Active Queue Management in OneWeb and Starlink LEO Satellite Networks

1. Introduction:

Low Earth Orbit (LEO) satellite networks are rapidly transforming global internet connectivity, offering the potential for high-speed broadband access to underserved regions and enabling a wide array of applications from remote work to real-time data transfer.[1] This proliferation of constellations, such as OneWeb and Starlink, signifies a major shift from traditional Geostationary Equatorial Orbit (GEO) satellites, which, due to their high altitude, inherently experience significant latency. LEO satellites, orbiting much closer to Earth, provide substantially reduced latency, making them suitable for applications demanding real-time responsiveness. This fundamental change in satellite communication necessitates the implementation of advanced network management techniques to ensure optimal performance.

A crucial aspect of efficient network management, particularly in the dynamic environment of LEO satellite networks, is effective queue management.[15] Given the constant movement of satellites and the resulting frequent handovers, LEO networks experience rapid changes in network conditions. Inefficient queue management in such scenarios can lead to network congestion, increased latency, and packet loss, all of which can severely degrade the user experience. Therefore, sophisticated mechanisms are required to proactively manage network traffic and maintain a high quality of service. This report aims to investigate the use of Active Queue Management (AQM) by OneWeb and Starlink within their LEO satellite networks, as well as to identify the default AQM algorithms they employ, based on available research.

2. Understanding Active Queue Management (AQM):

Active Queue Management (AQM) represents a significant advancement over traditional "drop-tail" queue management by proactively managing network queues to prevent congestion and enhance overall network performance.[19] Unlike drop-tail queuing, which only discards packets when the buffer is completely full, AQM strategically drops or marks packets *before* the queue reaches its maximum capacity. This early signaling mechanism alerts senders to potential congestion, prompting them to reduce their transmission rates preemptively. By doing so, AQM helps to avoid severe congestion episodes and the problem of bufferbloat, which can lead to excessively high latency.

The benefits of employing AQM in network devices are manifold.[20] Firstly, it contributes to a reduction in network congestion and the associated packet loss by managing queue sizes before overflow occurs. Secondly, AQM improves end-to-end latency by maintaining shorter average queue lengths, ensuring that packets spend less time waiting in buffers. A key advantage is the prevention of bufferbloat, a condition where excessively large buffers in network devices cause significant delays and jitter, negatively impacting interactive applications. Furthermore, by proactively managing queues, AQM helps to mitigate the issue of global synchronization among network flows, where multiple connections simultaneously back off and then increase their transmission rates, leading to inefficient link utilization.

Several common AQM algorithms are utilized in modern networks.[19] **Random Early Detection (RED)** and its variant **Weighted RED (WRED)** are designed to detect and signal congestion by probabilistically dropping packets based on the average queue size.[19] This probabilistic approach aims to randomize packet drops, preventing the synchronization of responses from multiple network flows and thereby promoting more stable link utilization. However, these algorithms often require careful tuning of their parameters to achieve optimal performance. **Explicit Congestion Notification (ECN)** provides a more refined mechanism for congestion signaling.[19] ECN allows routers to mark packets to indicate congestion to the communicating endpoints without actually dropping them, provided that both the sender and receiver support ECN. This approach avoids packet loss, which can be particularly beneficial in networks where retransmissions are costly or significantly impact performance. **Controlled Delay (CoDel)** and **Fair Queueing CoDel (FQ-CoDel)** represent more recent developments in AQM.[19] CoDel focuses on actively controlling the delay experienced by packets within the queue, aiming to minimize bufferbloat and improve network responsiveness. FQ-CoDel extends this by incorporating fair queueing, which helps to isolate and manage misbehaving flows that might otherwise monopolize network resources. Other AQM algorithms, such as PIE, Blue, and CAKE, also exist, each with its own specific mechanisms and performance characteristics.[20]

3. Challenges of Queue Management in LEO Satellite Networks:

LEO satellite networks present a unique set of characteristics that introduce significant challenges for traditional queue management techniques and necessitate careful consideration of AQM strategies.[15]

One of the primary challenges stems from the **high mobility of satellites and the resulting frequent handovers**.[15] As LEO satellites orbit the Earth at high speeds, the connection between a user terminal and the network needs to be handed over from

one satellite to another as satellites move across the sky. These frequent handovers can lead to transient disruptions in the data flow, potentially causing packet loss and out-of-order packet delivery. Effective queue management in this environment requires mechanisms that can maintain connection stability and manage queue behavior smoothly during these handover events.

Another significant factor is the **varying link capacities** inherent in satellite communication.[15] The capacity of the radio links between satellites and ground stations or user terminals can fluctuate due to several factors, including the distance between the communicating nodes, prevailing weather conditions such as rain attenuation, and potential interference from other sources. AQM algorithms deployed in LEO networks need to be adaptable to these dynamic changes in link capacity. They must be able to adjust queue management strategies in real-time to avoid either underutilization of available bandwidth or the onset of network congestion when capacity decreases.

While LEO networks offer significantly lower latency compared to GEO satellites, they still have **inherent propagation delays** due to the considerable distance signals must travel to space and back.[3] These propagation delays can impact the responsiveness of congestion control mechanisms that rely on feedback signals such as acknowledgments. AQM strategies in LEO networks might require careful tuning of parameters to account for these longer Round-Trip Times (RTTs) and ensure effective congestion control.

Finally, some LEO satellite constellations, notably Starlink, utilize **Inter-Satellite Links (ISLs)** to route traffic directly between satellites within the constellation.[6] This creates a more complex network topology where traffic might traverse multiple satellite hops before reaching its destination. In such architectures, managing queues effectively across multiple interconnected satellites requires coordination to ensure optimal end-to-end performance and avoid congestion hotspots within the constellation.

4. OneWeb and Active Queue Management:

An examination of the provided research material reveals a lack of explicit information regarding the use of Active Queue Management (AQM) within OneWeb's LEO satellites.[18] While the snippets offer insights into OneWeb's technical specifications, including satellite altitude, constellation size, and frequency bands [1], they do not specifically detail the queue management algorithms employed within the satellite routers themselves.

Despite the absence of direct mention, OneWeb consistently emphasizes low latency and high throughput as key differentiators of its network.[14] Achieving these performance metrics in a shared network environment necessitates the implementation of effective congestion control mechanisms, of which AQM is a crucial component. Snippet [47] states that "As OneWeb is an enterprise-grade constellation, users do not suffer issues associated with congestion." This claim suggests that OneWeb has implemented proactive network management strategies to minimize congestion for its users, and AQM could logically be a part of this strategy. Furthermore, OneWeb utilizes a Self Service Data Hub (SSDH) [45] for monitoring network performance and facilitating troubleshooting, indicating a strong focus on maintaining network health. While SSDH itself doesn't directly confirm AQM, the ability to monitor and address performance issues related to congestion is enhanced by the use of AQM.

OneWeb's network supports various wireless technologies, including 3G, LTE, 5G, and Wi-Fi.[1] Snippet [51] mentions that OneWeb's transport layer is based on 4G/LTE technology, utilizing AES-128 encryption and IPsec tunneling for Quality of Service (QoS) management. While these technologies often incorporate their own queue management features at different layers of the network stack, this does not definitively confirm the use of AQM within the satellite infrastructure. The focus on providing enterprise-grade connectivity with guaranteed availability and security [17] further implies the use of sophisticated network management techniques to ensure a consistent and reliable service, where AQM would play a valuable role.

5. Starlink and Active Queue Management:

In contrast to OneWeb, the research material provides explicit evidence of Starlink's use of Active Queue Management (AQM). Snippets [22] clearly state that Starlink has implemented **active queue management, specifically fq_codel, within the Starlink WiFi router.** This implementation at the user premises aims to enhance the quality of experience on the local network by preventing bufferbloat and ensuring that latency-sensitive applications, such as online gaming, are not adversely affected by bandwidth-intensive activities occurring simultaneously on the same network.

While the use of fq_codel in the user router is confirmed, snippet [10] indicates that the provided article does not explicitly state whether Starlink utilizes AQM within its satellite infrastructure. However, the article does discuss Starlink's use of transport layer congestion control algorithms, primarily TCP CUBIC as the default, with observed performance improvements when switching to BBR.[10] The choice of these algorithms at the transport layer interacts with how the underlying network handles

congestion signals, which could be influenced by the presence or absence of AQM at lower layers.

Research suggests that the inherent mobility of LEO satellites presents significant challenges for traditional congestion control algorithms, including CUBIC.[15] This underscores the need for robust congestion management strategies within the Starlink network, where AQM could play a crucial role in mitigating the impact of frequent network variations caused by satellite movement and handovers. Furthermore, Starlink has been actively engaged in efforts to reduce network latency and improve overall performance.[22] These efforts include optimizing the locations of ground gateways and, significantly, **improving queueing algorithms**.[22] The explicit mention of improving queueing algorithms in the context of latency reduction strongly implies the use of AQM techniques within Starlink's network infrastructure, although the specific algorithm used in the satellites themselves is not detailed in the provided materials.

6. Comparative Analysis and Discussion:

Comparing the available information, it is evident that Starlink explicitly employs AQM (fq_codel) in its WiFi routers, enhancing the user experience on the local network.[22] While there is no direct confirmation of AQM usage within OneWeb's user terminals from the provided snippets, both companies emphasize low latency and high throughput, indicating a focus on effective congestion control.[14] Starlink's active efforts to improve queueing algorithms to reduce latency [22] strongly suggest the implementation of AQM within their network infrastructure, although the specific algorithm used in the satellites is not specified. No such explicit mention of AQM within the satellite infrastructure is found for OneWeb in the provided research.

The use of FQ-CoDel by Starlink at the router level is likely to improve the quality of experience for users with multiple devices connected to their local network by managing bandwidth allocation and minimizing latency for interactive applications. Both companies rely on transport layer congestion control algorithms like TCP CUBIC and BBR [10] to manage end-to-end congestion. The unique challenges inherent to LEO networks, including satellite mobility, frequent handovers, and varying link capacities [15], necessitate robust congestion management strategies, and AQM is a critical tool for addressing these complexities.

One potential difference in their approaches might be influenced by their primary target markets.[4] OneWeb has a stronger focus on B2B and enterprise solutions, often with Service Level Agreements (SLAs) that guarantee certain levels of performance.[17]

This might lead OneWeb to implement more stringent or tailored AQM strategies within its network to meet the specific demands of enterprise users, although this is not explicitly detailed in the provided material. Starlink, while also offering business services, has a significant consumer base [4], and its AQM implementation might be geared towards providing a good overall experience for a broad range of users.

7. Research and Development in LEO Congestion Control:

The ongoing research efforts to optimize congestion control algorithms and queue management techniques specifically for LEO satellite networks highlight the complexities involved in ensuring efficient data transmission in these dynamic environments.[15] Traditional congestion control algorithms often struggle to cope with the rapid network variations caused by the mobility of LEO satellites.[15] Consequently, researchers are exploring ways to adapt existing algorithms, such as Copa and BBR, to be more aware of LEO-specific network characteristics.[15] Furthermore, new algorithms like StarQUIC [27] and MACO [88] are being developed specifically to address the challenges of LEO environments, taking into account factors like satellite handovers and fluctuating link capacities. The QUIC protocol, with its features like multiplexing and end-to-end encryption, is also being actively considered and optimized for satellite networks due to its potential for improved performance over TCP.[63] This active area of research underscores the continuous need for innovation in congestion control and queue management to fully realize the potential of LEO satellite networks.

8. Conclusion:

Based on the analysis of the provided research material, Starlink explicitly utilizes Active Queue Management (AQM) with the fq_codel algorithm in its WiFi routers.[22] There is also strong indication that Starlink employs AQM within its network infrastructure to optimize latency and performance, although the specific algorithm used in the satellites is not detailed. In contrast, the research snippets do not provide direct evidence of AQM being used within OneWeb's satellites. However, OneWeb's consistent emphasis on low latency and high throughput, coupled with the statement that their enterprise users do not typically experience congestion [47], suggests the likely use of advanced queue management and congestion control mechanisms within their network.

Efficient queue management is paramount for the successful operation of LEO satellite networks due to their unique challenges, including high satellite mobility, frequent handovers, and varying link capacities. While Starlink has been more

transparent about its use of AQM at the user router level and has indicated improvements to queueing algorithms within its infrastructure, specific details about AQM implementation within both OneWeb's and Starlink's satellites remain largely unconfirmed in the provided materials. Further investigation into technical documentation directly from OneWeb regarding their network implementation would be beneficial to gain a more comprehensive understanding of their AQM strategies.

Table 1: Comparison of OneWeb and Starlink Network Characteristics:

Characteristic	OneWeb	Starlink
Satellite Orbit Altitude	~1200 km [1]	~550 km [5]
Constellation Size (approximate)	>630 [2]	>4000 [5]
Target Markets	Primarily B2B, Enterprise, Government, Maritime, Aviation [2]	Consumer, Business, Maritime, Roam, Government [6]
AQM in User Terminals	No explicit evidence in provided snippets	Yes (fq_codel in WiFi router) [22]
AQM in Satellite Infrastructure	Implied (focus on low latency, high throughput, and congestion-free enterprise service)	Implied (efforts to improve queueing algorithms for latency reduction) [22]
Default Congestion Control Algorithms	Not explicitly stated in provided snippets	TCP CUBIC (default), users report improvements with BBR [10]
Typical Latency	<70 ms [17]	20-60 ms [6]
Typical Download/Upload Speeds	Up to 195 Mbps down, 32 Mbps up [60]	25-220 Mbps down, 5-20 Mbps up (Standard plan) [7]

Table 2: Common Active Queue Management (AQM) Algorithms:

AQM Algorithm Name	Description	Key Benefits	Potential Drawbacks/Considerations
Random Early Detection (RED)	Probabilistically drops packets based on average queue size.	Prevents global synchronization, signals congestion early.	Requires careful parameter tuning.
Weighted RED (WRED)	Variant of RED that considers packet priorities.	Provides differentiated treatment based on traffic type.	Still requires parameter tuning.
Explicit Congestion Notification (ECN)	Marks packets to signal congestion without dropping them (if supported).	Avoids packet loss, more graceful congestion management.	Requires support from both endpoints.
Controlled Delay (CoDel)	Focuses on controlling the delay within the queue.	Effectively combats bufferbloat, improves responsiveness.	May not be ideal for all types of traffic.
Fair Queueing CoDel (FQ-CoDel)	Combines CoDel with fair queueing.	Isolates misbehaving flows, ensures fairness among connections, combats bufferbloat.	Can be more complex to implement than basic CoDel.

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