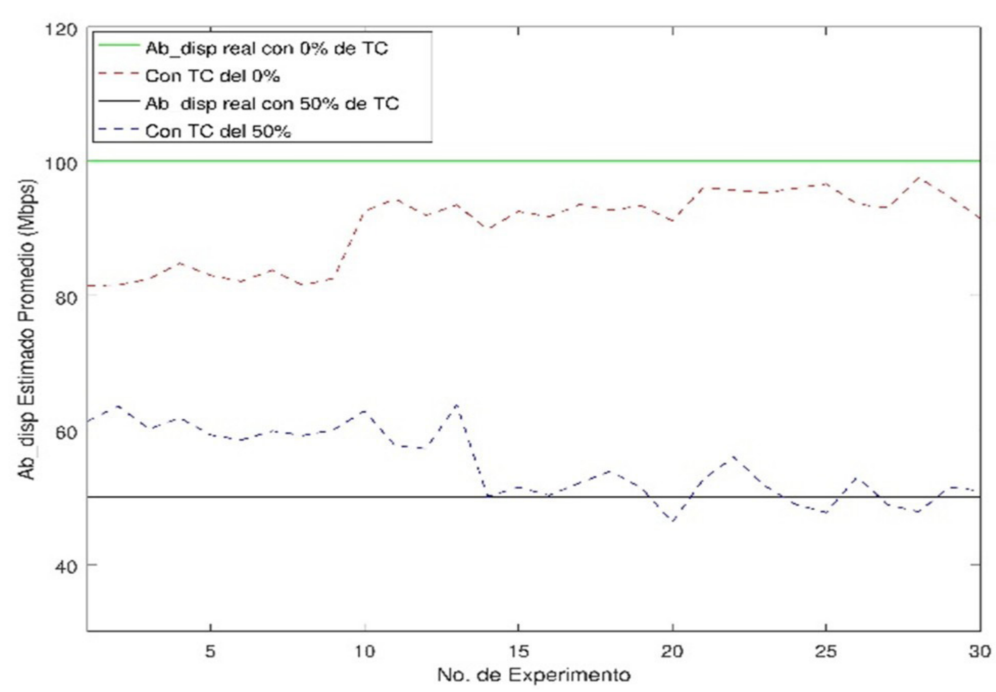

Figure 3. Av_bw average on wired link

Conversely, when assessing the trunk link under 50% CT, both tools showed suboptimal performance up to experiment 13, primarily due to an overestimation of av_bw relative to the expected value. Nonetheless, as shown in Figure 3, the av_bw estimation stabilizes, maintaining a throughput close to 90%, which aligns well with the actual expected value.

Based on the above observations, two key conclusions can be drawn. First, when estimating the av_bw on a wired trunk link under conditions of 0% CT, it is not valid to assume that the full capacity of the link is available. This is due to a measurement error known as overhead, which arises because the probing traffic used to estimate the av_bw is not accounted for in the final measurement. Second, in scenarios where the wired backbone link experiences 50% CT, it can be concluded that although the estimated av_bw may present a maximum average error margin of approximately 20%, it remains a sufficiently reliable metric for evaluating such environments. This is supported by theoretical assumptions indicating that wired backbone links typically exhibit a minimum of 30% CT, a condition attributed to the inherently bursty nature of Internet traffic.

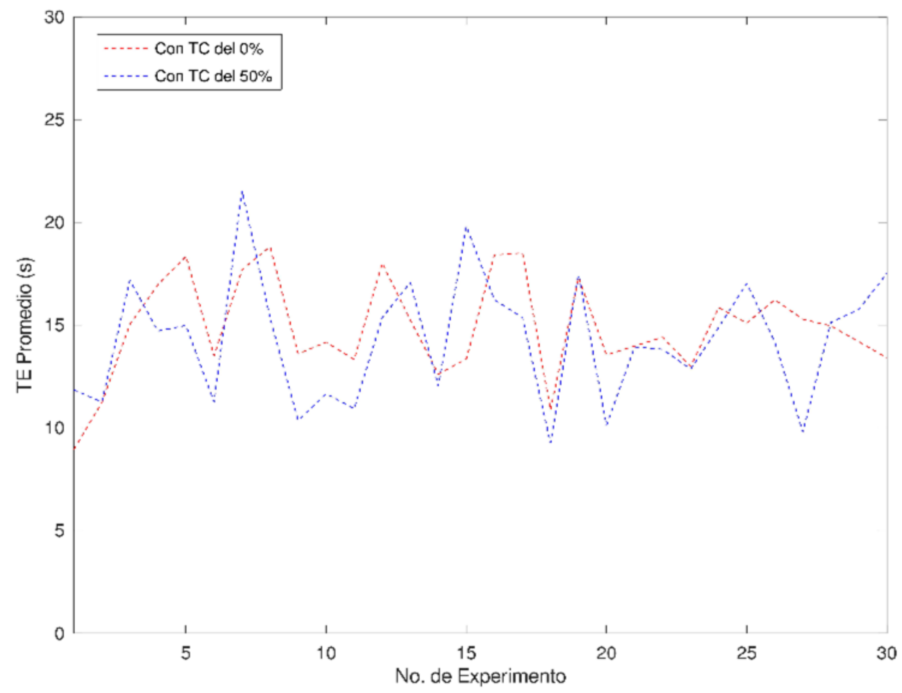

Figure 4. Estimation time average on a wired link

An analysis of the average estimation time employed by the tools to measure av_bw, as illustrated in Figure 4, reveals the following trend: when the wired backbone link experiences 0% CT, the tools require less time to complete the estimation process, with durations ranging between 9 and 13 seconds. In contrast, under the conditions of 50% CT, the estimation time increases notably. This behavior is attributed to link congestion; as CT intensifies, the probing traffic generated by the estimation tools increasingly interacts with the existing traffic on the link. This interaction introduces delays and results in longer processing times for the tools to accurately estimate av_bw.

Wireless link

The evaluation of the wireless trunk link (see Figure 3) conducted using the IGI, Traceband, and Pathload bandwidth estimation tools reveals notable variations in performance based on the presence of CT. When the link operates under 0% CT, the tools demonstrate reduced accuracy, with underestimation and overestimation errors of approximately 8% and 12%, respectively, relative to the actual av_bw. In contrast, under 50% CT conditions, the tools exhibit improved estimation performance, reducing the underestimation and overestimation margins to approximately 4% and 7%, respectively. These results suggest that the estimation tools yield more reliable av_bw measurements for wireless trunk links when moderate levels of CT are present.

These findings support the assertion that, for wireless trunk links, bandwidth estimation tools provide a viable means of approximating link throughput, with significantly improved accuracy observed when the link operates under conditions of approximately 50% CT.

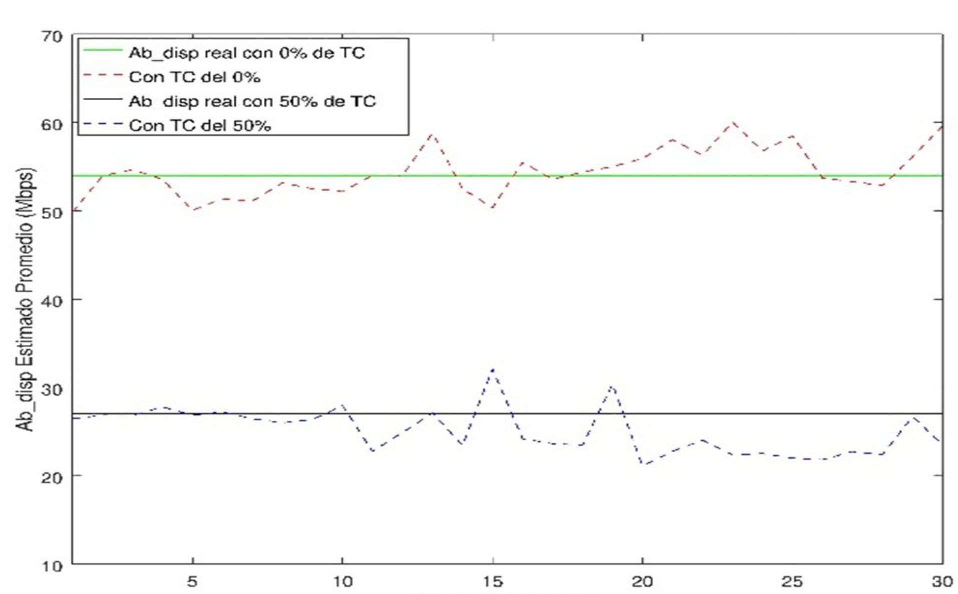

Figure 5. Average estimation time on a wired link

Figure 5 illustrates the average estimation time observed during the assessment of the wireless trunk link using the selected bandwidth estimation tools. Under both 0% and 50% CT conditions, the tools demonstrate slower performance relative to benchmark values reported in the literature, with estimation times reaching up to 17 seconds and 24 seconds, respectively. This increase in estimation time is primarily attributed to the latency inherent in wireless communication, which affects data transmission and reception at the physical layer of the network stack.

A comparative analysis of the results obtained for the wired and wireless trunk links reveals two key observations. First, concerning av_bw estimation, the tools demonstrated higher accuracy in the wireless trunk scenario, achieving up to 96% accuracy, in contrast to a maximum of 90% observed in the wired trunk scenario (refer to Figures 3 and 4). Second, in terms of estimation time (Figures 5 and 6), the wired trunk scenario exhibited slightly better performance. Although one of the estimation instances reached 20 seconds, this value remains below the estimation times recorded for the wireless trunk link, which ranged between 15 and 23 seconds.

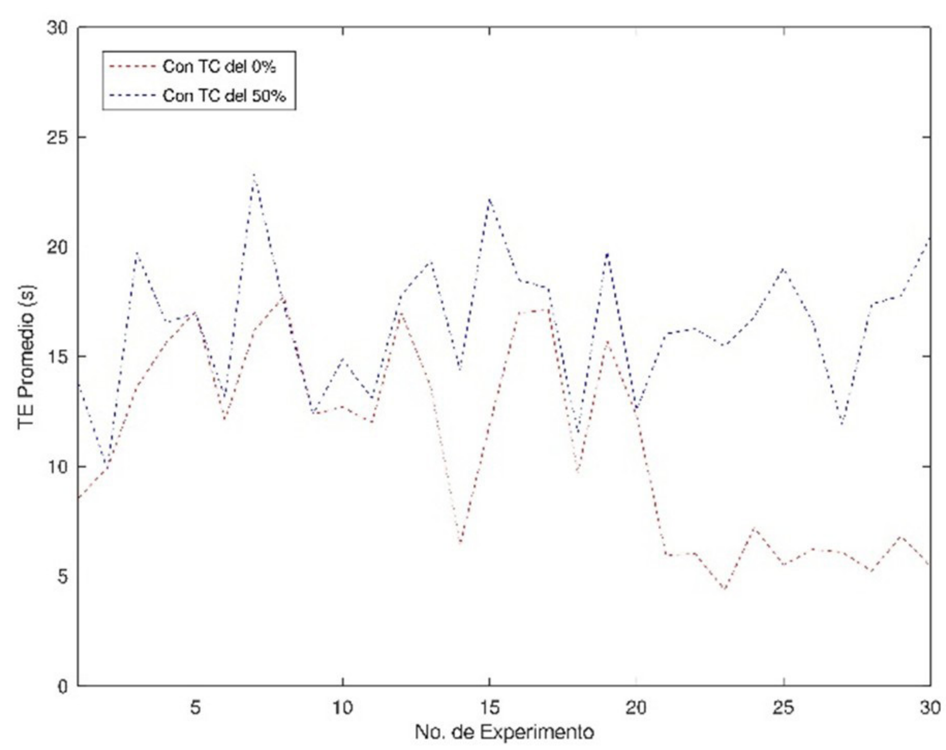

Figure 6. Average Estimation Time on a Wired Trunk Link Under 0% and 50% CT Condition

V. CONCLUSIONS

The development of this study led to two key findings:

First, when evaluating both wired and wireless backbone links, the av_bw estimations revealed that, under 50% CT, the tools provided values with acceptable accuracy. These results support informed decision-making in bandwidth resource management, a critical factor for the performance of real-time services. In contrast, it was confirmed that av_bw estimation under 0% CT is not a reliable indicator of full link availability (i.e., 100%).

Second, the estimation times observed during the evaluation of the tools indicated that wireless trunk links introduce additional latency when CT is present. This latency makes wireless segments a potential bottleneck for applications that rely on high-bit-rate Quality of Service (QoS) guarantees.

Finally, this work demonstrates that the metrics provided by av_bw estimation tools are effective for assessing and understanding the performance of both wired and wireless backbone links. As a result, this study serves as a foundation for evaluating the performance of network services increasingly accessed by mobile users. Moreover, it highlights new research challenges, particularly the need to enhance or develop av_bw estimation tools capable of supporting the dynamic selection of wireless access points offering higher available bandwidth.

Future work

Based on the findings of this study, several directions for future research are proposed. One area of interest is the optimization of estimation time for av_bw tools, particularly in wireless environments. The results indicated that current tools exhibit high estimation times—up to 24 seconds—when assessing wireless trunk links, largely due to latency introduced at the physical layer. Future work could explore lightweight or adaptive probing techniques that reduce estimation overhead while maintaining accuracy.

Additionally, further investigation is warranted into the behavior of av_bw estimation under varying traffic loads and dynamic wireless conditions. Since this study evaluated scenarios with fixed CT levels (0% and 50%), future experiments could introduce variable or bursty traffic patterns to better simulate real-world network dynamics.

Another promising direction is the development or enhancement of av_bw estimation tools tailored for heterogeneous networks, especially those with mobile nodes or rapidly changing wireless topologies. Incorporating machine learning models that predict bandwidth availability based on historical data and environmental factors could further improve performance.

Finally, extending this evaluation framework to emerging wireless technologies such as 5G – 6G and Wi-Fi 6 could provide deeper insights into the applicability and limitations of current av_bw estimation tools in next-generation network environments.

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AUTHOR CONTRIBUTION

The authors' contributions to this article are as follows:

Carlos Molina: Research, data analysis, visualization, writing, and editing.

Yair Rivera: Results analysis, testbed design, data analysis, visualization, writing, and editing.

Juan Manuel Torres: Writing and editing.

Angel Pinto Mangones: Results analysis, testbed design, data analysis, visualization, writing, and editing.

Cristian Revueltas: Research, data analysis, visualization, writing, and editing.

Nelson Pérez-García: Data analysis, writing, and editing.

The authors participated in the review of the results and approved the final version of the article.

CONFLICT OF INTERESTS

The authors declare they don't have interests or financial relationships that could have influenced this work.

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Author 1: He is an electronic engineer with a master's in environmental sciences and a PhD in information technology. He is a teacher in the field of hardware and telecommunications area in the systems engineering program of the science and engineering faculty at the University Elias Bechara Zainum (Monteria - Cordoba). Their research interests are primarily technology and information-oriented in the environment, as well as Internet of Things (IOT) applications. He can be contacted at email: carlosmolina@unisinu.edu.co

Author 2: He is a Full-time Lecturer at Universidad Americana in Barranquilla, Colombia, and was recognized as a Senior Researcher by Minciencias in 2025. He holds a Ph.D. in Systems and Computing Engineering and a Master's in Telematics and Telecommunications from Universidad del Norte. His research areas focus on secure IoT systems, tactile internet applications, and STEAM-based learning methodologies. His work aligns with ongoing research efforts at institutions such as the Deutsche Telekom Chair of Communication Networks and the Centre for Tactile Internet with Human-in-the-Loop (CeTI) at TU Dresden, as well as initiatives in low-latency communication and edge intelligence developed by the School of Electrical, Computer, and Energy Engineering at Arizona State University. He can be contacted at email: yrivera@americanaca.edu.co

Author 3: Computer Engineer from Universidad Católica, Antioquia, Colombia, specialization in Telecommunications Systems from Universidad Autónoma de Bucaramanga, Colombia. In addition, specialization in Educational Informatics, from the University of Santander, as well as PhD in Technology and Innovation and Post doctorate in Science and Technology Management, all at the University Rafael Belloso Chacín, Maracaibo, Venezuela. He is a senior researcher and director of the research group GNOCIX, which has an A1 classification in Colombia. He has more than 50 publications, including scientific journals, books, book chapters, and proceedings of national and international conferences. With over 20 years of professional experience and 12 years in the academic-scientific field, his research has been oriented to emerging technologies, educational technology and innovation, virtual education, and engineering management. He can be contacted at email: juannavarro@unisinu.edu.co

Author 4: He is Systems Engineer from the Universidad del Sinú, Montería, Colombia, specializing in Telecommunications Systems at the Universidad del Norte, Barranquilla, Colombia. In addition, he completed Master studies in Telematics, Doctorate and Post doctorate in Science and Technology, at the Rafael Belloso Chacín University, Maracaibo, Venezuela. He is currently a senior researcher at MinCiencia, Colombia. Full Professor of the Systems Engineering program at the University of Sinú – Elías Bechara Zainúm, Montería, Colombia. He has published over 50 articles, three books, and 28 book chapters authored and co-authored in Teleinformatics, Information Security, and science and technology management. His research interests include wireless communications systems, data transmission, artificial intelligence, convergence, and coding in data networks. He can be contacted at email: angelpinto@unisinu.edu.co

Author 5: He is a full-time Associate Professor at the Systems Engineering Department of the Universidad Cooperativa De Colombia, Monteria, Colombia, where I have been a professor since 2023. Also is master in Telematics and a PhD in Engineering at the Universidad Cooperativa de Colombia. Their research interests mainly focus on communications, wireless networks, and IoT. He can be contacted at email: cristian.revueltas@campusucc.edu.co

Author 6: He received the B.S. degree in electrical engineering from Universidad de Los Andes (ULA), Mérida, Venezuela, 1992, and the M.Sc. and Ph.D. degrees in electrical engineering (applied electromagnetism area) from Pontifícia Universidad Católica do Rio de Janeiro (PUC/Rio), Brazil, in 2000 and 2003, respectively. Since 1994, Professor (currently a Full Professor) and Researcher with the ULA, Mérida, Venezuela, and Visiting Professor in Brazil, Colombia, and Ecuador. His research interest includes the development of optimization techniques for planning and dimensioning optimization of telecommunications systems. He can be contacted at email: perezn@ula.ve