QoS (Quality of Service) – It's Not Just for DOCSIS Anymore

A technical paper prepared for presentation at SCTE TechExpo24

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1. Introduction

As internet services have become critical for streaming, gaming, and remote work, ensuring a high-quality user experience is paramount. This is where Quality of Service (QoS) steps in, prioritizing various types of network traffic to optimize performance. While both DOCSIS® (Data Over Cable Service Interface Specification) networks and Wi-Fi employ QoS mechanisms, they do so differently.

The rapid growth of internet usage has placed significant pressure on network infrastructure. QoS has become essential to ensure that users receive a seamless experience. We will delve into the QoS mechanisms employed by DOCSIS and Wi-Fi, highlighting their differences and examine how they can collaborate to create synergies, thereby enhancing network efficiency and user experience.

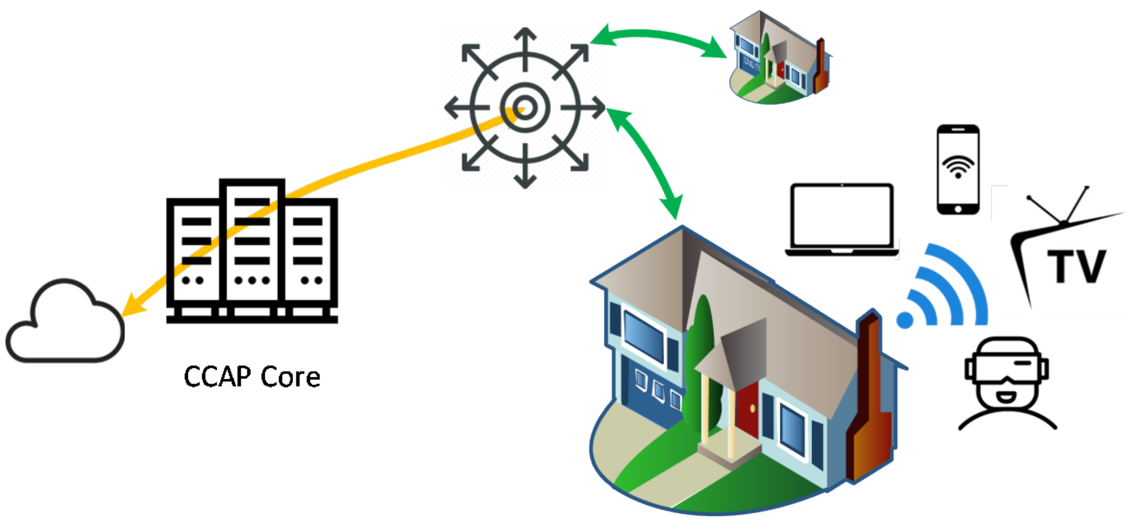

Figure 1 - Infrastructure Landscape for Cable Operators

2. Key Network Performance Metrics (KPIs)

To understand the importance of QoS, it's essential to grasp the key performance metrics that influence network efficiency and user experience. These metrics include throughput, latency, and jitter.

Throughput: Throughput measures the amount of data transferred over a network in a given period, usually in bits per second (bps). Higher throughput indicates a network's capacity to handle more data, which is crucial for bandwidth-intensive applications such as video streaming and large file transfers.

Latency: Latency refers to the delay in network communication, indicating the time taken for data to transfer across the network. Low latency is crucial for applications that require real-time data transmission, such as online gaming, video conferencing, and VoIP (Voice over Internet Protocol). High latency can lead to noticeable delays and a poor user experience.

Jitter: Jitter represents the variability in packet arrival time. Inconsistent packet delivery can affect the quality of audio and video data, leading to choppy or distorted playback. Minimizing jitter is essential for maintaining a smooth and reliable user experience, particularly for real-time applications.

3. DOCSIS

DOCSIS integrates QoS features to effectively manage and prioritize network traffic, ensuring high-priority traffic like video streaming and VoIP receives the necessary bandwidth and low latency for optimal performance. DOCSIS has evolved over the years, introducing various enhancements to improve network performance and user experience.

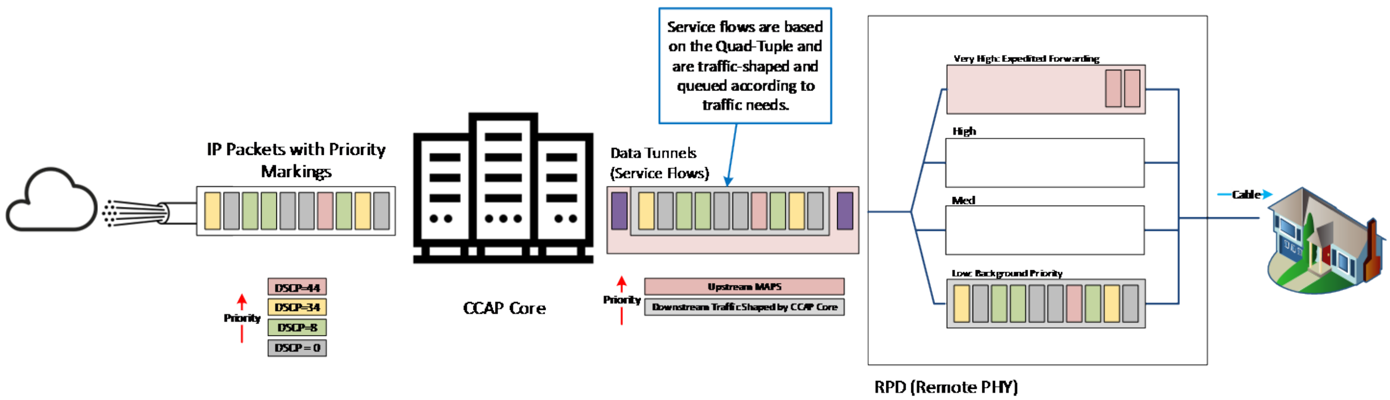

Figure 2 - DOCSIS QoS and Traffic Management

3.1. Standards

- **DOCSIS 3.1**: Introduced Orthogonal Frequency-Division Multiplexing (OFDM) and Orthogonal Frequency-Division Multiple Access (OFDMA) for improved spectrum efficiency and reduced latency. These technologies allow for more efficient use of available bandwidth, enabling higher data rates, better performance in congested environments, and support for low-latency applications.
- **DOCSIS 4.0**: Features symmetrical speeds, extended spectrum, proactive scheduling, and dual-queue AQM to significantly reduce packet latency. It also includes Low Latency Xhaul (LLX) services to optimize latency for mobile traffic. DOCSIS 4.0 represents a significant leap forward in network performance, supporting next-generation applications such as 8K video streaming, virtual reality (VR), and augmented reality **(AR).**

Table 1 - Evolution of DOCSIS Standards

DOCSIS Version	Year	Key QoS Features	Key Advancements
3	2006	Advanced QoS, dynamic service flows	Channel bonding, higher data rates, more complex service flows
3.1	2013	OFDM, OFDMA, low latency	Improved spectrum efficiency, reduced latency, enhanced QoS management
4	2020	Symmetrical speeds, extended spectrum, advanced QoS mechanisms	Higher upload speeds, better support for next-gen applications like 8K video streaming and VR/AR

3.2. Key QoS Concepts/Features

- **Priority Queuing**: Manages traffic based on priority levels to ensure high-priority traffic is transmitted with minimal delay. Priority queuing is essential for applications that require real-time data transmission, such as online gaming and video conferencing.
- **Service Flows**: Differentiates QoS for various traffic types by classifying packets into different service flows based on QoS parameters, ensuring appropriate bandwidth and latency guarantees. Service flows enable network operators to allocate resources efficiently, providing a better experience for high-priority applications.
- **Traffic Shaping**: Controls the traffic rate entering the network to ensure compliance with QoS policies, improving overall network performance. Traffic shaping helps prevent network congestion by regulating the flow of data, ensuring that high-priority traffic is not hindered by lower-priority traffic.
- **Active Queue Management (AQM)**: Enhances QoS by managing queue lengths and minimizing packet loss and delay through proactive queue management techniques. AQM techniques, such as Random Early Detection (RED) and Controlled Delay (CoDel), help maintain network stability by reducing congestion and ensuring timely delivery of packets.
- **Enhanced Hierarchical QoS (EHQoS)**: Provides granular QoS control with aggregate service flows, supporting both centralized and distributed modes for improved latency and bandwidth utilization. EHQoS enables more precise control over network resources, allowing for better management of complex service flows and high-priority applications.

The progression of QoS in DOCSIS networks starts with basic priority queuing to ensure minimal delay for high-priority traffic. It advances to service flows for differentiated QoS, traffic shaping to prevent congestion, and AQM for proactive congestion management. Finally, EHQoS provides granular control for optimal performance in complex and high-demand networks. This progression ensures that DOCSIS networks can meet the increasing demands of modern applications and services.

The DSCP field of the cable modem's upstream packets are marked by the demodulator/packet generator in accordance with the traffic shaping policy.

In a DOCSIS network, downstream Per-Hop Behavior (PHP) and Differentiated Services Code Point (DSCP) work together to ensure effective traffic management and QoS. Packets are classified and marked with DSCP values at the headend, indicating their required service level. As these packets travel downstream, each network node applies PHP based on the DSCP value, ensuring packets receive the appropriate priority and treatment. This process aids in traffic shaping by controlling data flow rates, preventing congestion, and ensuring high-priority traffic is delivered efficiently. The marked packets are then channeled to specific flow IDs, which categorize and manage individual traffic flows, ensuring that each receives the appropriate resources and QoS. Even though these mechanisms are part of the standard, they might not be implemented by every service provider.

3.3. Enhancements in DOCSIS 4.0

The DOCSIS 4.0 standard includes advanced QoS mechanisms to support next-gen applications such as 8K video streaming and VR/AR. These enhancements aim to provide higher data rates, lower latency, and improved overall performance.

- **Symmetrical speeds and extended spectrum**: Enable higher upload speeds and better support for next-gen applications. DOCSIS 4.0 offers significant improvements in both downstream and upstream performance, supporting the growing demand for high-quality internet services.
- **Proactive scheduling and dual-queue AQM**: Significantly reduce packet latency. Advanced queue management techniques help maintain consistent performance, even in congested network conditions, by proactively managing traffic and reducing delays.
- **Low Latency Xhaul (LLX) Services**: Optimize latency for mobile traffic on DOCSIS links. LLX services provide better support for mobile applications, ensuring that high-priority traffic receives the necessary resources for optimal performance.
- **Low Latency Low Loss Scalable throughput (L4S):** Enhances the low-latency performance of DOCSIS networks, particularly for real-time applications like gaming and video conferencing.
- **Non-Queue-Building (NQB) Flows**: Improve the handling of latency-sensitive traffic by separating it from bulk traffic, reducing queuing delays and ensuring smoother performance for applications like VoIP and video streaming.

4. Wi-Fi

Wi-Fi employs techniques to prioritize specific data services within a wireless network, improving KPIs such as latency, jitter, and reliability, thereby enhancing the user experience. As Wi-Fi technology has evolved, various QoS mechanisms have been introduced to address the growing demand for high-quality wireless connectivity.

4.1. Standards

- **802.11e**: Introduced EDCA and TSPEC for improved traffic management. The 802.11e amendment was a significant milestone in the development of Wi-Fi QoS, providing the foundation for subsequent enhancements.
- **802.11n/ac**: Enhanced throughput with features like MIMO (Multiple Input Multiple Output) and MU-MIMO (Multi-User MIMO), indirectly improving QoS by reducing congestion. These enhancements enabled higher data rates and more efficient use of available spectrum, improving overall network performance.
- **802.11ax (Wi-Fi 6)**: Introduced OFDMA (Orthogonal Frequency-Division Multiple Access), BSS Coloring, and 1024-QAM (Quadrature Amplitude Modulation), enhancing both throughput and QoS. Wi-Fi 6 represents a significant advancement in wireless technology, offering improved performance in congested environments and better support for high-density deployments.
- **802.11be (Wi-Fi 7)**: Added features like 320 MHz channels, 4096-QAM, and Multi-Link Operation (MLO) for further improvements in reliability and performance. Wi-Fi 7 aims to provide even higher data rates and lower latency, supporting the growing demand for high-quality wireless connectivity.

Table 2 - Evolution of Wi-Fi Standards

Year	IEEE	Wi-Fi Alliance	Comments	Feature	Throughput	QoS
1999	802.11	WiFi		DCF, PCF		
2004		WMM	from 802.11e	EDCA		✓
				TSPEC, Admission Control		✓
2007	802.11-2007		merged 802.11e	EDCA		✓
				HCCA		✓
				TSPEC, Admission Control		✓
2009	802.11n	WiFi 4		MIMO, Channel Bonding, Frame Aggregation	✓	
2012	802.11-2012		merged 802.11 n, s	MCCA		✓
				Path Selection		✓
				Airtime Link Metric		✓
				Interworking		✓
2013	802.11ac	WiFi 5		160Mhz, 256-QAM, MU-MIMO, Beamforming	✓	
2016	802.11-2016		merged 802.11aa, ac	SCS		✓
2020	802.11-2020			MSCS		✓
2021		QoS Management	from 802.11e	DSCP to UP mapping		✓

			SCS, MSCS		✓
2021	801.11ax	WiFi 6	TUA, OFDMA, BSS Coloring, Spatial Reuse, 1024-QAM	✓	✓
2022	802.11be	WiFi 7	320Mhz, 4096-QAM, MLO	✓	✓

4.2. Key QoS Concepts/Features:

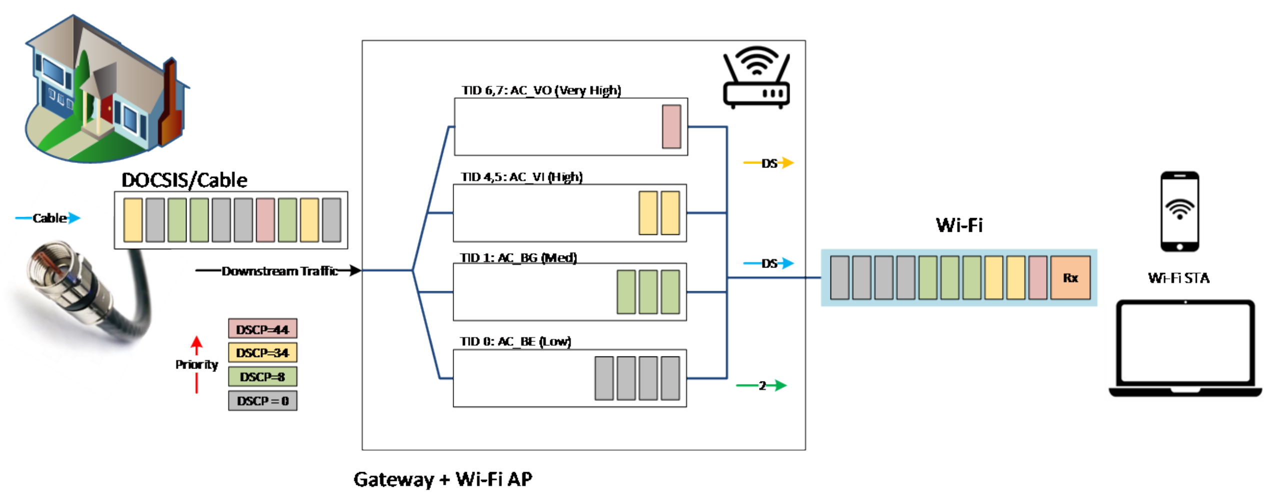

Figure 3 - Wi-Fi QoS and Traffic Management

- **Enhanced Distributed Channel Access (EDCA)**: Divides traffic into Access Categories (ACs) such as voice, video, best effort, and background, managing how these data packets are prioritized and transmitted. EDCA ensures that high-priority traffic, such as voice and video, receives preferential treatment, reducing latency and improving overall performance.
- **Traffic Specification (TSPEC)**: Defines the QoS requirements of a data flow, allowing devices to request the access point for specific QoS requirements. TSPEC enables more efficient management of network resources, ensuring that critical applications receive the necessary bandwidth and low latency.
- **Stream Classification Service (SCS)**: Allows a station to explicitly request downlink resources (UL added in “IEEE 802.11be”) to the access point for meeting QoS requirements for specific traffic flows. SCS provides a flexible and dynamic approach to traffic management, allowing for better allocation of network resources based on current conditions.

4.3. Enhancements in Wi-Fi 6 and 7

Wi-Fi 6 and Wi-Fi 7 introduce several enhancements to further improve QoS and overall network performance. These advancements aim to address the growing demand for high-quality wireless connectivity and support the increasing number of connected devices.

- **OFDMA (Orthogonal Frequency-Division Multiple Access)**: Allows multiple users to share a single channel, boosting efficiency and reducing latency. OFDMA enables more efficient use of available spectrum, improving overall network performance and reducing congestion.
- **1024-QAM and 4096-QAM**: High-density modulation schemes that increase data rates. These modulation techniques enable higher data throughput, supporting bandwidth-intensive applications such as 4K and 8K video streaming.
- **MLO (Multi-Link Operation)**: Allows a station to establish multiple links in multiple bands for improved reliability and throughput. MLO enhances the overall performance and reliability of Wi-Fi networks, providing better support for high-density deployments and reducing interference.
- **Trigger based:** Triggered Uplink Access (TUA) enhances uplink performance by enabling client devices to send data upon receiving a "trigger" frame from the access point. This synchronized approach cuts down on waiting periods and contention, thus lowering latency.
- **BSS Coloring**: Minimizes co-channel interference by labeling frame headers, enhancing network performance. This improvement is due to the combination of BSS Coloring and spatial reuse, which together help reduce interference and improve the efficiency of Wi-Fi networks, particularly in congested environments.

5. Synergy Between DOCSIS and Wi-Fi QoS

In the future, combining DOCSIS and Wi-Fi QoS mechanisms can significantly enhance network performance and user experience. By leveraging the strengths of both technologies, network operators can provide a more seamless and consistent experience for users.

5.1. Upstream Synchronization:

- Wi-Fi TXOP (Transmit Opportunity) synchronization with DOCSIS upstream MAP (Media Access Plan) (~4 ms) reduces latency, ensuring timely data transmission. Upstream synchronization helps maintain consistent performance for high-priority applications, minimizing delays and improving overall user experience.

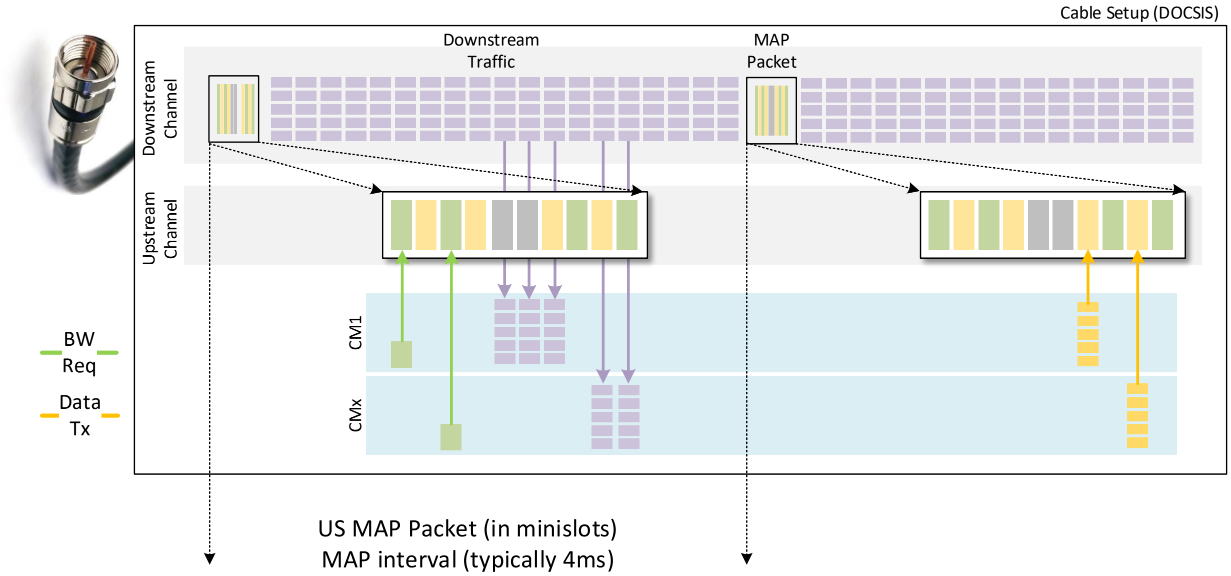

Figure 4 - Synchronization between Wi-Fi and DOCSIS

5.2. End-to-End Prioritization:

- **DOCSIS**: Prioritizes traffic from the ISP to the modem, maintaining QoS for critical applications. DOCSIS ensures that high-priority traffic, such as video streaming and online gaming, receives the necessary bandwidth and low latency for optimal performance.
- **Wi-Fi**: Extends prioritization from the modem to wireless devices, ensuring seamless and consistent prioritization. Wi-Fi QoS mechanisms, such as EDCA, TSPEC, and SCS, help maintain high-quality service for critical applications, even in congested environments.

5.3. Consistent User Experience:

- DOCSIS and Wi-Fi QoS reduce delays and ensure high-priority data is transmitted with minimal latency. By working together, these technologies can provide a seamless and reliable experience for users, regardless of the type of application or network conditions.
- High-priority applications like streaming and online gaming receive consistent bandwidth and low jitter. Ensuring that critical applications receive the necessary resources helps maintain a high quality of service, even in challenging network environments.

6. Networking Protocols

Advancements in networking protocols have been pivotal in addressing issues like congestion and QoS. Some of the most impactful improvements are detailed below.

6.1. CoDel

- This improves internet connections by addressing excessive queuing delay. It monitors packet time in queues and manages them to keep delays low. Technically, CoDel tracks minimum queuing delay over short intervals, dropping packets if delays exceed a target value. It uses a unique dropping strategy that adapts to persistent congestion. This approach signals the network to adjust data transmission, preventing long delays and maintaining smooth data flow, even during high network usage. CoDel can enhance performance for various internet activities, potentially improving the responsiveness and reliability of internet connections as it's adopted more widely.

6.2. L4S (Low Latency, Low Loss, Scalable throughput)

- L4S (Low Latency, Low Loss, Scalable throughput) is a technology that improves internet connections by addressing queuing delay and packet loss. It uses a novel congestion control approach to maintain high throughput with minimal delay. Technically, L4S employs a dual-queue coupled AQM system and make use of the ECN (Explicit Congestion Notification) protocol for precise congestion signaling. L4S-compatible senders rapidly adjust transmission rates based on these signals, keeping queue lengths extremely short.
- Unlike CoDel, which focuses on managing a single queue by selectively dropping packets, L4S uses two queues: one for L4S-capable traffic and another for classic traffic. L4S also provides more frequent and precise congestion feedback to endpoints, allowing for faster response times. While CoDel aims to keep delays below a target value, L4S strives for near-zero queuing delay consistently.
- This approach allows for near-zero queuing delay and minimal packet loss, even under heavy network load. L4S can enhance performance for various internet applications, potentially revolutionizing network performance management as it gains wider adoption.

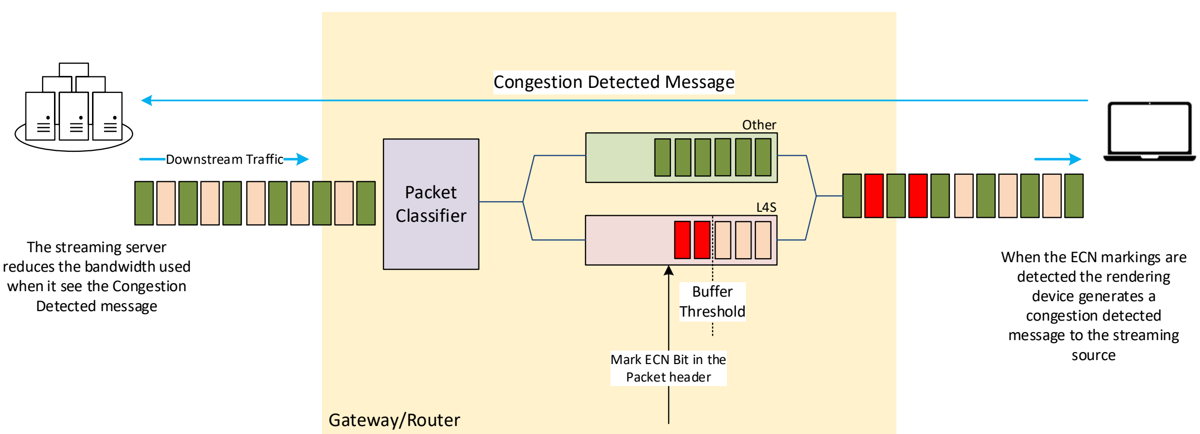

Figure 5 - L4S Algorithm

7. Conclusion

Integrating DOCSIS and Wi-Fi QoS mechanisms creates a robust framework for managing and prioritizing network traffic, enhancing overall network efficiency and user experience. As technology evolves, continuous improvements in QoS will be essential to meet the demands of modern applications and ensure a seamless, high-quality user experience.

By leveraging the advanced features of DOCSIS 4.0 and Wi-Fi 7, network operators can ensure that high-priority applications receive the necessary resources, thereby delivering a consistent and reliable user experience. The collaboration between DOCSIS and Wi-Fi QoS mechanisms provides a comprehensive solution for managing network traffic, optimizing performance, and maintaining a high quality of service in increasingly complex and demanding network environments.

As the number of connected devices continues to grow and the demand for high-quality internet services increases, the importance of QoS will only become more critical. By understanding and implementing the advanced QoS features available in DOCSIS and Wi-Fi, network operators can ensure that their networks are prepared to meet the challenges of the future and provide a superior user experience.

This white paper highlights the critical aspects of QoS in DOCSIS and Wi-Fi networks, emphasizing the importance of prioritizing traffic to maintain optimal performance and user satisfaction. By leveraging the advanced features of DOCSIS 4.0 and Wi-Fi 7, network operators can ensure that high-priority applications receive the necessary resources, thereby delivering a consistent and reliable user experience.

Abbreviations

AQM	Active Queue Management
AP	Access Point
AR	Augmented Reality
bps	bits per second
BSS	Basic Service Set
CoDel	Controlled Delay
DOCSIS	Data Over Cable Service Interface Specification
ECN	Explicit Congestion Notification
EDCA	Enhanced Distributed Channel Access
ISP	Internet Service Provider
KPIs	Key Performance Indicators
L4S	Low Latency Low Loss Scalable throughput
LLX	Low Latency Xhaul
MAP	Media Access Plan
MLO	Multi-Link Operation
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RED	Random Early Detection
SCS	Stream Classification Service
TSPEC	Traffic Specification
TXOP	Transmit Opportunity
VoIP	Voice over Internet Protocol
VR	Virtual Reality

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