Enhancing Social Experience in Smart Stadium with Wi-Fi 6 Quality Management

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ABSTRACT

Smart stadiums are revolutionizing live sports by creating digitally connected environments that turn spectators into active participants. However, when thousands of fans simultaneously use public Wi-Fi for streaming and sharing, network congestion often occurs. This overload degrades connectivity and disrupts live broadcasts for remote viewers, causing buffering, poor quality, and interruptions. Limited bandwidth and diverse user demands further challenge Wi-Fi performance, leading to inconsistent experiences. This study proposes a Wi-Fi 6-based Quality of Service (QoS) management framework to ensure uninterrupted, high-quality video streaming during live events. Developed using Python and NS-3 simulation tools, the framework employs the Priority Queuing algorithm to optimize traffic flow. Agile methodology guided iterative development for scalability and adaptability. Performance was evaluated under simulated high-density conditions using key QoS metrics: throughput, packet loss ratio, traffic volume, and bandwidth usage. Results show that Priority Queuing significantly reduces congestion, improves responsiveness, and supports real-time traffic optimization. the study highlights how reliable Wi-Fi 6 connectivity can enhance inclusivity, improve operational efficiency, and foster more immersive and equitable social experiences. Future work will explore advanced prioritization techniques, integration with emerging technologies, and personalization based on user feedback, which bridges technical precision with meaningful social impact in the Wi-Fi 6 era.

Keywords: Smart Stadiums, Wi-Fi 6 Technology, Priority Queuing, Traffic Prioritization, QoS Management

INTRODUCTION

The evolution of smart stadiums marks a significant transformation in how modern societies experience live sports and large-scale events. Unlike traditional venues, smart stadiums integrate advanced digital infrastructure, including Wi-Fi 6 networks, Internet of Things (IoT) sensors, and real-time data analytics, to enhance audience engagement and operational efficiency. Today's spectators are no longer passive observers; they actively participate by streaming replays, sharing content on social media, and interacting through mobile applications. This digitally mediated participation contributes to what scholars describe as the social experience: a blend of physical presence and digital interaction that shapes the atmosphere and communal value of contemporary events.

Connectivity is now central to this collective experience. When Wi-Fi networks become congested or unstable, audience engagement suffers, and the perceived quality of the event declines. Ensuring reliable connectivity is therefore not just a technical concern, but it is a matter of social equity and public satisfaction.

The concept of social experience extends beyond technical metrics to encompass how individuals perceive, communicate, and emotionally engage within connected public spaces. In smart stadiums, this includes sharing multimedia in real time, accessing personalized content, and participating in digital communities. High-quality wireless connectivity enables these interactions, fostering inclusivity and cohesion. Conversely, disruptions in connectivity fragment social unity and diminish immersion. Thus, wireless quality management directly influences how audiences connect, express, and co-experience events.

As integral components of the broader smart-city ecosystem, smart stadiums function as digitally enhanced venues that not only deliver immersive spectator experiences but also optimize crowd flow, energy consumption, and operational efficiency. By merging advanced connectivity with human-centered design, these environments exemplify the convergence of technology and social innovation.

To address the growing demand for reliable connectivity in these environments, this study proposes a Wi-Fi 6-based adaptive quality management framework that ensures stable network performance in smart stadiums. The framework is developed using Python and NS-3 simulation tools and incorporates the Priority Queuing (PQ) algorithm to manage network traffic efficiently. The system is evaluated based on key Quality of Service (QoS) parameters such as throughput, packet loss ratio, network traffic volume, and bandwidth usage to assess its effectiveness in minimizing latency, reducing packet loss, and maintaining seamless streaming under high-density conditions.

The paper is structured as follows: Section 2 begins with a review of related work that forms the foundation of this study. Following that, Section 3 outlines the methodology and simulation framework, detailing the technical approach and implementation process. Section 4 then presents the performance results, highlighting the outcomes of the simulation and analysis based on key evaluation metrics. Section 5 then discusses the findings in relation to the study's objectives and observed outcomes. Lastly, Section 6 concludes the paper by summarizing its significance, highlighting the main contributions, and suggesting directions for future research.

LITERATURE REVIEW

Wi-Fi 6 (IEEE 802.11ax) introduces several advanced features that significantly improve throughput, efficiency, and reliability in high-density environments. A study by [1] demonstrates that Wi-Fi 6 can support up to four times more concurrent users than Wi-Fi 5, while maintaining lower latency. However, these benefits are highly dependent on effective QoS control and real-time traffic prioritization. Without such mechanisms, network contention can still lead to performance degradation, especially in environments like smart stadiums where thousands of users compete for bandwidth simultaneously.

QoS mechanisms are essential for ensuring that critical data, such as live video streams, receive transmission priority over less time-sensitive traffic. Traditional models like Weighted Fair Queuing and Enhanced Distributed Channel Access (EDCA) have been widely implemented in wireless networks, but they often rely on static configurations that struggle to adapt to dynamic network conditions. Research in [2-8] advocates for adaptive QoS models that adjust priorities based on real-time network load and application requirements, offering more responsive and scalable solutions.

Smart stadiums, as part of the broader smart-city ecosystem, integrate digital technologies not only for connectivity but also for crowd behavior management, energy efficiency, and personalized user experiences [11-17]. From a social innovation perspective, these venues foster inclusive and interactive environments that enhance fan engagement, emphasizing the role of connectivity as a public good, where equitable digital access contributes to shared cultural and emotional experiences.

Several studies have explored QoS management strategies to improve the quality of sports broadcasting and multimedia streaming. Shabrina et al. in [18] investigated the use of Content Delivery Networks (CDNs) for

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HTTP Live Streaming (HLS) in Indonesia, focusing on affordability and performance for small and medium-sized enterprises. Meanwhile, [2] introduced an adaptive framework called ACCeSS to enhance live streaming performance, particularly in virtual and augmented reality applications. Work in [3] proposed adaptive error protection for video transmission over WLANs, while Bose and Sujatha in [19] developed a fuzzy logic-based QoS monitoring system for cloud-based media services.

While these studies offer valuable insights, a critical comparison reveals several gaps. Most prior works focus on isolated aspects of QoS, such as CDN deployment, fuzzy logic monitoring, or specific adaptive frameworks, without integrating multiple performance dimensions into a unified solution. Few studies address real-time traffic prioritization, dynamic resource allocation, and scalability in high-density environments simultaneously. Moreover, many models rely on static configurations or are tailored to specific use cases like VR/AR or cloud services, limiting their applicability to live sports broadcasting in smart stadiums.

The proposed study addresses these gaps by introducing a comprehensive Wi-Fi 6-based QoS management framework that integrates Priority Queuing [20], real-time monitoring, and adaptive bandwidth allocation. Unlike previous works, it is specifically designed for high-density environments and evaluated using key QoS parameters, i.e, throughput, packet loss ratio, network traffic volume, and bandwidth usage under simulated stadium conditions. This approach not only enhances technical performance but also supports social innovation by promoting digital inclusivity and immersive audience engagement.

METHODOLOGY

Research Design

Agile methodology, as represented in Fig. 1, shows a contemporary approach to software development that follows an iterative and incremental process, consistent with Software Development Life Cycle (SDLC) principles. It emphasizes collaboration, adaptability, and customer satisfaction, enabling rapid and responsive development [21].

This methodology suits the study due to its ability to accommodate the dynamic and evolving nature of enhancing sports broadcasting quality through Wi-Fi 6-based QoS management. Unlike traditional models such as the waterfall approach, which follow a linear and sequential SDLC structure, Agile supports continuous feedback and iterative refinement. This flexibility allows the study to respond effectively to changing requirements while maintaining a focus on delivering high-quality software.

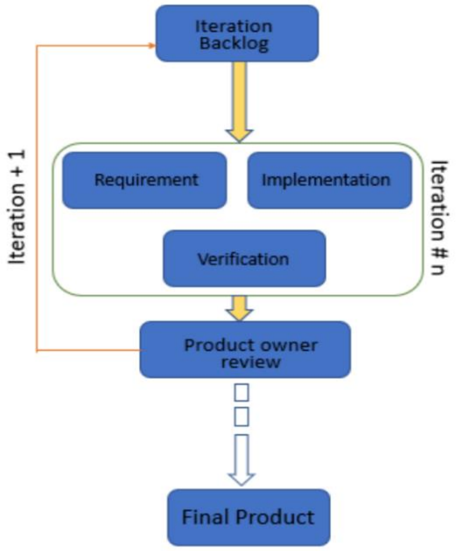

Fig. 1 Agile Methodology [21]

1) *Iteration Backlog*: The iteration backlog serves as a structured task list that defines the features and requirements to be implemented during each development phase. It helps prioritize tasks and ensures systematic

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progress, particularly in addressing real-time monitoring, traffic prioritization, and bandwidth management.

2) *Requirement:* The development process begins with a clear understanding of the study requirements. Emphasis is placed on identifying functional requirements related to QoS management, including real-time monitoring, traffic prioritization, and bandwidth optimization. These requirements guide the development and ensure alignment with the study's objectives.

3) *Verification:* Verification involves continuous testing and validation to ensure the software meets quality standards. This stage helps identify and resolve issues early, contributing to a reliable and robust QoS management solution.

4) *Implementation:* Implementation proceeds incrementally, with each iteration involving the coding, design, and integration of components necessary to achieve the goals. Python is used as the primary programming language, and best practices are followed to ensure structured and maintainable development.

5) *Product Owner Review:* These reviews assess the software's compliance with defined requirements and objectives, allowing for timely adjustments and improvements.

6) *Final Product:* The final product emerges through successive iterations, each contributing to the overall functionality and performance of the QoS management software. The result is a comprehensive solution that optimizes network performance and enhances the streaming experience.

System Design

With the requirements established, Fig. 2 illustrates the system design flow of the high-level architecture of the web-based application. The architecture includes both the backend and frontend components. The backend, developed using Python, handles the implementation of traffic prioritization, real-time monitoring, and bandwidth management functionalities. The frontend, created using HTML, CSS, and JavaScript, provides the user interface for interacting with the system.

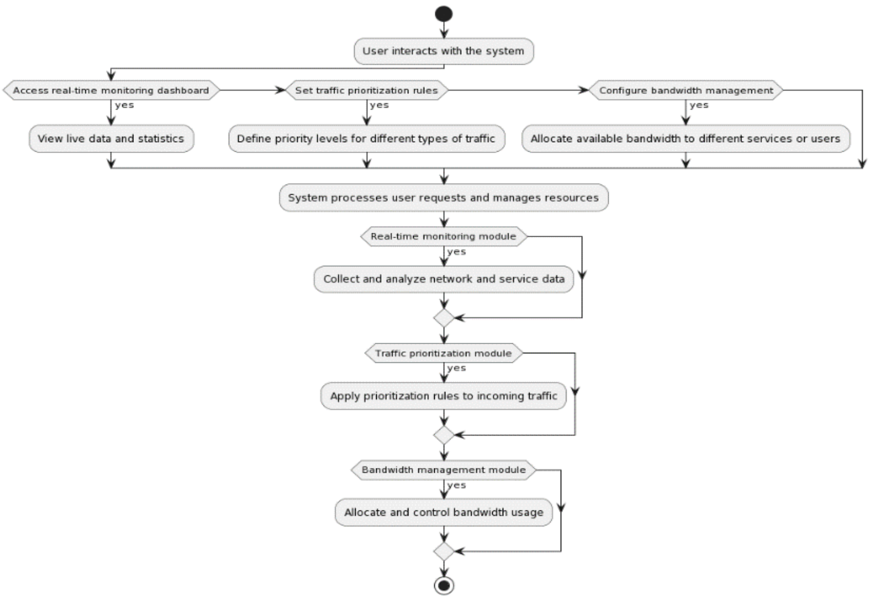

Fig. 1 System Design Flow Chart

Simulation Design

Fig. 3 shows that 50 nodes were created in NS-3 to simulate a realistic stadium environment. The red dots represent the nodes in the wireless network. Node 50 is the access point, while the other remaining nodes are the mobile stations. The grid lines do not represent the distance between nodes; instead, the grid lines are there to aid the visualization and understanding of the network layout.

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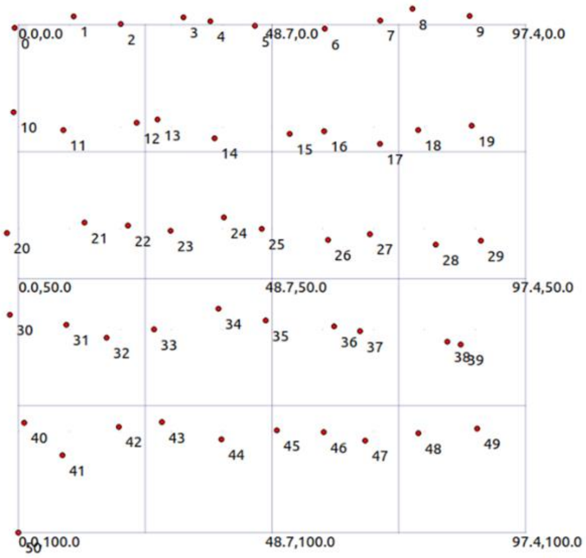

Fig. 3 Wireless Network Topology in NS-3

RESULTS AND ANALYSIS

Coding and Scripting

Python Implementation

The Python program was structured into modular scripts to manage different functionalities:

1. main.py – Controls the overall program flow and integrates all components.
2. real_time_monitor.py – Captures and monitors packets in real time for traffic analysis.
3. traffic_prioritization.py – Implements the Priority Queuing algorithm for traffic optimization.
4. bandwidth_manager.py – Allocates bandwidth dynamically and displays usage for the target address.

This Python-based QoS framework was later integrated into an NS-3 simulation to evaluate performance under realistic stadium conditions.

NS-3 Simulation

Two simulation scenarios were developed:

1. Baseline Scenario (Without QoS)

The baseline scenario represents a stadium wireless network topology consisting of 50 mobile stations connected to a single access point. To replicate real-world conditions, high traffic congestion was introduced within the network environment. In this setup, no QoS algorithm was applied, allowing the network to operate under default conditions without prioritization or traffic management mechanisms.

2. Enhanced Scenario (With Priority Queuing)

The enhanced scenario maintains the same stadium wireless network topology and traffic conditions as the baseline configuration, with 50 mobile stations connected to a single access point under high congestion. However, in this setup, Priority Queuing is implemented at the access point to optimize traffic flow. This mechanism ensures that higher-priority packets are transmitted first, reducing delays for critical data and improving overall network performance compared to the baseline scenario.

Test Result

QoS Algorithm Preliminary Evaluation in NS-3

To identify the most suitable QoS algorithm for the simulated stadium environment, several algorithms were tested in NS-3. The goal was to determine compatibility with wireless network topology and assess feasibility for implementation. The algorithms evaluated include:

1. *Weighted Fair Queuing (WFQ)* – Ensures fair bandwidth allocation by assigning weights to flows; higher-weight flows receive proportionally more bandwidth.
2. *Token-Bucket Filtering* – Shapes traffic by regulating packet transmission rates using a token bucket mechanism.
3. *First-In-First-Out (FIFO)* – Processes packets in the order of arrival without prioritization.
4. *Priority Queuing (PQ)* – Assigns priority levels to packets; higher-priority packets are transmitted first.
5. *Round-Robin* – Allocates resources cyclically, ensuring equal distribution among flows.

Table I Algorithm preliminary test results

QoS algorithm	Supported in NS-3	Network Topology
Weighted-fair queueing	No	n/a
Token-bucket filtering	Yes	Point-to-point
First-in-first-out (FIFO)	Yes	Point-to-point
Priority queuing (PQ)	Yes	Wireless
Random Early Detection	Yes	Dumbbell
Round-Robin	No	n/a

The results indicate that most algorithms are either unsupported in NS-3 or limited to point-to-point topologies, making them unsuitable for wireless stadium environments. Priority Queuing emerged as the most appropriate choice, as it is fully supported in NS-3 and can be implemented within a wireless network topology. It meets all requirements for this study, enabling effective traffic prioritization under high-density conditions.

Python System Testing and Results

System testing represents a critical phase in validating the Python-based QoS management system. This process ensures that the system meets functional requirements and delivers a user-friendly interface. Comprehensive testing helps identify and resolve potential bugs, usability issues, and performance gaps, thereby improving overall reliability and user experience. Ultimately, successful testing confirms compliance with project objectives and supports the core goal of providing an effective and intuitive QoS management solution.

Testing Procedure

The following steps outline the system testing workflow:

1. *Program Initialization*

   - Execute the main Python program via the command prompt and select the desired option.

2. *Real-Time Monitoring*

- Enter the target IP address.
- The system displays real-time packet flow details.

3. *Bandwidth Management*

- Select the option to manage bandwidth.
  - Allocate Bandwidth: Specify the target address and packet details.
  - Adjust Bandwidth: Provide the target address and new bandwidth value.
  - Display Bandwidth: View allocated bandwidth for a specific address.

4. *Traffic Prioritization*

- Select the option to access the PQ feature.
  - Add Packets: Input packet details, and assign priority (lower number = higher priority).
  - Process Queue: Perform repeatedly until all packets are processed.
- The system confirms completion with the message “Queue is empty.”

NS-3 Simulation Testing and Results

The objective of NS-3 simulation testing was to evaluate the impact of QoS algorithms in a congested wireless network environment. By simulating high-density traffic conditions, the tests provided insights into the effectiveness of QoS strategies in managing congestion, ensuring timely data delivery, and maintaining service quality. These results guide the selection and optimization of QoS mechanisms for robust and reliable network performance.

Testing Procedure

1. Baseline Simulation (Without QoS)

The baseline simulation begins by executing the first NS-3 script, which models a stadium wireless network without applying any QoS algorithm. This configuration allows the network to operate under default conditions, providing a reference point for performance evaluation. During the simulation, key performance metrics such as throughput, packet loss ratio, network traffic volume, and bandwidth usage are recorded. These metrics serve as the foundation for later analysis and comparison with enhanced scenarios.

2. Enhanced Simulation (With Priority Queuing)

The enhanced simulation involves running the second NS-3 script, which incorporates the Priority Queuing algorithm at the access point. This approach introduces traffic prioritization to improve network performance under high congestion conditions. Similar to the baseline simulation, the enhanced setup generates key performance metrics, including throughput, packet loss ratio, network traffic volume, and bandwidth usage. These results are collected for comparative evaluation against the baseline scenario to assess the impact of implementing Priority Queuing.

The baseline scenario exhibited significant congestion, resulting in reduced throughput and higher packet loss. In contrast, the Priority Queuing implementation improved traffic flow, minimized packet loss, and optimized bandwidth utilization under identical conditions. These findings confirm Priority Queuing as an effective QoS strategy for high-density wireless environments.

NS-3 Test Result Analysis

To facilitate comparison, the simulation results were visualized in graph form. In NS-3, flows represent unidirectional data transfers between a source and destination node, serving as logical channels for packet transmission. The analysis focused on key performance metrics: throughput, packet loss ratio, and network traffic volume.

Throughput

- Fig. 4 illustrates the throughput comparison between the baseline scenario (No Algorithm) and the enhanced scenario (Priority Queuing) across three flows. In the No Algorithm case, throughput values are extremely low, with Flow 1 and Flow 3 registering near zero and Flow 2 achieving only about 0.035 Mbps. These negative or negligible values indicate severe congestion and the inability of the network to deliver packets effectively under high traffic conditions.

- Conversely, the Priority Queuing scenario demonstrates a significant improvement in throughput. Flow 1 achieves approximately 0.085 Mbps, which is more than double the highest value recorded in the baseline scenario. Flow 2 also shows improvement, reaching around 0.018 Mbps, while Flow 3 remains very minimal. This distribution reflects the effect of prioritization, where higher-priority flows receive more bandwidth, ensuring critical data is transmitted successfully even during congestion.

- Overall, the graph confirms that Priority Queuing not only enables successful packet delivery but also optimizes throughput for prioritized flows, making it a robust solution for congested wireless environments.

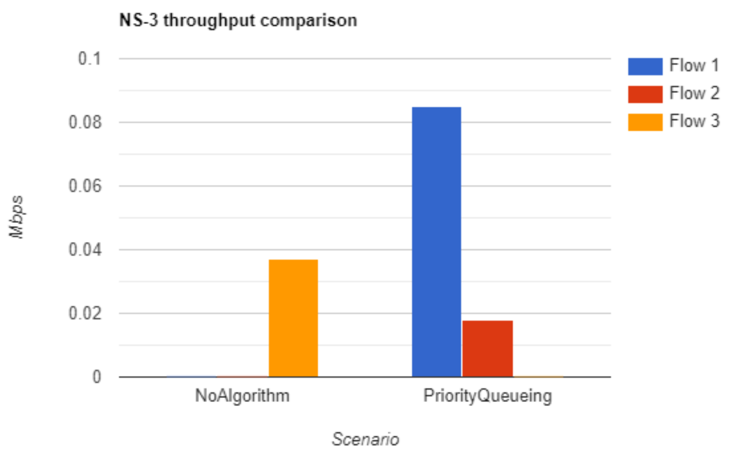

Fig. 4 NS-3 Throughput Comparison Graph

Packet Loss Ratio

- Fig. 5 presents the packet loss ratio comparison between the baseline scenario (No Algorithm) and the enhanced scenario (Priority Queuing) across three flows. In the No Algorithm configuration, all flows exhibit a packet loss ratio of 1.0 (100%), meaning every transmitted packet was lost due to severe congestion and lack of traffic management. This indicates that the network was unable to deliver any data successfully under high-load conditions.

- In contrast, the Priority Queuing scenario shows a packet loss ratio of 0 for all flows, signifying complete packet delivery without any loss. This dramatic improvement highlights the effectiveness of Priority Queuing in managing congestion and ensuring reliable data transmission. By prioritizing critical packets, the algorithm eliminates packet drops, which is essential for maintaining service quality in dense wireless environments.

- The graph clearly demonstrates that Priority Queuing transforms network performance from total failure to full reliability, making it a superior solution for scenarios with heavy traffic.

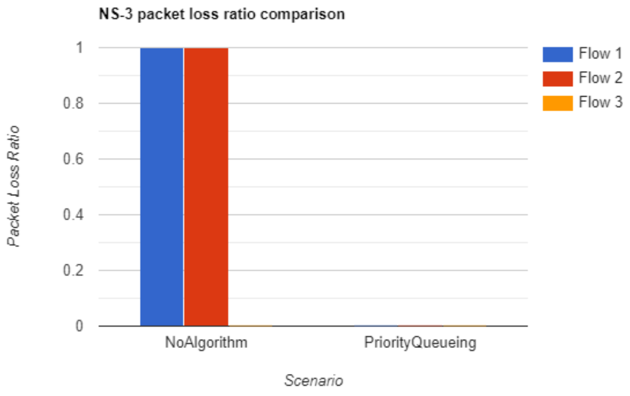

Fig. 5 NS-3 3 Packet Loss Ratio Comparison Graph

Network Traffic Volume

- Fig. 6 compares the network traffic volume between the baseline scenario (No Algorithm) and the enhanced scenario (Priority Queuing) across three flows. In the No Algorithm configuration, traffic volume is extremely low, with Flow 1 and Flow 2 showing negligible values and Flow 3 reaching only about 20,000 bytes. This indicates that most packets were dropped, and very little data reached the destination under congested conditions.
- In contrast, the Priority Queuing scenario demonstrates a substantial improvement. Flow 1 achieves approximately 85,000 bytes, which is more than four times higher than the highest value in the baseline scenario. Flow 2 also shows improvement, reaching around 15,000 bytes, while Flow 3 remains minimal but positive. This distribution reflects the prioritization mechanism, where higher-priority flows receive more bandwidth and transmit significantly more data.
- The graph clearly illustrates that Priority Queuing enables actual data transmission under heavy congestion, ensuring that critical flows maintain service quality while reducing packet loss and improving overall network efficiency.

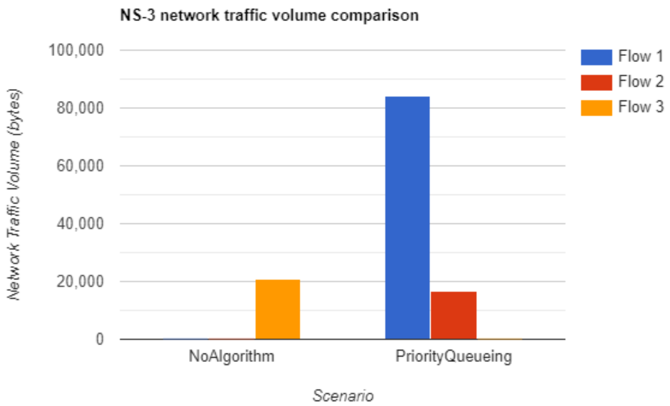

Fig. 6 NS-3 3 Network Traffic Volume Comparison Graph

The testing phase, conducted in NS-3 after validating the Python QoS system, demonstrates that Priority Queuing (PQ) is highly effective in congested wireless environments. PQ significantly reduces packet loss, ensures successful data transmission, and improves resource utilization compared to scenarios without QoS. These findings validate PQ as the optimal algorithm for this study.

DISCUSSION

The findings of this study demonstrate the technical feasibility and practical value of an adaptive Wi-Fi 6 quality management framework in smart stadium environments. By implementing real-time bandwidth allocation and traffic prioritization, the system effectively mitigates service degradation under high-density conditions. The integration of a Python-based control mechanism further enhances scalability and supports flexible deployment in real-world scenarios, making it a viable solution for large public venues.

Beyond its technical contributions, the study highlights the broader social and managerial implications of reliable wireless connectivity. In digitally connected public spaces, network performance directly influences digital inclusion. When connectivity is stable and equitable, all attendees can access digital services such as live streaming, social media sharing, and interactive applications without disruption. This fosters a more inclusive and participatory environment, where spectators are not only consumers of content but active contributors to the event experience. From a management perspective, the framework introduces a new dimension of operational innovation. By leveraging live network data, venue operators can make informed decisions about infrastructure, crowd flow, and safety communications, treating connectivity as a strategic asset rather than a background utility.

Smart stadiums, in this context, evolve into spaces of technological citizenship where equitable access to information and digital experiences contributes to a shared sense of community. This study illustrates how Wi-Fi 6 quality management supports digital inclusion, which in turn enhances the social experience of live events.

CONCLUSION

This study developed and evaluated an adaptive Wi-Fi 6 quality management framework aimed at improving both broadcasting performance and the overall social experience in smart stadium environments. Through simulation and analysis, the system demonstrated its ability to reduce latency and packet loss, maintain stable throughput under high-density conditions, and deliver smoother live streaming. These technical improvements contribute to a more immersive and satisfying experience for spectators, reinforcing the importance of reliable connectivity in shaping collective engagement. The findings underscore the idea that connectivity is not merely a technical utility but a form of social infrastructure. In public venues like smart stadiums, dependable wireless service enables inclusive participation, real-time interaction, and audience satisfaction. As such, Wi-Fi 6 quality management is positioned not only as an engineering achievement but also as a social innovation that supports equitable access and digital transformation.

This research contributes to the field by introducing a technically advanced framework for adaptive QoS management in Wi-Fi 6 networks, validated through NS-3 simulations. It also offers a conceptual perspective that integrates digital inclusion and social experience into the analysis of wireless systems, presenting a new way to interpret connectivity in public event settings. Looking ahead, future research may explore the integration of machine learning for predictive congestion control, the orchestration of hybrid 5G Wi-Fi networks, and the inclusion of user-centered methods such as ethnographic studies or satisfaction surveys. These interdisciplinary extensions will further align technical system design with meaningful social outcomes. In an era where human connection increasingly depends on digital infrastructure, managing network quality becomes an act of social design. Smart stadiums exemplify how technological excellence, when guided by social purpose, can transform collective experiences into shared innovation.

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