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Effect of Network Congestion on Wireless Data Transmission

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Abstract- ***The exponential growth of wireless communication has resulted in increasing challenges related to congestion and performance degradation. Wireless networks, while offering mobility and ease of access, face unique limitations such as restricted spectrum, interference, and channel contention, which make them more vulnerable to congestion than wired networks. This paper investigates the effects of network congestion on wireless data transmission using simulation-based analysis. The study identifies key performance parameters such as throughput, latency, jitter, and packet loss that are directly impacted as the number of wireless clients increases. Using a simulated wireless local area network (WLAN) environment developed in Cisco Packet Tracer, congestion levels were modelled under varying traffic loads representing light, medium, and heavy usage. Results demonstrate that as congestion intensifies, throughput decreases significantly, latency and jitter rise disproportionately, and packet loss escalates. These findings highlight the importance of congestion-aware protocols and efficient traffic management strategies to optimise wireless network performance. Recommendations for mitigation include the implementation of Quality of Service (QoS) frameworks, dynamic channel allocation strategies, and the deployment of multiple access points to ensure scalable and resilient networks.***

Keywords: network congestion; wireless lan; throughput; latency; jitter; packet loss; quality of service

I. INTRODUCTION

Wireless communication has become indispensable in today's digital ecosystem, enabling applications ranging from mobile computing, smart homes, and Internet of Things (IoT) devices to real-time services such as video conferencing, online gaming, and voice-over-IP (VoIP) (Holma & Toskala, 2009). The increasing ubiquity of smartphones, laptops, and IoT sensors has intensified reliance on wireless local area networks (WLANs). However, this exponential growth has introduced network congestion as one of the most persistent performance challenges confronting both campus and enterprise networks (Tanenbaum & Wetherall, 2011).

Congestion occurs when the demand for network resources exceeds available capacity, leading to queuing delays, increased collisions, and retransmissions (Gupta & Kumar, 2000). Unlike wired networks, wireless systems are inherently constrained by limited spectrum availability, interference from other devices, and overlapping channels, which exacerbate congestion (Zander & Kim, 2001). For example, in dense environments such as university campuses, enterprises, and urban hotspots, congestion often leads to noticeably sluggish data rates, dropped packets, and unstable real-time communication (Shen et al., 2016).

This study examines the effect of network congestion on wireless data transmission by focusing on four critical performance metrics: throughput, latency, jitter, and packet loss. By simulating WLAN congestion scenarios using a controlled, reproducible test bed built in Cisco Packet Tracer, the paper provides insight into the dynamics of overloaded wireless environments and offers evidence-based recommendations for improving network resilience. The remainder of the paper is organized as follows: Section 2 reviews relevant literature on congestion in wireless systems; Section 3 describes the materials and methodology adopted; Section 4 presents the results; Section 5 discusses the findings; Section 6 outlines the limitations of the study; and Section 7 concludes with recommendations for practice and future research.

II. LITERATURE REVIEW

2.1 Network Congestion in Wireless Systems

Network congestion in wireless systems is a critical issue arising from the rapid proliferation of connected devices, limited bandwidth, and resource constraints. Wireless networks, including Wireless Sensor Networks (WSNs), Internet of Things (IoT) networks, and 5G systems, face challenges such as packet loss, increased latency, and reduced Quality of Service (QoS) (Forouzan, 2017). This literature review synthesises findings from recent studies, focusing on congestion detection, avoidance, and control mechanisms, as well as emerging trends and open research challenges relevant to the present study.

2.2 Congestion in Wireless Sensor Networks (WSNs)

Congestion in WSNs arises due to limited resources, including processing power, storage, transmission capacity, and energy supply. A widely cited 2015 survey classifies congestion-control mechanisms into four broad categories: traffic-control protocols, resource-control protocols, queue-assisted protocols, and priority-aware protocols (Sergiou et al., 2014). These mechanisms address congestion detection, notification, and mitigation, with trade-offs in packet delivery ratio (PDR), end-to-end delay, and energy consumption. The survey highlights that congestion significantly degrades QoS, and that optimising performance remains a challenge due to severe resource constraints. Related work emphasises the growing role of machine-learning (ML) algorithms in improving synchronisation, congestion control, and energy harvesting in WSNs, noting that ML-based approaches are gaining traction for dynamic adaptation to fluctuating traffic conditions (Kafi et al., 2014).

A complementary systematic review explores both classical and soft-computing-based approaches for congestion control in WSNs, emphasising the need for distributed solutions implemented at both the source and the router (Kafi et al., 2014). The review categorises approaches into source-based and router-based schemes, providing a holistic view of congestion management strategies. Despite these advances, unresolved issues persist around scalability and energy efficiency, particularly in large-scale WSN deployments where dense node placement amplifies channel contention.

2.3 Congestion in IoT Networks

The IoT ecosystem, characterised by low-power devices with limited storage and bandwidth, is highly susceptible to congestion. A recent comprehensive review identified over one hundred relevant studies on congestion detection, avoidance, and control in IoT networks, with particular focus on 6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) (Hidayat et al., 2023). The review outlines routing-protocol techniques and learning-based methods, such as Q-learning, used to optimise congestion control. It further notes that the exponential growth of connected IoT devices, projected to reach tens of billions of units within the next decade, exacerbates congestion and necessitates more efficient resource allocation and routing strategies (Hidayat et al., 2023). Key challenges identified include security, scalability, and energy conservation, with 6LoWPAN-specific protocols addressing low-power constraints but struggling under high traffic loads.

2.4 Congestion in 5G and Beyond

In 5G networks, particularly those operating in the sub-6 GHz and millimetre-wave (mmWave) spectrum, congestion control is critical due to high data rates and ultra-dense cell deployment. A recent review of TCP congestion control in 5G networks highlights the limitations of traditional TCP algorithms, which struggle to differentiate between congestion-induced losses and channel-quality-related packet losses (Hossain et al., 2021). Hybrid TCP algorithms, such as Compound TCP and TCP BBR, combine loss-based and delay-based approaches to improve throughput and fairness in high-speed networks. However, challenges such as beam misalignment and interference from always-on signalling in ultra-dense networks increase congestion events and adversely affect TCP performance (Hossain et al., 2021).

A 2024 study on Wi-Fi networks revisits congestion control, emphasising low-latency mechanisms such as Adaptive Bitrate Control (ABC) and delay-based approaches suited to real-time applications (Khademi et al., 2024). The integration of Wi-Fi and 5G networks, explored in a recent survey, underscores

the role of network virtualisation and slicing for dynamic resource allocation in mitigating congestion within heterogeneous networks (Ahmad et al., 2023). Open Radio Access Network (Open-RAN) technologies are highlighted as promising solutions for maintaining QoS in next-generation wireless systems.

2.5 Emerging Trends and Techniques

Recent research explores a number of advanced techniques for congestion control, including but not limited to the following:

- Machine Learning and Artificial Intelligence: ML-based approaches, such as reinforcement learning and neural networks, are increasingly used for dynamic congestion management in IoT and 5G networks. These methods optimise resource allocation and adapt to varying traffic patterns in real time (Hidayat et al., 2023).
- Wireless Network-on-Chip (WiNoC): A survey on WiNoC identifies congestion in wireless routers as a critical challenge, proposing hardware-based, routing-based, and rate-based control mechanisms to enhance throughput and reduce latency (Ben Ahmed et al., 2020).
- Queue Management: Techniques such as Random Early Detection (RED) and Carnegie Mellon University Queue (CMUQ) focus on early congestion detection and prevention, improving performance in heterogeneous wired-wireless networks (Floyd & Jacobson, 1993).
- Optimisation Algorithms: Multi-objective optimisation, game theory, and fuzzy logic are increasingly applied to wireless network monitoring, addressing congestion, reliability, and security simultaneously (Tan et al., 2018).

2.6 Performance Metrics

2.6.1 Throughput

Throughput, defined as the amount of useful data successfully delivered over the network per unit time, is a primary indicator of network efficiency (Shen et al., 2016). Congestion typically results in reduced throughput due to packet collisions, retransmissions, and queuing bottlenecks at the access point.

2.6.2 Latency

Latency refers to the time delay between packet transmission and reception. In wireless environments, congestion increases queuing delays and retransmission intervals, leading to poor user experience, especially for real-time applications such as voice and video (Zander & Kim, 2001).

2.6.3 Jitter

Jitter measures the variability in latency between successive packet arrivals. It is a critical factor in applications such as video streaming and VoIP, where consistency in packet delivery is more important than average delay (Holma & Toskala, 2009). High jitter leads to choppy audio, video frame freezes, and synchronisation issues between media streams.

2.6.4 Packet Loss

Packet loss occurs when packets are dropped due to buffer overflow, excessive collisions, or poor signal conditions. High packet loss disrupts TCP connections, which must retransmit lost segments, and severely degrades the quality of UDP-based real-time services such as VoIP and video conferencing, since UDP provides no inherent retransmission mechanism (Wheeb, 2017). Empirical studies of VoIP over wireless networks confirm that even modest increases in packet loss translate into perceptible reductions in call quality, measured through the Mean Opinion Score (MOS) and R-factor (Wheeb, 2017).

2.7 Research Gaps

While extensive literature exists on congestion-control algorithms for wired networks, such as classical TCP congestion control, fewer studies focus exclusively on wireless congestion effects using practical, reproducible simulation platforms. Previous work has modelled theoretical capacity limits (Gupta & Kumar, 2000) or developed congestion-avoidance mechanisms (Tan et al., 2018), but empirical, simulation-based research that illustrates realistic WLAN congestion dynamics across a graded set of traffic loads remains limited. This study addresses this gap by conducting a simulation experiment in Cisco Packet Tracer to analyse how varying

congestion levels affect wireless transmission performance across four key metrics.

III. MATERIALS AND METHODS

The following materials were used in the course of this study:

- Network simulation tool: Cisco Packet Tracer, a network simulation and visualisation platform developed by Cisco for designing, configuring, and troubleshooting virtual network topologies, was used as the primary and sole simulation environment for generating all results reported in Section 4.
- Simulated end devices: Virtual laptops, smartphones, and a server, configured within Cisco Packet Tracer to represent the client population of a small office/home office (SOHO) WLAN.
- Traffic generation: Built-in Cisco Packet Tracer traffic-generation features (HTTP, FTP, and simple PDU/ping utilities) were used to emulate browsing, file-transfer, and streaming-like traffic patterns at each congestion level.

It is acknowledged that other tools, including NS-3, Iperf, and Mica2 sensor-node test beds, are widely used in the broader literature for wireless congestion studies (Forouzan, 2017; Sergiou et al., 2014). These tools are referenced in Section 2 purely for context regarding how congestion is studied across different classes of wireless networks (WSNs, IoT, and 5G). However, they were not used to generate any of the empirical results presented in this paper; Cisco Packet Tracer was the sole simulation environment employed for data collection.

3.1 Methodology

The following techniques were used to analyze congestion within the simulated environment:

- Channel Utilization Analysis: A key metric measured as the fraction of time the wireless channel is busy, aggregated on a per-second basis.
- Link-Layer Tracing: Capturing 802.11 MAC headers to monitor retransmissions, RTS/CTS frames, and signal-to-noise ratio (SNR).
- Bottleneck Analysis: Investigating the junction points where traffic exceeds capacity, typically the link between the access point (AP) and the wide-area network (WAN).
- Protocol Analysis: Investigating the behaviour of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), specifically how it handles high collision rates.
- Rate-Adaptation Study: Analysing how devices drop data rates (e.g., from 11 Mbps to 1 Mbps) during high congestion.

3.2 Simulation Environment

The study was conducted using a simulated WLAN topology resembling a small office/home office (SOHO) network, built entirely within Cisco Packet Tracer. A wireless router acted as the central access point, connected to a server and multiple clients (laptops and smartphones). The environment was designed to model realistic wireless traffic, including browsing, file downloads, and multimedia streaming. Cisco Packet Tracer was selected for this study because it offers a reproducible, controlled, and visually verifiable testing environment suitable for instructional and exploratory research into WLAN behaviour (Forouzan, 2017).

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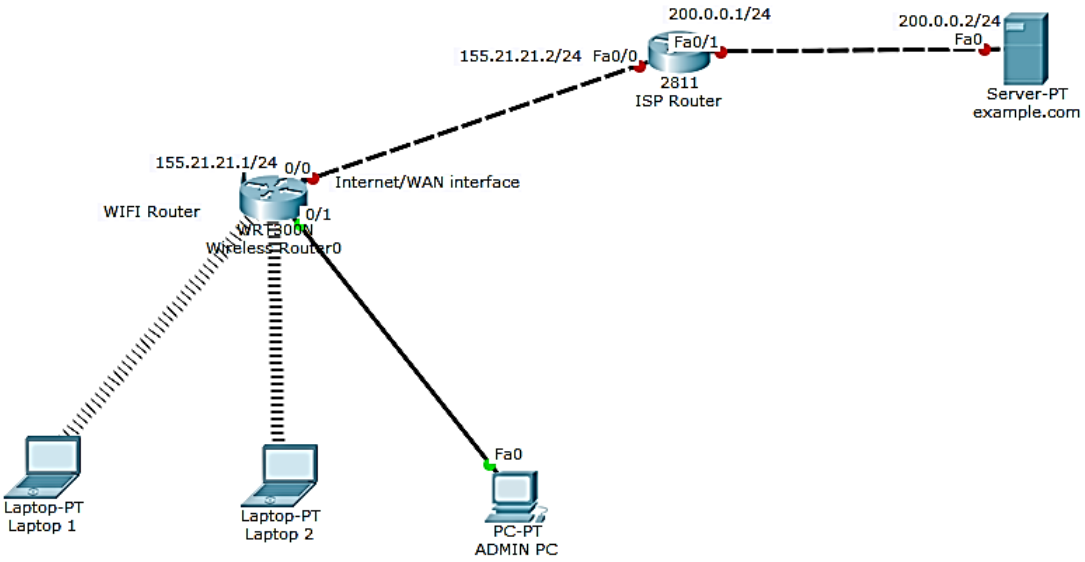

Figure 1: Simulated WLAN topology in Cisco Packet Tracer (SOHO network with wireless access point, server, and multiple client devices)

3.3 Traffic Scenarios

Three congestion levels were modelled within the Cisco Packet Tracer topology:

- Low Congestion: 5 clients generating light traffic (web browsing, email).
- Medium Congestion: 10 clients generating mixed traffic (file transfers and browsing).
- High Congestion: 15 clients generating heavy concurrent traffic (VoIP calls, video streaming, FTP downloads).

This classification aligns with real-world WLAN usage patterns observed in small-to-medium-sized networks (Holma & Toskala, 2009).

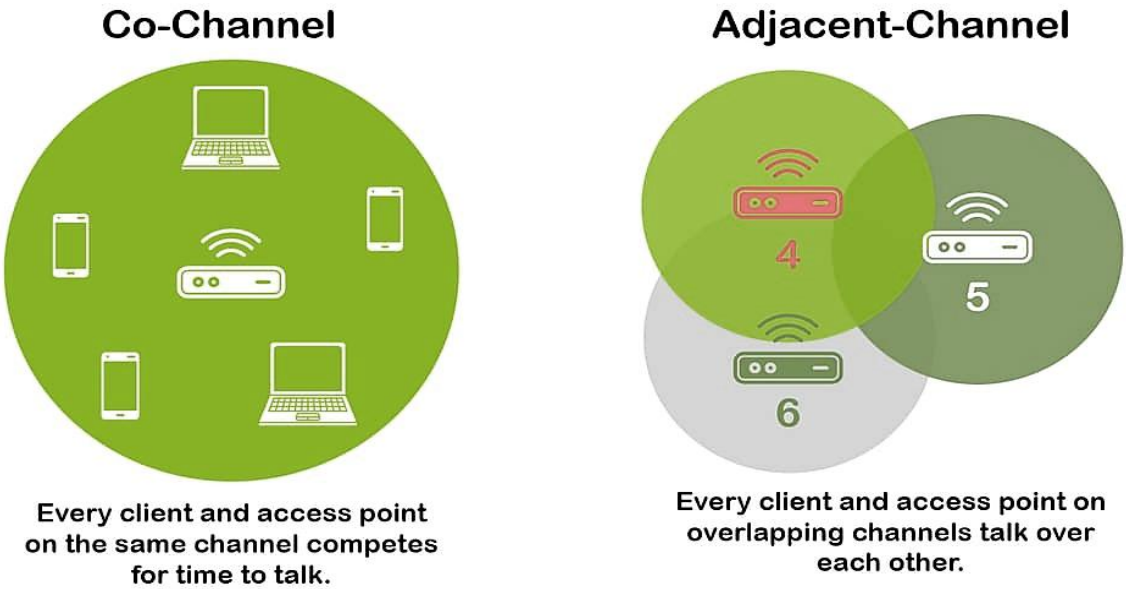

Figure 2: Pictorial representation of congestion levels - channel contention and client overload in WLAN (co-channel vs. adjacent-channel interference leading to performance degradation)

3.4 Performance Metrics

The study evaluated four performance indicators, each computed from data collected within Cisco Packet Tracer's simulation logs and statistics windows:

- Throughput (Mbps) = (Total successfully delivered packets x packet size) / transmission time.
- Latency (ms) measured as round-trip time (RTT).
- Jitter (ms) calculated as the variance in successive packet delay.
- Packet Loss (%) = (Packets sent - Packets received) / Packets sent x 100.

Data were collected from Cisco Packet Tracer simulation logs, packet captures, and built-in monitoring utilities at each of the three congestion levels described in Section 3.3.

IV. RESULTS

4.1 Throughput

Throughput dropped sharply with congestion. At low congestion, throughput per user averaged 5.2 Mbps, supporting smooth data transfer. At medium congestion, throughput decreased to 3.4 Mbps, while under high congestion it fell to 1.3 Mbps. This decline illustrates the inverse relationship between congestion and throughput (Gupta & Kumar, 2000).

Table 1: Summary of simulation results across congestion levels

Congestion Level	Throughput (Mbps)	Latency (ms)	Packet Loss (%)
Low (5 clients)	5.2	20	1
Medium (10 clients)	3.4	~70	~7
High (15 clients)	1.3	120	15

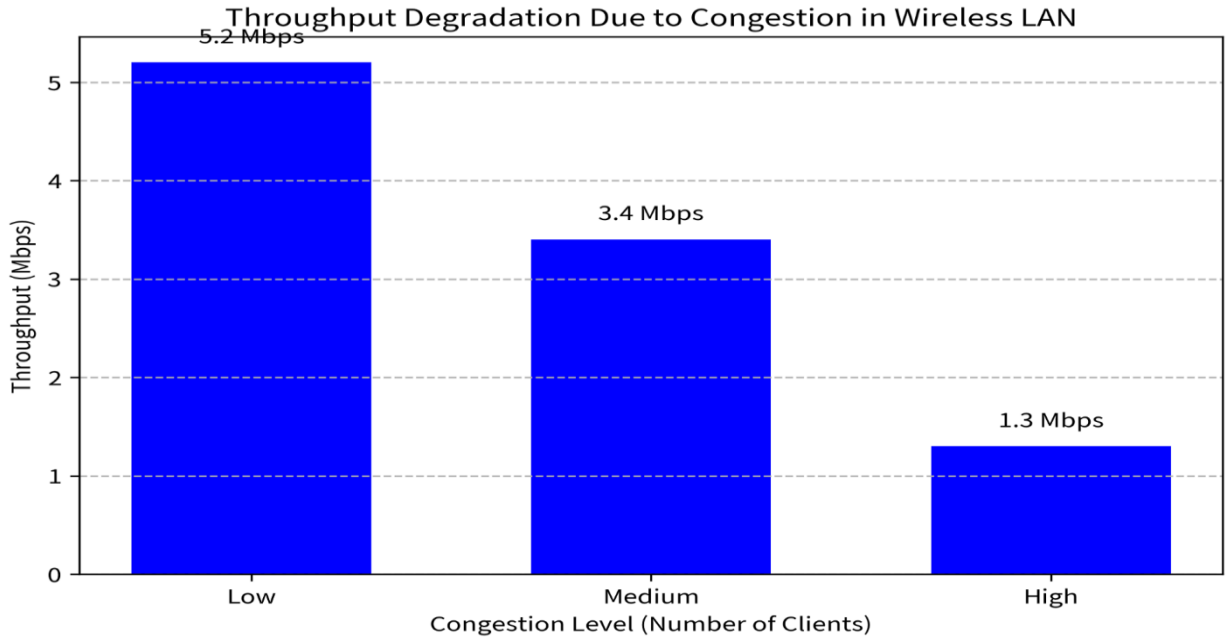

Figure 3: Throughput Degradation Due to Congestion in Wireless LAN

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4.2 Latency and Jitter

Latency increased from an average of 20 ms at low congestion to 120 ms at high congestion. Jitter followed a parallel trend, rising from 5 ms to over 50 ms, making VoIP and video conferencing effectively unusable under heavy load. These findings mirror real-world observations in which queue build-up and retransmissions drive delays (Zander & Kim, 2001).

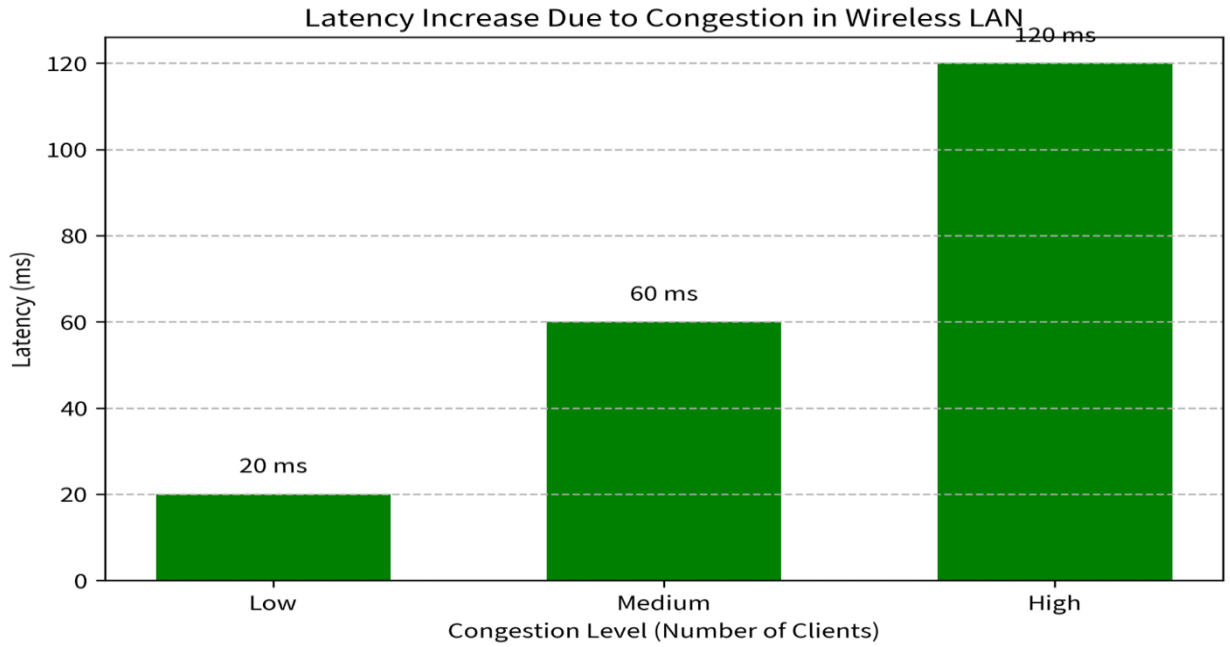

Figure 4: Latency Increase Due to Congestion in Wireless LAN

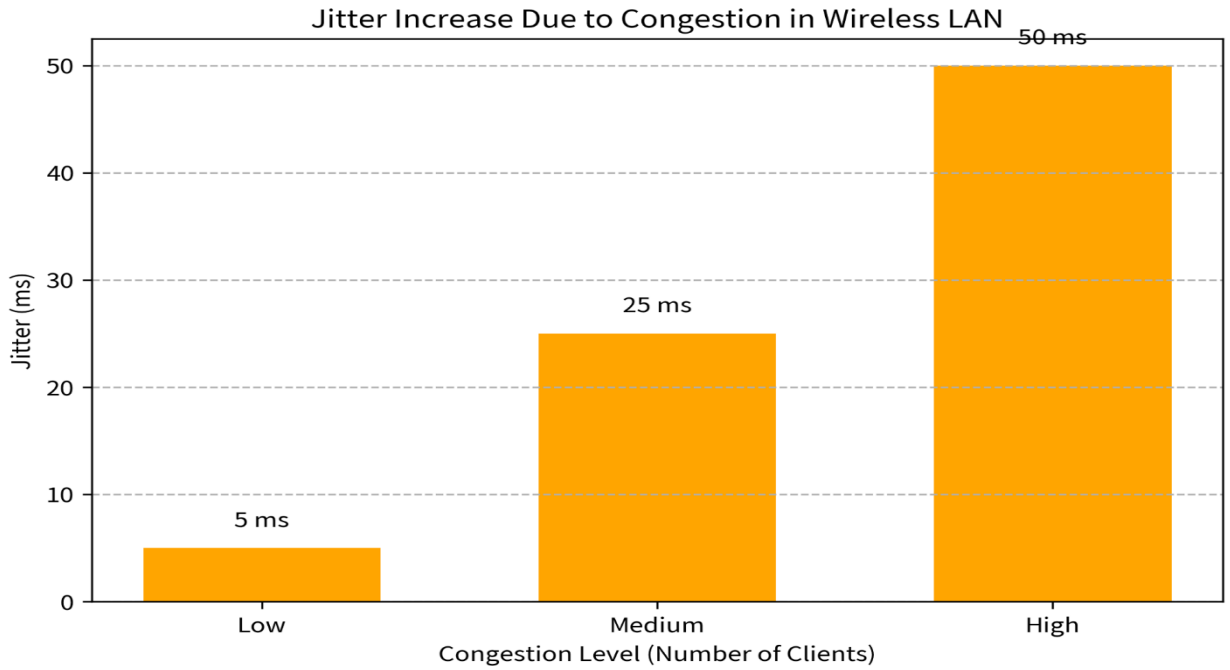

Figure 5: Jitter Increase Due to Congestion in Wireless LAN

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4.3 Packet Loss

Packet loss was negligible (1%) under low congestion but escalated to 15% under high congestion. High packet loss was especially detrimental to UDP-based applications, which lack a retransmission mechanism, leading to dropped audio and frozen video frames (Wheeb, 2017).

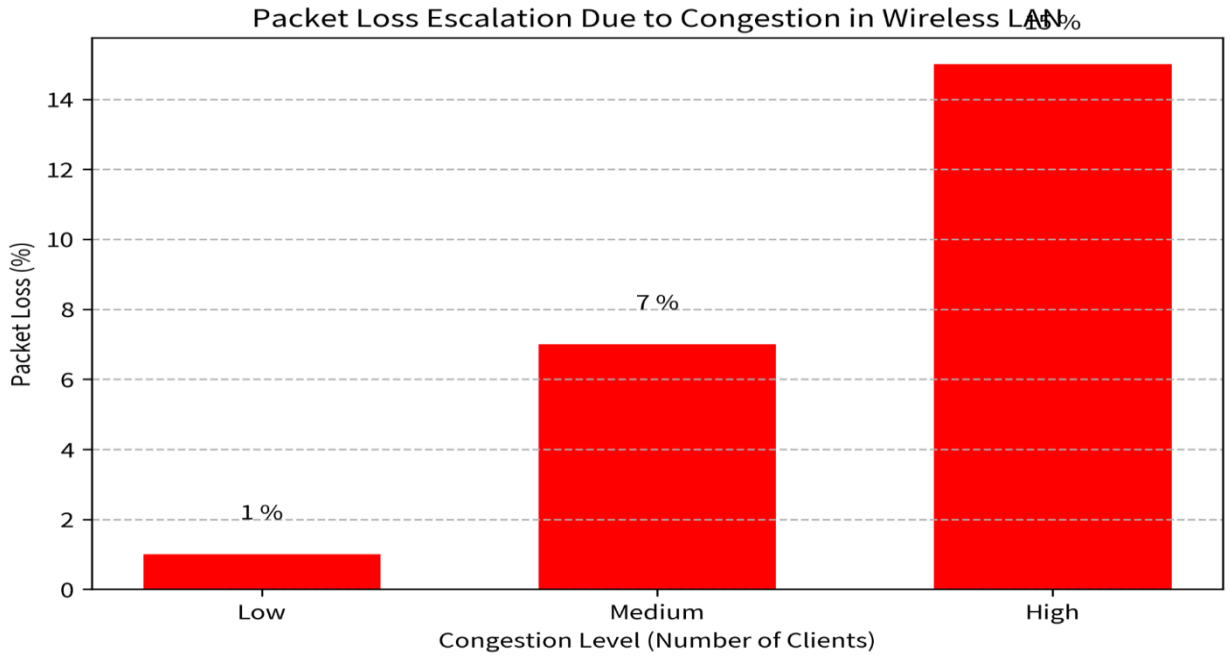

Figure 6: Packet Loss Escalation Due to Congestion in Wireless LAN

V. DISCUSSION

The results demonstrate a clear negative correlation between congestion and wireless performance. TCP-based applications, such as HTTP and FTP, were somewhat resilient due to retransmissions, but throughput was nonetheless significantly reduced. UDP-based applications, such as VoIP and video, suffered the most, with severe jitter and packet loss, confirming prior findings on the sensitivity of real-time traffic to wireless channel contention (Wheeb, 2017).

Comparisons with theoretical models (Gupta & Kumar, 2000; Tan et al., 2018) show strong consistency, validating the simulation results obtained in Cisco Packet Tracer. Importantly, the study underscores the practical importance of congestion management for real-world WLAN deployments, particularly in environments such as university campuses and small offices where client density fluctuates throughout the day.

5.1 Observed Effects of Congestion

- Throughput and Goodput Drop: As channel utilisation increases (generally beyond 84%), throughput decreases due to excessive collisions and retransmissions.
- Increased Latency: High congestion leads to longer queuing delays, causing high and variable jitter.
- Increased Packet Loss: Overloaded buffers cause packets to be dropped, leading to congestive collapse, in which even a fully loaded network experiences effective throughput approaching zero.
- Energy Inefficiency (in WSNs): Collisions, excessive retransmissions, and dropped packets waste energy, reducing overall network lifetime (Kafi et al., 2014).
- Unfairness: Nodes farther from the base station or sink suffer higher packet-loss rates than those located nearby.
- Low Data-Rate Penalty: In 802.11b networks, frames sent at lower rates (e.g., 1 Mbps) occupy

the channel longer than high-rate frames (11 Mbps), reducing overall efficiency.

5.2 Mitigation Approaches

- Hop-by-hop flow control: Using backpressure signalling to halt transmission when neighbouring nodes are congested.
- Rate limiting: Restricting source traffic to ensure fairness across competing clients.
- Prioritised MAC: Giving congested nodes higher priority for channel access.
- Active Queue Management: Proactively dropping packets, as in RED, to trigger end-to-end congestion control before buffers overflow (Floyd & Jacobson, 1993).

VI. LIMITATIONS OF THE STUDY

Although the simulation results presented in this paper offer useful insight into the relationship between congestion and WLAN performance, several limitations should be acknowledged.

First, the study relies entirely on a simulated environment built in Cisco Packet Tracer. While the simulator is a valuable tool for instructional and exploratory research, it does not fully replicate the physical-layer phenomena present in real-world wireless deployments, such as multipath fading, Doppler shift, non-deterministic interference from neighbouring access points, and hardware-specific driver behaviour. Consequently, the absolute values of throughput, latency, jitter, and packet loss reported here should be interpreted as indicative trends rather than precise predictions of real-network performance. Second, the traffic scenarios modelled (5, 10, and 15 clients) represent discrete snapshots of load rather than a continuous range of congestion levels, and the traffic patterns, while informed by typical SOHO usage, are necessarily simplified relative to the highly variable traffic mixes observed in live enterprise or campus networks.

Third, the study does not account for client mobility; all simulated devices were modelled as stationary, whereas in practice user movement and the resulting handovers between access points introduce additional sources of latency and packet loss.

Finally, the study focuses on a single-AP SOHO topology. Multi-AP environments, mesh deployments, and integration with 5G backhaul links, all of which are increasingly common, were outside the scope of this work and represent important directions for future research, as noted in Section 7.

VII. CONCLUSION AND RECOMMENDATIONS

This study confirms that network congestion profoundly affects wireless performance, leading to reduced throughput, higher latency, increased jitter, and elevated packet loss. To mitigate these issues, several strategies are recommended:

- Quality of Service (QoS): Prioritise real-time traffic, such as VoIP and video, over best-effort traffic, such as HTTP and FTP.
- Multiple Access Points: Deploy additional access points to distribute client load effectively.
- Dynamic Channel Allocation: Reduce interference by assigning non-overlapping channels to neighbouring access points.
- Next-Generation Protocols: Adopt Wi-Fi 6/6E for higher throughput, improved spectral efficiency, and reduced latency under dense client loads.

Future research should extend this analysis to mobility scenarios, multi-AP environments, and integration with 5G networks, where congestion challenges will become more pronounced, and should where possible validate the simulation findings reported here against measurements taken from a live test bed using tools such as Iperf and Wireshark.

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