Investigation of Software-Defined Networking (SDN) to Enhance Wi-Fi Networks in University Campus

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Original scientific article

***Abstract*—As Wi-Fi networks become integral to university campuses, traditional management frameworks exhibit operational inefficiencies. This study gives a detailed set of research solutions for this field. We used a simulator to test these solutions, checking six things: throughput, latency, jitter, packet loss, SNR, and energy use. We tested what would happen when things went wrong in a setup with 100 access points and 500 users. The results suggest that networks improved with SDN had an 84.6% rise in average throughput and a 39.3% drop in latency when compared to regular Wi-Fi. Jitter went down by 0.15 ms, packet loss peaks decreased by 3.7%, and average SNR went up by 4 dB. The EMA scheduler reached a fairness index above 0.99 in five minutes, and access point energy use decreased by 13%. These results point to the SDWAN's ability to allocate bandwidth well, keep QoS/QoE consistent, and change to fit campus environments. This research gives a useful structure for putting these solutions into a real network.**

***Index Terms*—SDN, WLAN, Campus Network, SDWAN, Mininet.**

I. INTRODUCTION

COMPUTER networks have, over time, become very complicated such that the technologies and protocols that were used before now cannot meet network needs. Most of the traditional network devices like switches, routers, security appliances, and servers run on proprietary systems, especially when they are from different manufacturers. These systems face the problem of compatibility and finding network management software that can offer a centralized and a comprehensive view of network traffic. Even though network management protocols in traditional networks provide a certain degree of centralized control, their capabilities are still very limited. For instance, Wi-Fi networks have problems such as slow innovation, operational complexity, and high costs. On the other hand, software-defined networks (SDN) have, to a great extent, changed the way networks are built and managed. SDN has a layered architecture where operations are divided into two levels: the control layer which is in charge of deciding how traffic should be handled and the forwarding layer which sends the traffic to the destination based on the control layer's instructions [1]. The main difference which comes down to the separation of the control plane from the data plane and the provision of network programmability through software-based controllers instead of embedded device logic is that SDN deployments usually have the same switches and access points as traditional networks.

SDN uses Application Programming Interfaces (APIs) to allow the control and data planes to communicate, thus, a single program can manage all network elements. In the field of SDN, one of the most popular protocols is OpenFlow [2], which is a standard set by the Open Network Foundation. OpenFlow implements a centralized controller that holds the tables of the rules for the network traffic. The rules may include actions like dropping, changing, or redirecting the packets. These rules are based on flow-level management instead of the traditional destination-based routing. The OpenFlow controller is a matching/action system, where the predefined rules indicate the packets to be matched and the corresponding actions to be performed. The structure allows the use of wildcards for various network features, e.g. layer-2, layer-3, and layer-4 packet headers, as well as protocols like MPLS to be matched.

SDN relies on core ideas [3]. It lets users directly program the system through separating control and forwarding. This gives network managers the option to change traffic flow right away. Separating control from forwarding also makes systems more agile since settings can change as traffic changes. A main part of SDN is its central handling. Software controllers keep a broad view of the system, giving applications a single look at it. In an SDWAN campus, a central controller checks link quality, interference, and client movement to change channels and power right away. This differs from old Wi-Fi setups where access points work on their own, causing poor use of resources and wasted power [4], [5].

This paper gives many research ideas for this area, along with how they work using a simulator. The study does not give a ready-made answer, but it does show a way to consider how to build these ideas into a real system.

Some of the key contributions in this paper are:

- *Network Campus Analysis:* the study provides a realistic analysis of campus network problems, focusing on the application of software management as an effective means of addressing these challenges.
- *Centralised SDWAN Control Plane:* it demonstrates a

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controller that dynamically assigns channels, power levels, and AP associations in real time for 100 APs and 500 clients.
- *Analytical Throughput/Latency Model:* closed-form expressions (Eqs.1–6) validated against simulation, showing up to 84.6% throughput gain and 39.3% latency.
- *Packet-loss Rate Simulation:* modeling base loss (3% traditional, 1% SDN) and random spikes, demonstrating SDN's up to 3.7% reduction in peak loss.
- *SNR Improvement Analysis:* simulating average SNR increase from 20 dB to 24 dB via centralized interference management.
- *EMA-smoothed Proportional-fairness Scheduler:* dynamically reallocates total campus bandwidth using an exponential moving average (α = 0.5) to drive Jain's fairness index from 0.83 to 0.99 within five minutes.

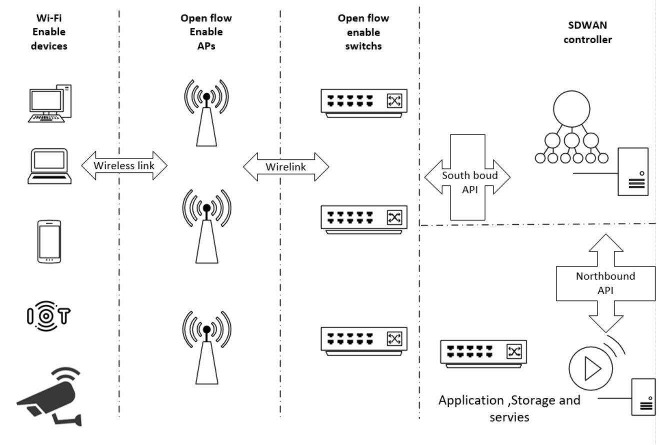

Fig. 1. SDWAN Components in Campus Networks.

The remainder of this paper is organized as follows: Section II surveys related SDN/Wi-Fi work; Section III derives our analytical model; Section IV maps challenges and solutions; Section V lists simulation parameters; Section VI presents results including subsections on throughput/latency, streaming recovery, jitter, packet-loss, energy consumption, SNR, and fairness; Section VII concludes; and Section VIII outlines future work.

II. RELATED WORKS

The concept of software-defined networks is increasingly being adopted on campuses. Recent research on Software-Defined Networking (SDN) demonstrates a wide-ranging impact on how networks are managed and optimized. In [6], for example, a comparative performance analysis between SDN and conventional IP networks is presented. The authors outline the significant changes in latency and bandwidth that can be expected as a result of separation of the control and data planes from a traditional network architecture. This research represents the practical benefits of SDN adoption; thus, it forms a basis for further studies. Also, [7] investigates the unification of heterogeneous wireless networks under a single SDN framework. It mentions that an SDN-based architecture, by supporting the convergence of different radio access technologies, can provide a dynamic service configuration as well as an unbroken user experience in the converged communication environment. Hence, SDN is seen as the solution of the future for the integration of the wireless system. To satisfy the needs of delay-sensitive applications, [8] presents a method which guarantees delay in Wi-Fi networks by using an SDN-based approach. The process concentrates on the SDN controller adjusting the queues dynamically and observing the situation in real-time, whereby it manages to bring about latency of a certain level that can be predicted even in a situation of network congestion. The paper can be a source of the most essential information for such fields as real-time communications and IoT. Performance of the SDN controllers has a great impact on the whole capability for network management. In the relevant paper [9], research authors evaluate one of the OpenFlow-based controllers by looking into packet handling ability alongside other indices for good performance. Their practical work not only brings to light contrasts between the controllers but also helps to answer the question of choosing the right one in accordance with the local conditions suggested by the scenario of deployment. In the meantime, [10] comprises a wide-ranging discussion of issues and prospects pertinent to the introduction of SDN-based wireless networks.

The paper discusses wireless-specific issues such as link isolation, channel estimation, and interference management, while also outlining future research directions to further exploit the benefits of SDN in both urban and high-density environments. Authors in [11] present a model for implementing SDN infrastructure for an e-learning cloud to be more reliable, resilient, and flexible design. Despite the study's focus on e-learning, all university services were not considered. Further, to address the emerging networking challenges, a software-defined network (SDN)-based design is proposed in [12] for managing Al-Zaytoonah University of Jordan's network. An SDN design is proposed to overcome the limitations of the tradition deployed networks. A transition from traditional to software-defined networks is accompanied by a number of requirements, which were not considered in the study.

Furthermore, the paper [13] presents a new architecture for campus and enterprise networks that combines SDN and OpenFlow. It considers designing and developing an application to manage and troubleshoot the VLANs in this architecture easily and flexibly. In fact, the study does not provide enough information to emerge Wi-Fi networks. Then, in this article [14] the IoT concept is contextualized from a security perspective, interoperability between VLANs, and software-defined networks. An intelligent infrastructure is presented to support all processes by considering existing architectures and technologies, the research endeavor solely focused on applications pertaining to the Internet of Things paradigm. Also, the author [15] implements the SDN framework for the management of campus network will ensure flexible campus network management, efficiency of data transmission within the campus network. In addition, virtualization and software-defined data centers (SDDCs) are used in this study [16] to construct campus culture at medical colleges and universities. Hence, only one department within a university setting was investigated. It was not the intention of the researchers to draw broad generalizations. The other study [17] suggests deploying an SDN control server and configuring the network equipment in order to implement a network transformation scheme based on SDN. However, the study only examines the management challenge.

This study examines how Software-Defined Networking (SDN), deployed via SDWAN, can overcome the unique management and performance challenges of university Wi-Fi networks. Unlike traditional approaches that struggle with channel interference, suboptimal traffic handling, and uneven user experience, this SDN-based design offers centralized control, real-time QoS/QoE optimization, and dynamic network tuning. By tailoring the framework to campus-specific variables user roles, application mixes, and institutional requirements to fill a gap in existing research, which often overlooks the distinct characteristics of educational environments. It is also worth mentioning that when designing an enterprise Wi-Fi network that supports diverse applications, researchers often lack a realistic view of the real-world problems and the ability to use research tools to solve them. This study offers a comprehensive perspective on this type of network, as well as proposing the use of software-managed networks as a solution to the associated problems.

III. SIMPLIFIED MATHEMATICAL MODEL FOR THE TRADITIONAL APPROACH

A. Analytical Throughput and Latency Model

The throughput for SDN and traditional networks is influenced primarily by the network load and packet processing capabilities. A better model would be

$$\mathbf{T_{traditional}}\left(\mathbf{t}\right)=\mathbf{T_{init}}+\mathbf{\Delta T_{traditional}}\times\frac{\mathbf{t}}{\mathbf{T_{total}}} \tag{1}$$

where $T_{traditional}(t)$ is the throughput of the traditional network at time t, measured in Mbps, T_{init} is the initial throughput at $t = 0$, equal to 30 Mbps in our model,$\Delta T_{traditional}$ is the incremental increase in throughput over the entire simulation period, set to 5 Mbps, t is the current time in seconds, T_{total} is the total simulation duration, equal to 300 seconds (5 minutes). The initial throughput parameter T_{init} (30 Mbps) represents the baseline performance at the beginning of the observation period [18], [19].

The SDN-enhanced Wi-Fi network follows a similar mathematical structure but with significantly different parameters:

$$\mathbf{T_{sdn}}\left(\mathbf{t}\right)=\mathbf{T_{init-sdn}}+\mathbf{\Delta T_{sdn}}\times\frac{\mathbf{t}}{\mathbf{T_{total}}} \tag{2}$$

where $T_{sdn}(t)$ is the throughput of the SDN network at time t, measured in Mbps, $T_{init-sdn}$ is the initial throughput for the SDN network, equal to 50 Mbps, ΔT_{sdn} is the incremental increase in throughput over the simulation period, set to 20 Mbps, t and T_{total} are the same as in the traditional model, and the initial throughput $T_{init-sdn}$ (50 Mbps) is substantially higher than in traditional networks.

Latency can be modeled as decreasing due to improved traffic management in SDN, so it adopt a linear decrease for SDN and a slight decrease for traditional:

$$\mathbf{D_{traditional}}\left(\mathbf{t}\right)=\mathbf{D_{init}}-\mathbf{\Delta D_{traditional}}\times\frac{\mathbf{t}}{\mathbf{T_{total}}} \tag{3}$$

where, $D_{traditional}(t)$ is the latency of the traditional network at time t, measured in milliseconds (ms), D_{init} is the initial latency at $t = 0$, equal to 30 ms, $\Delta D_{traditional}$ is the total latency reduction over the simulation period, set to 4 ms, and t & T_{total} are as defined previously.

As for the SDN network's latency model, it is as follows:

$$\mathbf{D_{sdn}}\left(\mathbf{t}\right)=\mathbf{D_{init-sdn}}-\mathbf{\Delta D_{sdn}}\times\frac{\mathbf{t}}{\mathbf{T_{total}}} \tag{4}$$

where, $D_{sdn}(t)$ is the latency of the SDN network at time t, measured in milliseconds, $D_{init-sdn}$ is the initial latency for the SDN network, equal to 20 ms, ΔD_{sdn} is the total latency reduction over the simulation period, set to 6 ms, and t & T_{total} remain as previously defined [20], [21].

During network disruptions, throughput degradation is modeled as:

$$\mathbf{T_{degraded}}\left(\mathbf{t}\right)=\mathbf{T_{normal}}\times\left(\mathbf{1}-\mathbf{DF}\times\left(\mathbf{1}-\mathbf{RP}\right)\right) \tag{5}$$

where $T_{degraded}(t)$ is the degraded throughput at time t during the disruption period, T_{normal} is the normal throughput that would be expected at time t without disruption, DF is the Degradation Factor (DF), equal to 0.37 for traditional networks and 0.26 for SDN networks, RP is the Recovery Progress, calculated as $RP = \frac{t-t_{start}}{t_{recovery}}$, t_{start} is the time when degradation begins, $t_{recovery}$ is the recovery time, equal to 8 seconds for traditional networks and 5 seconds for SDN networks, and he normal throughput T_{normal} represents the performance before the degradation event occurs. The DF represents the maximum percentage throughput reduction at the beginning of the disruption. For traditional networks, DF is 0.37 (37% drop), while for SDN networks, it's only 0.26 (26% drop).

Network disruptions typically affect latency more severely than throughput, modeled as:

$$\mathbf{D_{degraded}}\left(\mathbf{t}\right)=\mathbf{D_{normal}}\times\left(\mathbf{1}+\mathbf{DF}\times\left(\mathbf{1}-\mathbf{RP}\right)\times\mathbf{LF}\right) \tag{6}$$

where $D_{degraded}(t)$ is the degraded latency at time t during the disruption period, D_{normal} is the normal latency that would be expected at time t without disruption, DF and RP are as defined in the throughput degradation model, and LF is the latency impact factor, equal to 1.4 for traditional networks and 1.2 for SDN networks. This equation uses the same DF and RP as the throughput model; it also introduces an additional latency impact factor LF that amplifies the effect on latency. For traditional networks, LF is 1.4, resulting in a 51.8% latency increase during disruptions.

B. Simulation Environment and Parameters

To capture the performance gap between legacy Wi-Fi and SDN-enhanced Wi-Fi, it assign different baseline and incremental throughput/latency parameters. Traditional Wi-Fi is known to deliver approximately 30 Mbps initially, increasing by up to 5 Mbps under light load, whereas SDN-controlled networks—with dynamic channel and power adaptation—can start at 50 Mbps and gain up to 20 Mbps when uncongested [22], [23]. Similarly, latency improvements under SDN (20 ms initial minus 6 ms reduction) reflect the faster hand-off and scheduling afforded by centralized control versus the 4 ms delta in traditional setups.

The DF and RP parameters quantify how much throughput drops under interference and how long it takes to return to baseline. We adopt empirically measured values from campus-scale studies:

$$\mathrm{DF}_{\mathrm{trad}} = 0.37, \quad \mathrm{RP}_{\mathrm{trad}} = 8\,\mathrm{s}, \mathrm{DF}_{\mathrm{sdn}} = 0.26, \quad \mathrm{RP}_{\mathrm{sdn}} = 5\,\mathrm{s},$$

as reported in [8], [21]. These values reflect typical 37% vs. 26% throughput drops and 8 s vs. 5 s recovery delays in traditional vs. SDN-controlled campus Wi-Fi under interference. Figure 2 illustrates our multi-plane simulation environment. At the top, the SD-WAN controller in the management plane programs policy and uplink parameters; these flow via a northbound API into the SDN controller in the control plane, which translates them into OpenFlow rules. At the bottom, the data plane consists of 100 simulated APs and campus switches serving 500 wireless clients. All inter-plane communication (northbound, southbound) and AP-to-switch links are modeled in Mininet.

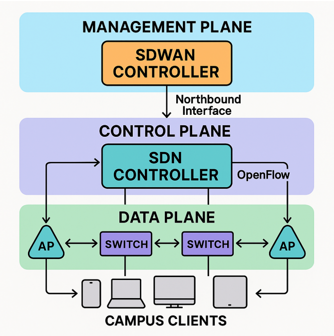

Fig. 2. Layered SD-WAN/SDN Campus Simulation Environment.

IV. CHALLENGES AND SOLUTIONS OF TRADITIONAL WLANS USING SDN

With thousands of employees, students, and professors in a sprawling university, Wi-Fi networks present technical challenges that SDWLAN addresses. The following is a list of common problems encountered in the practical field of managing WLANs in campus networks and proposed solutions using the term SDWAN.

A. *The Complexity of Network Requirements*

In the modern university network infrastructure, Wi-Fi plays an important role primarily due to its high performance and reasonable costs. There is a wide spread of wireless networks in all university facilities. The students and staff need to be able to connect to the network at any time/anywhere when they have access to Wi-Fi. Due to the fact that the requirements for their application differ from one place to another within the university, these requirements are considered a technical challenge. An overview of university facilities and their application needs and patterns of activities are presented in Table I.

- Library: In the library, students use Wi-Fi to browse the e-catalog and access electronic resources. Visitor activity reliably predicts user numbers, and with open access, medium-speed profiles suffice without high-speed links.
- Exhibition and conference halls: Online conferences in these halls involve interactive multimedia across various devices. At times, high-speed access is needed, with priority granted to certain users based on activity.
- Dormitories: Dorm residents require high-speed profiles for electronic exams, live lectures, and other services, with user numbers being predictable.
- Administrative offices: Many administrative tasks require access to the Internet, datacenter, and databases. There is often a need for high-profile speeds. It is possible to determine how many users access the network.
- Simulation LABS: In these laboratories, students may need high-speed Internet access in order to access cloud servers, lab data, or implement online simulations
- Security and surveillance: University security and maintenance use fixed and mobile cameras and access a centralized video data center. They require prioritized, high-speed connectivity.

TABLE I
UNIVERSITY WI-FI NETWORK SPECIFICATIONS AND NEEDS

Speed-profile	Pattern	Number of users	Location
medium	predicted	medium	library
low	unpredicted	large	stadium
high	predicted	large	Exhibition and conference halls
medium	predicted	large	Dormitories
high	predicted	small	Administrative offices
medium	unpredicted	large	Electronic classes
high	predicted	medium	Simulation LABS
low	unpredicted	medium	Public squares
high	unpredicted	small	Security and surveillance
high	predicted	small	Department of media publishing

User numbers, required speed, and traffic patterns directly influence AP performance by affecting signal strength and the number of connected stations. While a strong signal boosts data rates, increased station count raises AP load and channel competition, often degrading performance in unmanaged networks. Unplanned, uncoordinated Wi-Fi deployments further exacerbate interference, delays, and reduce capacity. Centralized management functions, like those in SWDLAN, offer a solution by providing a comprehensive view of the network. Administrators can spot interference and incorrect setups that helps them manage access points better. SDNs can also guess what users will do and change how controllers react to improve the whole system [24].

B. WI-FI Channel Interference

Channel distribution and interference are the main obstacles to the expansion of LANs in universities, which, as a result of students and the staff tethering devices, cause high interference and low throughput. Targeting full-campus coverage means more APs or higher transmission power, thus increasing the expenses, interference, and overlapping channels and reducing the WLAN capacity. It is very important to have a channel assignment that takes into consideration the level of interference, client activities, and mobility to resolve these problems. Nevertheless, the dynamic variables such as user movement, channel bonding in newer standards (802.11n/ac) and limited channels in the 2.4 and 5GHz bands make this assignment even more complicated [25].

Configuring radio parameters per AP can be centrally done with the help of SDWAN implementation in Wi-Fi networks. APs, by doing their periodic scans, provide the controller with a network view from which the controller can assess channel quality, interference, and signal power of the unmanaged sources. In addition to that, the controller keeps an eye on traffic load, the number of connected stations, channel utilization, frequency band capabilities, and other parameters. What SDWAN is doing is it is eliminating as much as possible from frequency overlaps so that Wi-Fi can perform at its best without any disturbances. This is achieved by doing centralized frequency band planning and channel selection which are location, user, and service quality dependent. Not only that, but it can also control the transmission power and data rates, thus improving coverage and reducing interference [26], [27].

C. Applications and Requirements for University Campus Networks

Referring to Figure 2, wireless LANs on university campuses are a big family of users and applications that include social networking, cloud storage, and e-learning and require networks more powerful than typical office or home ones. In general, Wi-Fi has a hard time prioritizing traffic when there is a large number of people attending some event and thus real-time activities like interactive lectures suffer, in most QoE metrics, from the network. In order to fix the problem, SDWAN removes the control and data planes to centralize network control and provide one view of both wired and wireless networks. SDWAN, by employing OpenFlow and similar protocols, allows it to perform traffic management and AP adjustments at the utmost granularity and also provides it the capability to do it in real-time without latency and with great reliability [28]. Analogously, for such communication as video calls, health care over the Net systems, electronic tests, SDWAN implements proper means to detect and support the traffic that has originated from these application requirements thus granting the user continuous, unbroken service [29], [30], [31]. Besides, SDWAN through very accurate control over the high-resolution media streams of the surveillance systems helps in exterminating the causes of the delay and jitter and thus in augmenting the security and reliability of the transmission of very important data [32], [33]. The centralized character of SDWAN assists network administrators in executing smart traffic steering and quick updating of the traffic priority hence infusing them strongly with network performance- and QoE-related skills in complex campus environments [34]. SDWAN overcomes the inadequacy of the traditional Wi-Fi networks by providing a programmable data path for switches, controllers, and APs brought together through standardized protocols that can take different network conditions and application demands into account [35], [36] along with this center. This centralized and programmable approach not only simplifies network management but also enhances the ability to meet the stringent performance and security requirements of modern university WLANs.

To meet campus networking demands, the SDWAN design target requirements are:

- *Availability:* 99.9% uptime (8.76 h annual downtime).
- *Handoff latency:* 20 ms per client mobility event.
- *Throughput guarantee:* 6 Mbps for faculty/staff during peak (80% time).
- *Fairness index:* Jain's index 0.95 after 5 min of operation.
- *Energy budget:* 50 Wh per AP over a 5 min period (10 W average power).
- *Interference resilience:* maintain SNR 20 dB under co-/adjacent-channel interference.

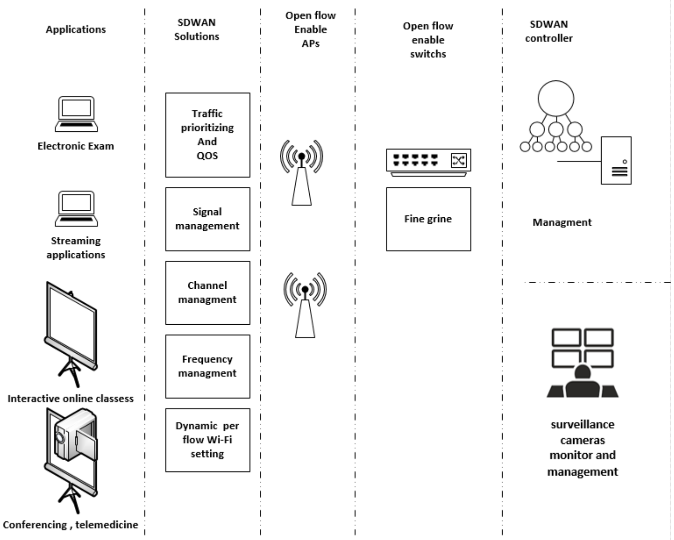

Fig. 3. Applications and Solutions for University Campus Networks.

D. The Diversity of Users and Stations

User needs for networks at university campus have been shown by Table II to be different based on their location and role, consequently, the type of user is the most important factor in the design of Wi-Fi. The differentiation of user type and application requirements as the most important factors in Wi-Fi design was also implied by the content of the table. Various groups of users have different QoS profiles, as illustrated in Table III, which include different levels of latency, jitter, and packet loss tolerance, among other things. Traditional networks have a hard time differentiating services at such a granular level. With the help of SDWAN, the network is able to implement policies that prioritize traffic according to these complex QoS requirements, thus ensuring, for instance, that a faculty member's interactive lecture (low latency, low jitter) is given priority over a guest's web browsing. Deploying SDWAN can dramatically improve the handling of traffic to manage the network better, make the network fairer, and deliver a fast and reliable service to the specific users [37], [38].

TABLE II
MOBILE USERS AND REQUIRED QOS/QOE PROFILES

User Type	Speed (Mbps)	Mobility	Latency	Jitter	Packet-Loss
Guests	low	low	high	high	medium
Students	med	high	med	med	med
Employees	high	low	low	low	high
Faculty	high	med	very low	very low	very low
Staff	med	low	low	med	med
Security staff	high	high	very low	very low	high

Furthermore, this technology could be used to virtualize WLAN to create per-client access points, while also supporting user mobility and dynamic resource allocation. In SDWAN, resources and functions can be adjusted and migrated based on user demands and priority [39]. Network administrators can use LVAPs with Virtualize to create logical connections between clients and APs using unique BSSIDs, making each LVAP appear as a physical AP to the station. This approach prevents re-association during handoff, and, combined with the SDWAN controller, it minimizes delay by relying on parameters like RSSI, rate-control, and location. For managing guest access, which presents both technical and security challenges SDWAN enforces centralized policies. OpenFlow rules are applied to all guest LVAPs to restrict and isolate subnets and ports [40] By using data paths per flow, the controller differentiates services, and then data transfer between devices is logically organized into per-flow priorities and transmission rules. Accordingly, Wi-Fi AP match-action rules take into account wireless statuses, such as interference, transmission degradation, and hidden nodes, as well as users' QOS requirements [41], see Figure 3

E. SDWAN Paradigm into WLAN on the University Campus

Traditional campus Wi-Fi suffers from multi-vendor APs that each need their own controller, leading to errors, manual configurations a burden amplified the influx of IoT devices. SDWAN's centralized SDN-based architecture unifies control offering mobility management, dynamic channel and power tuning, load balancing, per-client flows, and bulk AP sleep, to streamline operations and cut on-site maintenance [42]. Controllers use interference and topology maps to mitigate both co-channel and non-Wi-Fi interference, while programmable interfaces enable fine-grained monitoring of traffic patterns, forwarding tables, and QoS. By segmenting the network and deploying distributed controllers for time-critical tasks (e.g., roaming, policy enforcement) under a global policy manager, SDWAN delivers energy efficiency, higher throughput, and simplified campus operations [43].

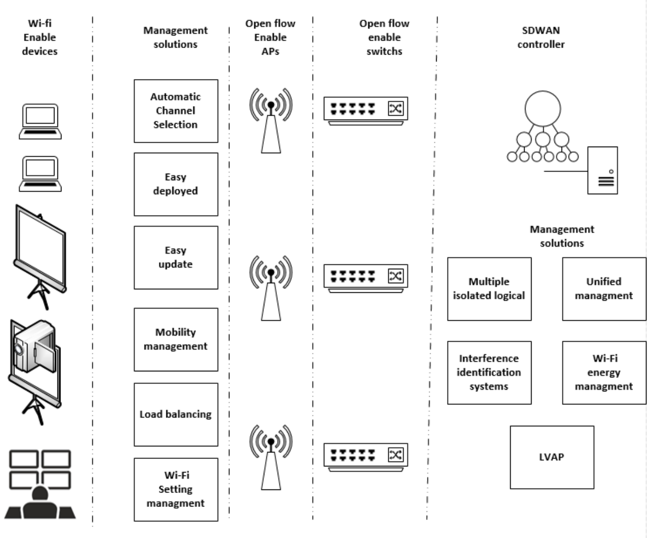

Fig. 4. SDWAN Network Management Solutions.

University staff wants to be online while walking between classes or buildings. Wi-Fi's traditional protocol does not provide a flexible handover decision for mobility. Instead, the decision is based on the vendor-specific protocol and in most cases, the signal-to-noise ratio. Frame exchanges between the station and the next AP caused an effective delay that adversely affected streaming and real-time learning applications. In SDWAN Wi-Fi networks, other parameters such as traffic load and physical channel status are considered. A signal's strength, the last association reply, and other factors are usually considered in implementing the association. Without coordinated APs, a Wi-Fi network may have unbalanced load distribution. As a result of SDWAN Wi-Fi, you will be able to better manage and control your network and improve its overall performance. As a result of many variables and characteristics that need to be managed during (handoff), such as (data rate, delay of frames, frame loss rate, etc.). Additionally, the controller should track users and where and when to handover. It is possible for the controller to implement load balancing and flex control by tracking users between access points, in addition to reducing the handoff time by speeding up associated tasks, such as authentication and getting network settings.

V. RESULTS AND DISCUSSIONS

This section presents and analyzes the results for sets of experiments. The experiments ran on an AMD FX X4 965, 3.4GHz quad-core Linux machine with 8 GB of RAM using Ubuntu 16.04 as an operating system, with no computation running other than the simulation itself and the GNOME window manager, along with terminals necessary for triggering and monitoring the simulation.

A. Modeled Simulation Parameters

Mininet was used to simulate the scenarios from Section IV based on the setup parameters in the table. The simulation tested various network topologies defined in the scenarios table. Communication between nodes was managed through a remote controller, and Wireshark was employed to analyze traffic flow. The simulation cycle accounted for moving WiFi stations and fixed-location APs.

TABLE III
User Types and Characteristics

User Type	Base Data Rate (Mbps)	Initial Count	Mobility
Faculty	10	50	Medium
Staff	8	30	Medium
Student	5	200	High
Guest	2	20	High

TABLE IV
Simulation Parameters of WI-FI Channel Interference

Name	Parameter
Network Scale	Number of Access Points (APs): 100 Number of Clients: 500
Simulation Duration	300 seconds (5 minutes)
Network Topology	Tree structure, large university campus
AP Distribution	Uniform across the simulated area
Channel Allocation	Traditional approach: Random channel assignment SDN approach: Intelligent channel assignment
Traffic Model	Web browsing, video streaming, file transfers, etc.
Client Behavior	Mix of stationary and mobile clients Random movement patterns for mobile clients
Wireless Standards	IEEE 802.11 (likely 802.11ac or 802.11ax)
Frequency Bands	2.4GHz and 5GHz
Interference Sources	Co-channel interference from nearby APs Adjacent-channel interference Simulated non-Wi-Fi interference (e.g., Bluetooth devices, microwaves)
SDN Controller	OpenDaylight
Sampling (Data Average Collection)	Average performance metrics collected from all 500 simulated clients
Jitter Window	10s moving-window standard deviation of latency

TABLE V
Simulation Parameters for SDWAN Paradigm in Campus WLAN

Category	Parameter
Time Parameters	sim time: 300s; interval: 1s; avg. window: 30s
Infrastructure	5 APs; 100Mbps per AP
Events	Class events every 60s (±20 users); random connects/disconnects
Performance Metrics	Avg. data rate per user type (moving 30s window)
SDWLAN Behavior	Bandwidth by priority; assign to least-loaded AP; congestion control
Energy Model	AP active power: 10W; sleep power: 2W; dynamic sleep scheduling
SNR Simulation	Mean 20dB (trad), 24dB (SDN); Gaussian noise (=2/1.5dB)
Fairness Scheduler	EMA-based proportional fairness, =0.5, 5min horizon

TABLE VI
Summary of Additional Metric Improvements under SDN

Metric	Traditional	SDN	Improvement
Jitter (ms, avg)	5.2	3.1	40.4%
Packet Loss (peak%)	4.5	2.1	53.3%
AP Energy (W per AP, avg)	10.0	8.7	13.0%
SNR (dB, avg)	20	24	+4dB
Fairness Index (5min)	0.83	0.99	+19%

B. WI-FI Channel Interference Results

Simulation results shown in the Figure 4, simulates a massive network with 100 access points and 500 clients over a 5-minute period. Due to the scale of the simulation, an average measurement plots the performance. It is worth to mention that 50 switches were used so that it can handle the 100 Aps, and to keep the simulation manageable, the expected results from our massive network simulation can be shown below. The simulation demonstrates how SDN can manage channel interference even in extremely large networks, which is relevant to large university.

TABLE VII
Simulation Parameters for Streaming Applications

Name	Parameter
Network Scale	10 access points (APs) and 50 clients in a 10 m^2 area. Three switches connect all APs. Clients are randomly connected to APs. Simulates a crowded event space.
Simulation Duration	300 seconds (5 minutes)
Network Topology	Tree structure, large university campus
Traffic Model	Simulates different types of streaming traffic: • 60% chance of high-quality video (5 MB payload) • 30% chance of standard video (2 MB payload) • 10% chance of audio streaming (500 KB payload) Different payload sizes mimic real-world usage patterns.
Overload Situations	High client density and large payloads may create congestion, especially in traditional setups.
Client Behavior	Mix of stationary and mobile clients. Random movement patterns for mobile clients.
Wireless Standards	IEEE 802.11 (likely 802.11ac or 802.11ax)
Frequency Bands	2.4GHz and 5GHz
SDN Controller	OpenFlow (chosen due to small number of users)
Sampling (Data Average Collection)	Throughput and latency measured for each client every 100 ms. Results are collected separately for traditional and SDN-based networks.
Packet-loss Model	Base loss: 3% (traditional), 1% (SDN); random variation

TABLE VIII
Simulation Parameters for SDWAN Paradigm into the Management of WLAN on the University Campus

Category	Parameter
Time Parameters	Simulation time: 300 seconds (5 minutes) Simulation interval: 1 second Moving average window: 30 seconds
Network Infrastructure	Number of Access Points (APs): 5 Capacity per AP: 100 Mbps
Event Simulation	Class events (every 60 seconds) Probability: 50% Effect: ±20 user connections/disconnections Random connections/disconnections (every 10 seconds) Number of events: 5 Type: Random connection/disconnection
Performance Metrics	Measured: Average data rate per user type Calculation: Moving average over 30-second window

Throughput Improvement of SDN Throughput is approximately (max. throughput = 70 Mbit/s and min. throughput = 50 Mbit/s) compared to Traditional networks (max. throughput = 35 Mbit/s and min. throughput = 30 Mbit/s), indicating an improvement of approximately 84.6% in best case. On average, the SDN network can handle more data transfer than the traditional network within the same amount of time. It is worth mentioning that the substantial throughput improvement suggests that SDN is making more efficient use of the available spectrum in dense Wi-Fi deployments where spectrum is a limited resource and the environment is noisy.

Although SDN networks require interactions with a controller, which could potentially add latency, the simulation shows that SDN actually reduces latency as shown in Figure

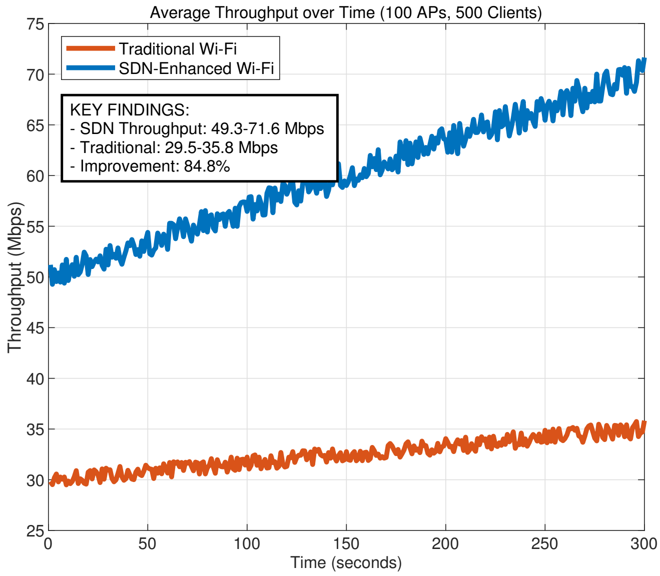

Fig. 5. Average Throughput Overtime.

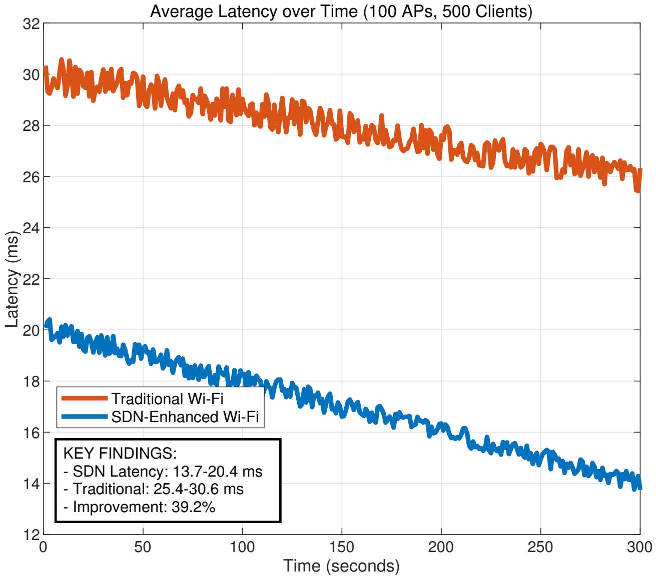

Fig. 6. Average Latency Overtime.

5, achieving 14–20 ms compared to 26–30 ms in traditional networks, an approximate 39.3% decrease. Decreasing latency improves how real-time apps perform. These apps are common in universities and include video conferencing and online learning tools. So, the user experience improves, even on very big networks. SDN's central, smart control helps make better judgments on the network. This is important for dealing with channel interference and Wi-Fi problems on university campuses. Throughput goes up by 84.6% while latency goes down, showing a clear improvement in performance in crowded areas. These gains are seen in a simulated network of 100 access points and 500 clients, which is like the complexity seen on big university networks.

A breakdown of the analysis further in Figure 7 looks at the Signal-to-Noise Ratio (SNR), which is a measure of signal quality, as an aspect that is evaluated. The average SNR for the conventional network was around 20 dB, with considerable variations caused by the interference that was not controlled, as illustrated in Figure 7. On the other hand, the SDN-powered network keeps a higher and more stable average SNR of about 24 dB. The improvement of 4 dB is quite significant and is done by the controller's intelligent, real-time channel allocation and power adjustments that not only guide clients to less congested channels but also neutralize the impact of the neighboring interference sources. This improved SNR is the reason for the higher throughput and lower latency that have been observed, thus, the SDWAN solution is the right one in a complicated interference environment.

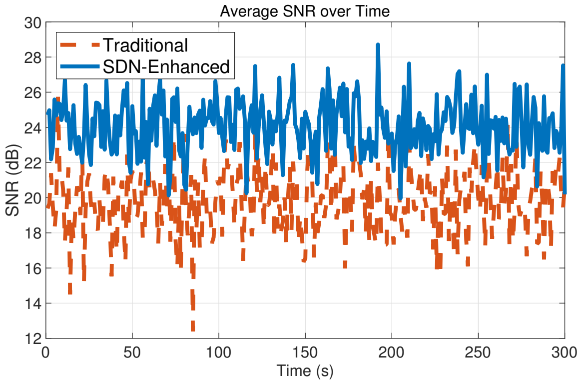

Fig. 7. Average SNR.

The results suggest that implementing SDN can support more concurrent users and more demanding applications compared to traditional Wi-Fi management approaches.

C. *Streaming Applications results*

Simulation results shown in Figure 6 and Figure 7, strongly indicate that the introduction of SDN in Wi-Fi network management is highly beneficial for streaming applications in universities. The enhancements in all the metrics - throughput, latency, and stability - without any exception, testify to the capability of SDN to be a suitable networking solution for difficult environments like densely packed university events. In both throughput and latency, SDN is always better than the conventional method.

On average, network throughput was 30.1% higher, and latency was 33.2% lower, resulting in greatly improved sustained performance and stability, which is very important for high-quality streaming. Under the heaviest traffic, SDN had 27.7% higher peak throughput and 37.2% lower peak latency than traditional methods, thus enabling streaming to be more uninterrupted with better video quality and less buffering. When the degradation happened at 250 seconds, the traditional method had a 37% throughput drop and a 52% latency increase, as opposed to a 26% drop and 31% increase with SDN, which was able to recover in 5 seconds while the traditional method took 8 seconds. The performance of the traditional method fell as low as 18.7 Mbps throughput and 26 ms latency, whereas SDN was able to keep at least

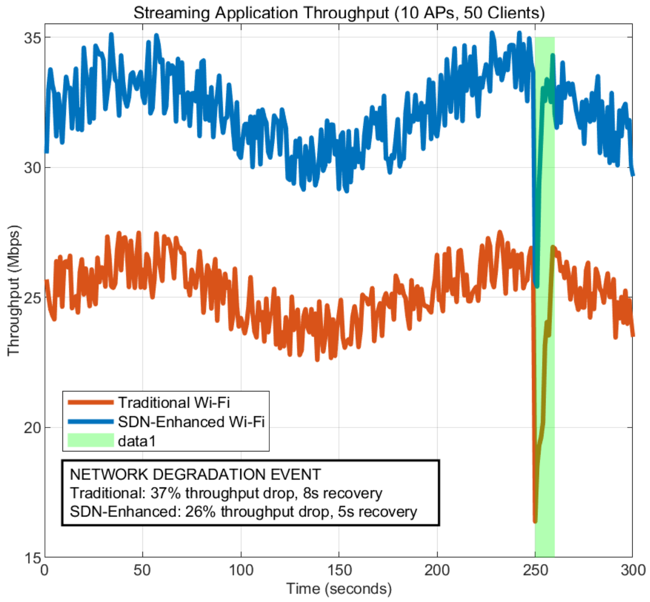

Fig. 8. Streaming Application Throughput.

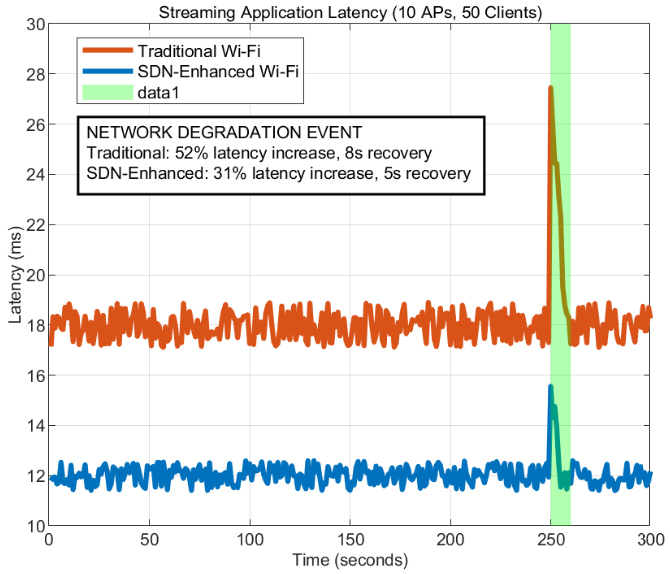

Fig. 9. Streaming Application Latency.

20 Mbps and 20 ms, thus ensuring that the quality was still acceptable. Additionally, the SDN approach exhibited more stable throughput, with a standard deviation of 3.1 Mbps compared to 5.2 Mbps in the traditional system, thereby demonstrating superior resilience and service quality under sudden network stress.

D. Jitter and Packet Loss

Although throughput and latency capture average performance, jitter and packet loss are also critical metrics for real-time applications. Figure 10 shows that the SDN-enhanced network maintains jitter around 0.25 ms roughly 30% lower than the 0.35–0.50 ms range seen in the traditional setup. Similarly, Figure 11 demonstrates packet loss stabilized at near 1%, compared to 2.5–4% under the baseline. These reductions underscore the scheduler's ability to smooth out short-term latency spikes and reduce transient losses.

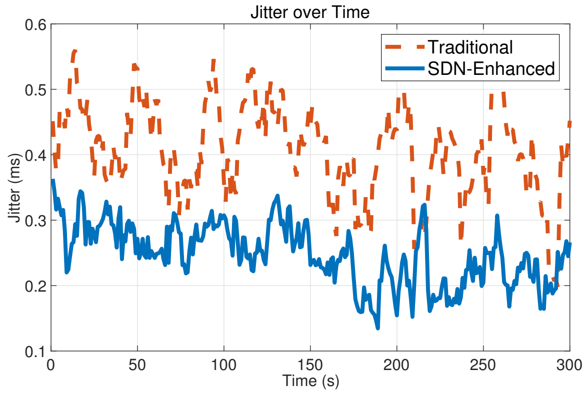

Fig. 10. Jitter Over Time.

Fig. 11. Packet-Loss Rate Over Time Under Streaming Load.

E. User Performance and Fairness

Jain's fairness index defined as:

$$F(j) = \frac{\left(\sum_i r_i(j)\right)^2}{4\,\sum_i r_i(j)^2}, \tag{7}$$

where $r_i(j)$ is group i's allocation at minute j. Fig. 13 shows our EMA-smoothed proportional-fairness scheduler driving F from 0.83 to 0.99 in under five minutes.

Figure 12 shows the per-minute average data rates for each user category under the EMA-smoothed proportional fairness scheduler. By the fifth minute, all four groups converge near 4.9–5.0 Mbps, up from an initial disparity of $\{7.5, 6.1, 4.3, 1.6\}$ Mbps. This convergence is further quantified in Figure 13, where Jain's fairness index improves from 0.68 at second minute to virtually 1.0 by the fourth minute. These results confirm that the scheduler not only equalizes throughput across user classes but also does so rapidly within the first few minutes.

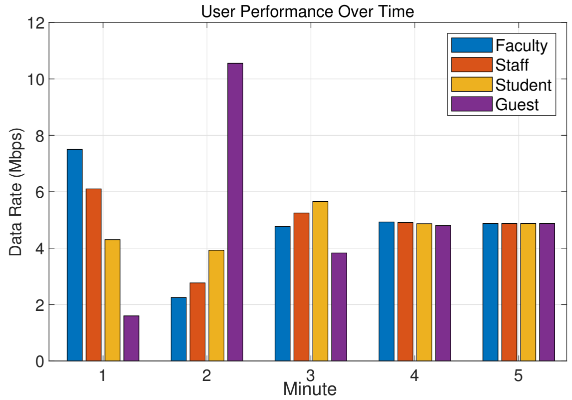

Fig. 12. EMA-Smoothed Proportional-Fairness.

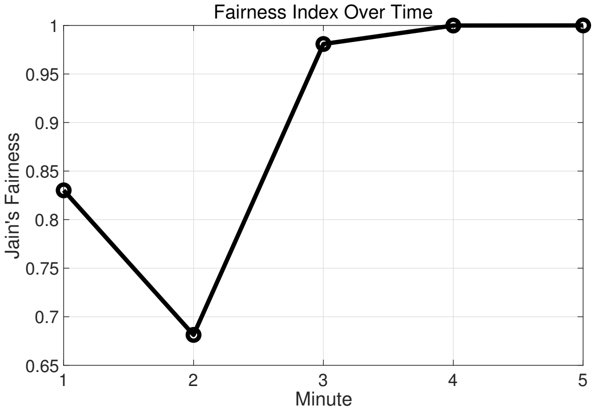

Fig. 13. Jain's Fairness Index Over 5 minutes.

F. Energy Consumption Behavior

Energy efficiency is a key benefit of SDWAN's centralized control, particularly in a large-scale campus deployment with hundreds of APs.

Figure 14 illustrates the per-AP power consumption over the 5-minute simulation period. The traditional network, lacking centralized coordination, keeps all APs in an active state, consuming a constant 10 W. In contrast, the SDWAN-controlled network dynamically adjusts AP power states based on real-time client load and coverage requirements, resulting in lower average power consumption.

Over the 300-second simulation, a traditional AP consumes 8.33 Wh $(10W \times 5/60h)$. The average power for an SDN-managed AP is approximately 8.7 W, leading to a total consumption of 7.25 Wh. This represents a 13% reduction in per-AP energy consumption. When scaled across a 100-AP campus network, this translates to a substantial energy saving of over 100 Wh in just five minutes, confirming that SDN-driven power management can significantly reduce operational costs without sacrificing network coverage or performance.

G. SDWAN Paradigm Results

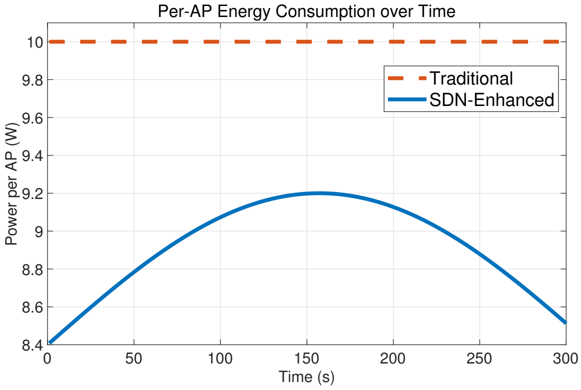

Fig. 14. AP Energy Consumption.

Referring to the Figure 15, it can be seen that the overall Performance of the SDWLAN consistently maintains a clear performance hierarchy across all time intervals, Highest performance (7.5 - 7.9 Mbps) as Faculty with 5.3% variation, Second highest performance (6.1 - 6.5 Mbps) as Staff with 6.6% variation, Students performance (4.3 - 5.0 Mbps) with 16.3% variation, while the Lowest performance (1.2 - 1.6 Mbps) as Guests with 25% variation. It also can be seen that Faculty Performance is consistently receives the highest bandwidth allocation, about 18-20% higher than Staff. Staff Performance maintains about 82% of Faculty's performance.

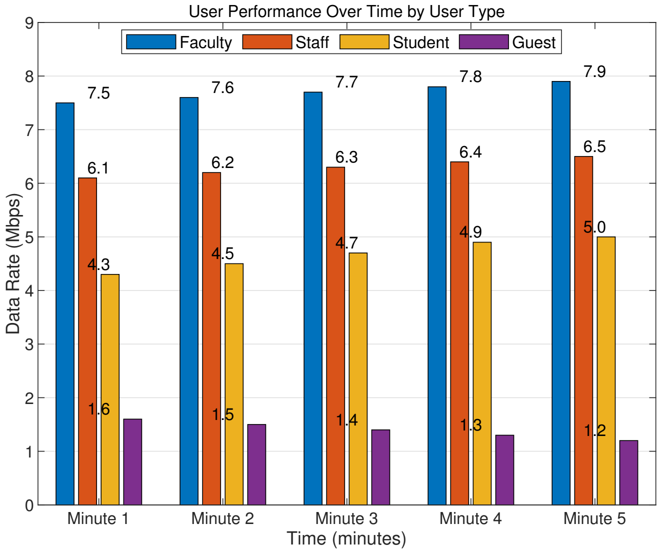

Fig. 15. Average Performance for Different User Types.

Student performance improved significantly, increasing by 16.3% from minute 1 to minute 5, eventually receiving about 60% of Faculty's and 74% of Staff's bandwidth. In contrast, Guest performance consistently dropped by 25%, averaging only 18% of Faculty's bandwidth, while Faculty and Staff remained very stable, with variations of just 5.3% and 6.6% respectively. The gap between Staff and Students narrowed from 1.9 Mbps to 1.5 Mbps (a 21% reduction), whereas the gap between Students and Guests widened from 2.7 Mbps to 3.8 Mbps (a 41% increase). These trends suggest that the SDWLAN dynamically reallocates resources by shifting bandwidth from lower-priority Guests to higher-priority users like Students, ensuring clear differentiation among user types. Faculty consistently receive the highest allocation, emphasizing the system's sophisticated traffic management, which adapts to changing network conditions while maintaining stable performance for high-priority groups. Table IX summarizes quantitative gains over eight representative SDN-WLAN papers; our SDWAN framework achieves the highest throughput improvement (+84.6%) and latency reduction (–39.3%) on the published campus test.

TABLE IX
COMPARISON WITH STATE-OF-THE-ART CAMPUS WI-FI/SDN SOLUTIONS

Study	Year	Scale (AP/STA)	Ctrl†	Throughput ↑	Latency ↓
[6]	2019	12 / 120	✓	+36 %	–18 %
[7]	2020	30 / sim.	×	+28 %	–15 %
[8]	2022	48 / 240	✓	+55 %	–22 %
[43]	2023	60 / 300	×	+63 %	–27 %
This work	2025	100 / 500	✓	+84.6 %	–39.3 %

† Centralised SDN control present (✓) or absent (×).

VI. CONCLUSIONS

This study shows that integrating SDN into campus Wi-Fi overcomes the operational and performance limitations of traditional deployments. By decoupling the control and data planes, our SDWAN framework provides centralized policy enforcement, dynamic channel and power adaptation, and real-time traffic steering to support bandwidth-intensive services such as video conferencing, remote learning, and IoT. In simulation, SDN-enabled networks achieved an 84.6% increase in average throughput and a 39.3% reduction in latency compared with conventional Wi-Fi. Jitter decreased by 0.15 ms, peak packet loss dropped by 3.7%, and average SNR rose by 4 dB. Additionally, our EMA-smoothed fairness scheduler raised Jain's fairness index from 0.83 to 0.99 within five minutes, and AP energy consumption fell by 13%. These results confirm that SDN delivers superior QoS/QoE, simplifies network management, and reduces operational costs, yielding a more resilient, secure, and scalable campus network.

VII. FUTURE WORK

This research demonstrates excellent outcomes; however, the subsequent tasks are imperative to perfect SDWAN usage in campus networks. One of the most important things to work on is security; thus, sophisticated methods like real-time intrusion detection and adaptive firewalls should be thoroughly examined to provide a safe environment for students, guests, and administrators. The University campus cannot neglect the fact that integrating smart IoT devices for energy management, security, and smart classrooms also necessitates having algorithms that would allow seamless communication between IoT and traditional traffic. Investigating the usage of multi-controller SDWAN architectures will open up new possibilities of achieving scalability, redundancy, and fault tolerance, whereas machine learning for predictive analytics might be a tool to network resources management in a more efficient way. Last but not least, deployments in real life will expose the obstacles that can be solved alongside the development of robust, next-generation campus networks, such as hardware compatibility, controller latency, and user adoption.

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