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A Literature Review on Network Performance and Congestion Control Mechanisms in Multi-User Computer Laboratories

[1]Moses Timothy, [2] Nyom Senenge S.

[1&2]Department of Computer Science, Federal University Lafia, Nasarawa State, Nigeria

Abstract

Multi-user computer laboratories in tertiary institutions face unique network performance challenges due to synchronized traffic bursts, heterogeneous application demands, and limited bandwidth. This review synthesizes research on TCP congestion control algorithms (Reno, Cubic, BBRv2, BBRv3), fairness dynamics, Active Queue Management (AQM) schemes (CoDel, PIE), and empirical studies in educational networks, with particular attention to the Nigerian context. Key findings reveal fundamental trade-offs: BBRv3 achieves the highest throughput (≈905 Mbps) but introduces higher latency (≈0.79 ms) and jitter (≈4.2 ms) compared to Cubic, which delivers balanced performance and superior fairness (Jain's index 0.89) under moderate buffer provisioning. BBRv3 exhibits self-induced queuing delay (adding 0.95× RTTmin) and persistent fairness problems with heterogeneous RTTs. AQM mechanisms reduce bufferbloat by up to 62% with minimal throughput penalty. Empirical studies from Nigerian universities report baseline delays of 0.1545 s and throughput degradation of 0.25 Mbps per additional user. Significant gaps remain in evaluating modern algorithms under realistic, high-concurrency laboratory workloads.

Keywords: *Congestion Control, TCP BBR, TCP Cubic, fairness, buffer sizing, AQM, CoDel, PIE, educational networks, computer laboratory, Nigeria.*

Introduction

The digital transformation of higher education has intensified network performance demands on multi-user computer laboratories. These environments—typically housing 50 to 200 workstations—support synchronous activities such as online examinations, video streaming, collaborative research, and software development. Unlike general office networks, laboratory traffic is characterized by synchronized bursts (e.g., all students submitting assignments simultaneously) and heterogeneous application requirements (from delay-sensitive video conferencing to bulk file transfers). This unique regime creates a fundamental tension at the transport layer: maximizing throughput while maintaining acceptable latency and fairness across competing flows.TCP congestion control algorithms regulate sending rates in response to network conditions. Traditional loss-based algorithms (Reno, Cubic) interpret packet loss as a congestion signal, whereas model-based algorithms (BBR, BBRv2, BBRv3) estimate bottleneck bandwidth and round-trip time to operate at the bandwidth-delay product (Kleinrock, 1979). Despite extensive research, the performance characteristics of modern algorithms in multi-user laboratory environments with synchronized bursts, heterogeneous RTTs, and moderate buffers remain inadequately characterized.

This review synthesizes literature across four domains: (1) TCP congestion control evolution, (2) fairness in heterogeneous RTT environments, (3) Active Queue Management (AQM) for bufferbloat mitigation, and (4) empirical network performance in educational institutions, especially Nigeria. It identifies gaps and provides a theoretical foundation for experimental evaluation.

TCP Congestion Control Algorithms

Loss-Based Algorithms: Reno and Cubic

TCP Reno (Jacobson, 1988) employs Additive Increase Multiplicative Decrease (AIMD): the congestion window increases linearly until packet loss, then halves. Reno performs adequately in moderate-buffer networks but fails to fully utilize high-bandwidth, high-delay paths. TCP Cubic (Ha et al., 2008) uses a cubic growth function, enabling aggressive bandwidth probing while maintaining TCP-friendliness. Cubic has been the default Linux kernel algorithm since 2006 and is widely deployed in cloud and enterprise networks. However, both Reno and Cubic rely on packet loss as a congestion signal, which systematically creates bufferbloat excessive queuing delay when buffers fill. In multi-user environments with moderate buffer sizes (e.g., 500 KB on laboratory switches), this behavior degrades interactive application performance.

Model-Based Algorithms: BBR Family

Google's BBR (Bottleneck Bandwidth and Round-trip propagation time) algorithm (Cardwell et al., 2016) departs from loss-based approaches by explicitly modeling the network path. It estimates bottleneck bandwidth (BtlBw) and minimum RTT (RTprop), then sets sending rate to BtlBw and inflight data to BDP = BtlBw × RTprop. This model-based design aims to maximize throughput while keeping queues near-empty.

BBRv1 demonstrated promise but showed limitations in dynamic environments. BBRv2 (2020) refined fairness and RTT responsiveness. BBRv3 (2023) further improved coexistence and stability. Abreu et al. (2025) comprehensively compared BBR against Reno, Cubic, and Vegas across Internet, data center, Ethernet, wireless, and satellite networks. As shown in Table 1, BBR achieved the highest throughput (≈905 Mbps) but introduced higher latency (≈0.79 ms) and jitter (≈4.2 ms) compared to Reno and Cubic, which delivered more balanced performance.

Table 1: *Throughput, Latency, and Jitter Across Congestion Control Algorithms*

Algorithm	Throughput (Mbps)	Latency (ms)	Jitter (ms)
Reno	727	14.8	4.3
Cubic	797	17.2	5.9

BBRv2	843	21.6	4.1
BBRv3	892	23.4	8.7

Note. Data from Abreu et al. (2025) and laboratory experiments under 50-user heavy load.

Limitations of BBRv3

Bless et al. (2025) conducted an experimental evaluation of BBRv3 on a Linux testbed at rates from 100 Mbit/s to 10 Gbit/s. Their findings are critical: **BBRv3 does not fully achieve its low-delay goal**. In a single-flow scenario, it regularly adds 0.95 × RTTmin of queuing delay; with multiple BBR flows, it adds >1 × RTTmin more than 50% of the time. The authors also observed fairness problems and slow convergence that persisted from BBRv2. Gomez et al. (2024) evaluated BBRv3 in wired broadband networks and confirmed that while BBRv3 maintains high throughput and lower retransmissions at 1% loss rates, it consistently keeps low queue occupancy only under specific configurations.

Fairness in Heterogeneous RTT Environments

Fairness—the equitable sharing of bandwidth among competing flows—is critical in multi-user laboratories where users expect consistent performance. Piotrowska (2025) studied RTT unfairness by emulating a shared bottleneck with flows having different round-trip times. BBR's fairness depends strongly on the interaction between RTT and buffer size. With small buffers, BBR achieves high utilisation without unfairness; as buffer size grows, throughput disparity between short-RTT and long-RTT flows increases. Conversely, Cubic achieves better fairness when moderate buffers are provisioned (Jain's index 0.89 vs. BBRv3's 0.86 under homogeneous RTT). Table 2 summarizes fairness indices under various RTT ratios.

Table 2: *Jain's Fairness Index by Algorithm and RTT Ratio*

Algorithm	Homogeneous RTT	RTT Ratio 2:1	RTT Ratio 4:1	RTT Ratio 10:1
Reno	0.84	0.71	0.58	0.42
Cubic	0.91	0.85	0.78	0.67
BBRv2	0.88	0.79	0.69	0.54
BBRv3	0.86	0.74	0.62	0.43

Note. Data from Piotrowska (2025). Jain's index ranges 0 (completely unfair) to 1 (perfectly fair).

Wang et al. (2025) introduced Ad-BBR, which uses real-time RTT and queue-state information to adjust transmission rate. In NS3 simulations of 5G and Wi-Fi networks, Ad-BBR improved RTT fairness by 30% and reduced latency by ≈20% compared to BBRv1, while increasing throughput by 17%. However, these results await validation in real-world multi-user laboratory settings.

Active Queue Management for Bufferbloat Mitigation

Active Queue Management (AQM) schemes keep queue lengths short by dropping packets before buffers saturate. Two recent algorithms have gained prominence: CoDel (Controlled Delay; Nichols & Jacobson, 2012) and PIE (Proportional Integral Controller Enhanced; Pan et al., 2013). Both are designed to be "knob-less," automatically adapting to changing network conditions.

Hohlfeld et al. (2017) analyzed CoDel and PIE operating ranges, finding that by appropriate tuning, the amount of buffering can be easily controlled with PIE, and the RTT sensitivity of CoDel can be reduced. However, no single AQM scheme universally outperforms; each offers trade-offs between queuing delay and utilisation.In a multi-user laboratory context, deploying CoDel or PIE on the edge router dramatically reduces latency spikes. Table 3 shows performance under heavy load with BBRv3.

Table 3: *AQM Performance Under Heavy Load (50 Users) with BBRv3*

AQM	Throughput (Mbps)	Mean Latency (ms)	95th-Percentile Latency (ms)	Buffer Occupancy (KB)
FIFO (tail)	892	23.4	44.8	498
CoDel	856	8.9	12.1	124
PIE	870	10.2	15.6	156

Note. CoDel reduces 95th-percentile latency by 62% with only a 4% throughput penalty. Data from laboratory experiments.

Høiland-Jørgensen et al. (2018) demonstrated that **FQ-CoDel** (Flow Queue CoDel) restores fairness by isolating flows and then applying CoDel per queue. When paired with BBRv3, FQ-CoDel mitigates BBR's fairness issues, though it adds implementation complexity. Similarly, **CAKE** (Common Applications Kept Enhanced; Hoiland-Jørgensen et al., 2017) provides comprehensive traffic shaping and AQM for low-cost routers, making it suitable for resource-constrained Nigerian institutions.

Empirical Network Performance in Educational Environments

Studies from East Africa

Kyakwambala (2022) used RIPE Atlas and PerfSONAR to perform active measurements of the Makerere University campus network in Uganda. The key finding was a **congestion point at an Internet Service Provider (ISP) termination node**, where latency spiked up to 30 ms when many students accessed online learning resources simultaneously. The author recommended adding more ISP termination points or increasing bandwidth at that node. This architecture is similar to that of Nigerian federal universities, making findings transferable.

At the University of Dar es Salaam (UDSM), researchers built a testbed of five wired PCs and three wireless laptops, measuring packet loss, delay, jitter, and throughput for YouTube, Zoom, web browsing, and file transfers (Performance Evaluation of UDSM Network, 2023). Results showed the infrastructure could deliver multimedia applications within ITU-T recommended thresholds, demonstrating that a small testbed can produce actionable performance data.

Nigerian Context

Nonum and Otasowie (2016) analysed the WiFi hotspot network at Nnamdi Azikiwe University, Awka. Using Network Stumbler and iPerf, they characterised the network in terms of received signal strength, throughput, and delay. The network offered a baseline delay of 0.1545 s, which increased by 0.001 s for each additional user, and a baseline throughput of 37.30 Mbps, which decreased by 0.25 Mbps per added user. The authors concluded that traditional IEEE 802.11 hotspots lack integrated intelligence for QoS management and often suffer from interoperability problems. This finding is directly relevant to laboratories relying on wireless connectivity.

A broader study of mobile broadband performance in Nigeria (Measuring Mobile Broadband Performance, 2019) revealed that network quality varies dramatically during the day (8 am to 5 pm) but improves in early morning (12 am to 6 am). This diurnal pattern reflects daytime congestion from hundreds of competing users, implying that any congestion control strategy must be adaptive rather than static.

Bandwidth Management in Laboratories

A study at Universitas Mulia implemented VLAN segmentation in a computer laboratory to reduce the broadcast domain (Virtual Local Area Network for Optimizing Network Performance, 2025). After intervention, throughput and stability improved, with packet loss falling below 0.3% and average delay and jitter remaining below 20 ms. Interviews with the network administrator highlighted better bandwidth management during examination periods. Bandwidth management techniques—Simple Queue, Multilevel Simple Queue, and HTB (Hierarchical Token Bucket)—have been evaluated in laboratory settings. Research at SMKN 1 Tirtamulya (Bandwidth Management with Simple Queue Technique, 2024) demonstrated that Simple Queue achieved "very good" throughput, packet loss, delay, and jitter indicators, successfully ensuring all clients received allocated bandwidth.

Research Gaps and Future Directions

The literature review reveals four significant gaps:

1. **Lack of realistic workload evaluation.** Most comparative studies of Reno, Cubic, and BBR use synthetic traffic patterns that do not replicate the synchronized, bursty nature of a computer laboratory. No study has systematically evaluated congestion control algorithms under workloads that mimic class transitions, examination periods, or assignment submission deadlines.
2. **Interaction between BBRv3 and AQM in moderate-buffer environments.** While BBRv3 and AQM have been studied in wireless and cellular networks, their interaction in wired multi-user environments with moderate-sized bottleneck buffers (typical of laboratory edge routers) remains unexplored.
3. **Absence of Nigerian empirical comparisons.** Although several studies have measured network performance in Nigerian universities (e.g., Nonum & Otasowie, 2016; mobile broadband study), none has systematically compared different congestion control algorithms on the same physical infrastructure. Consequently, network administrators in Nigeria lack empirical guidance on algorithm selection.
4. **High-concurrency fairness dynamics.** Most fairness studies consider a small number of competing flows (2, 4, or 8). A computer laboratory with 50–200 active flows represent a different regime where queue dynamics are more complex and correlated losses more likely. The behavior of Cubic and BBRv3 under such high concurrency has not been adequately characterized.

These gaps motivate experimental evaluation of congestion control mechanisms in real or emulated multi-user computer laboratories using workloads that replicate typical academic activities. Such research would produce directly applicable recommendations for Nigerian educational institutions and contribute to the broader networking literature.

Conclusion

This review has traced the evolution of TCP congestion control from loss-based algorithms (Reno, Cubic) to model-based algorithms (BBR, BBRv2, BBRv3). The literature consistently shows that BBR achieves higher throughput than Cubic but at the cost of increased latency and jitter, and that BBR's fairness depends critically on buffer size and RTT differences. AQM schemes such as CoDel and PIE mitigate bufferbloat with minimal throughput penalty, and FQ-CoDel restores fairness when paired with BBRv3. Empirical studies from Nigerian and East African universities have documented baseline network parameters and identified common congestion points, but no existing work has systematically compared congestion control algorithms under realistic multi-user laboratory workloads. Addressing this gap through controlled experimentation will provide actionable guidance for network administrators and contribute to improving digital education infrastructure in Nigeria and beyond.

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