RYSAVY RESEARCH

How Title II Net Neutrality Undermines 5G

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Introduction

Engineers and scientists have applied their ingenuity to create 5G, the next generation of wireless technology. Today, all major operators in the United States are deploying the technology. 5G will further unleash the explosive potential of wireless networking by dramatically lifting data throughput rates, expanding capacity, reducing network delays, increasing reliability, and achieving higher security. 5G network platforms will accommodate the variety of applications and uses that now demand wireline networks. And, the network and service capabilities that 5G makes possible will enable a vast number of new use cases for mobile and fixed wireless technologies.

Unfortunately, network neutrality rules that do not take into account the specific needs of wireless networks, such as the FCC's previous open internet rules premised on Title II of the Communications Act, may be reinstated. When applied to 5G network deployment and operation, such reinstated regulations would likely have the perverse effect of thwarting many of the most consumer-friendly 5G use cases. The purpose of this paper is to make clear how some of the Title II-based regulations related to net neutrality would sacrifice the very 5G characteristics that hold the most promise for consumers, innovation, and economic growth across multiple sectors of the U.S. economy.

The Collision of Title II-Based Open Internet Rules and 5G

The millions of mobile applications already transforming the world are just the dawn of the next frontier in mobile broadband—humanity has barely begun exploiting the full potential of wireless technology. The Internet of Things, which will interconnect objects to increase their utility and efficiency, will account for tens of billions of new connections by next decade. IoT's potential is limited only by imagination; use cases include self-driving cars with pre-crash sensing and mitigation, health biometric sensing and response, telemedicine, and proactive monitoring of critical physical infrastructure such as transmission lines.

What many of these new applications have in common are stringent data communication requirements, such as high reliability or minimal delay. This is true even for use cases without particularly onerous bandwidth demands. For example, a self-driving car or autonomous robot may need only a small amount of data, but it might have to receive that data within a few thousandths of a second. In contrast, a consumer watching a movie through a bandwidth-intensive service that uses content buffering experiences no interruption to the viewing experience, even if network speeds vary.

The federal government's decision in 2015 to classify mobile broadband as a Title II common carrier service, intended to subject mobile broadband to net neutrality rules, happened at the same time that standards-based mobile technologies, such as LTE, were beginning to provide quality-of-service (QoS) management capabilities to network operators. Such QoS capabilities improve mobile traffic flows and can enhance user experiences. The timing of Title II-based net neutrality for mobile could not have been worse. That should have been the time for operators to start using QoS parameters to serve different use cases and to experiment with various business models that could support them.

However, with Title II as the baseline regulation, it was unclear whether QoS capabilities could be used as intended. For example, the rules banned paid prioritization but allowed reasonable network management and specialized services not relying on a broadband internet access service, and they came with a complex waiver process. The uncertainty engendered in this framework stifled innovation, and conservatively interpreted, resulted in the absurd requirement that a heart monitor transmission to a hospital emergency room could not be treated differently from a cat video.

The FCC's Title II-based restrictions on handling different kinds of traffic based on what the bits require slammed the door on a vast number of new applications that are actually pro-consumer and pro-innovation. Although these rules were repealed by the FCC in 2018 under a new administration, legislation or court action could reinstate the Title II restrictions. If this happens, without changes to the regulations, the full potential of 5G will never be realized.

How Quality-of-Service Works

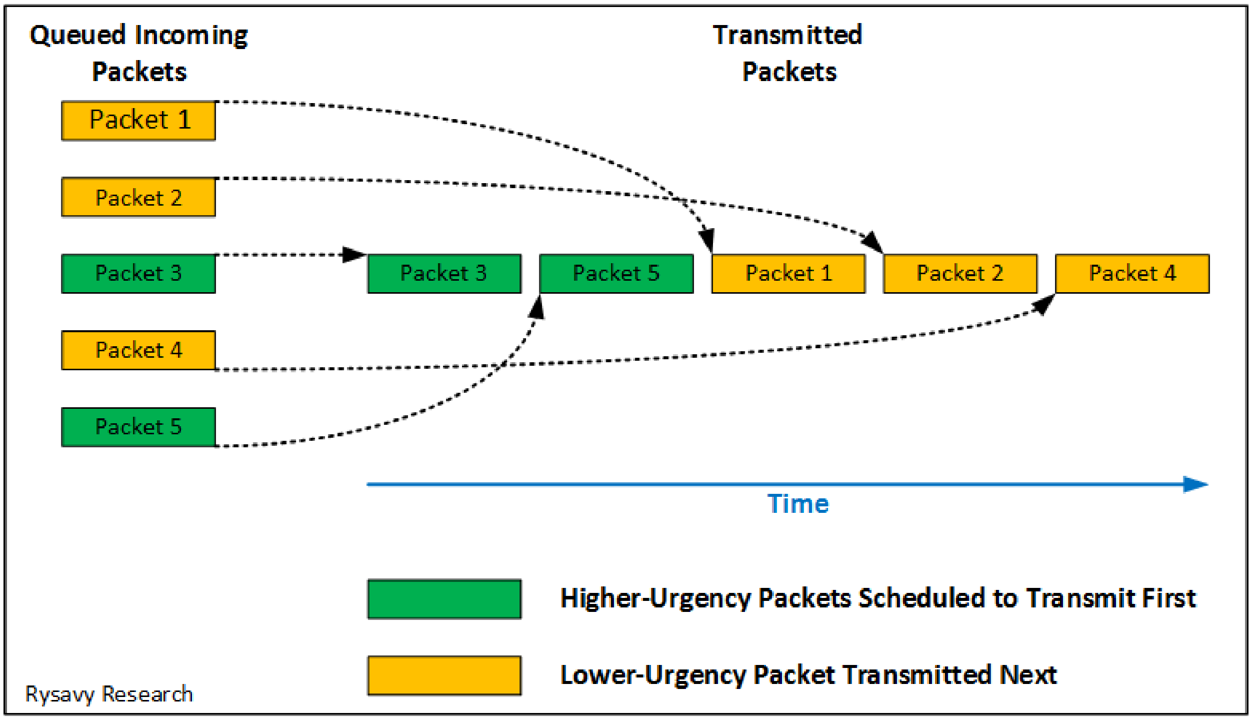
Engineers have designed controls for how packets flow between base stations and users over the radio interface. Traffic-flow parameters include whether bit rates are guaranteed, their priority relative to other traffic flows, the maximum amount of packet delay that can be tolerated by the traffic in question, and the extent of permissible packet loss. LTE and 5G define quality-class identifiers, each with unique parameters.[1] For example, Voice over LTE (VoLTE), which is based on voice-over-IP protocols, uses these QoS mechanisms to provide carrier-grade voice service. Without this control, an LTE voice call would disintegrate if surrounding users were consuming large amounts of data—the network prioritizes voice as higher priority than data. The same prioritization of voice over data also happens in 2G and 3G networks.

VoLTE is an operator specialized service, not a broadband Internet service, so Title II net neutrality allows this specific form of prioritization. However, the rules restrict many other potential Internet-based applications from using QoS capabilities. VoLTE exemplifies the critical need for QoS management. The fact that it is almost the only widespread wireless application deployed that uses QoS demonstrates the chilling effect network neutrality has had on innovation.

Figure 1 shows how, in a QoS-enabled network, the network may schedule higher-urgency packets to transmit first, ahead of those with lower urgency.

[1] For 5G QoS details, refer to the Appendix. For details about LTE QoS, refer to 3GPP TS 23.203. *Technical Specification Group Services and System Aspects; Policy and charging control architecture*, available at http://www.3gpp.org/DynaReport/23203.htm. Specifically, see Table 6.1.7, "Standardized QCI characteristics."

Figure 1: Transmission of Packets According to Their Urgency in a QoS-Enabled Network



5G will employ similar, yet more sophisticated, mechanisms to handle different kinds of traffic flows. This is critical because engineers are designing 5G for a wider range of use cases than prior technology generations, such as 3G and 4G. As described below, 5G will employ a "network slicing" architecture that will depend heavily on QoS management. Many of the applications envisioned for 5G are of a control nature, which means they need minimal delay and high reliability.

Table 1 lists some typical applications and their QoS requirements.

Table 1: Examples of Applications and QoS Requirements

Application	Requirements
Speech	Guaranteed bit rate, low delay, but can tolerate some packet loss.
Internet of Things	Varying requirements depending on use case, but mission-critical applications will require low error rate and low delay.
Streaming (music, video)	High throughput but can tolerate delay and some packet loss.
Health and medicine	Throughput-rate requirements vary. High priority for critical health applications.

Application	Requirements
Autonomous vehicles	Not necessarily high throughput. Low delay and low packet loss.
Video conferencing and telepresence	High average throughput, low delay, can tolerate some packet loss on video but less on voice.
Operating system or application update	Can run in the background over an extended period, so QoS requirements are minimal.
Web browsing	High average throughput, low error rate, can tolerate slight delay.

As a more detailed example, an analysis by the GSM Association (GSMA) shows that a strongly interactive virtual reality session would require the network parameters shown in Table 2. Without appropriate traffic prioritization, VR will not be dependable over a 5G connection.

Table 2: Strong-Interactive VR Requirements[2]

	Entry-Level VR (Now – 2 years) (8K 2D/3D)	Advanced VR (3 to 5 years) (12K 3D)	Ultimate VR (6 to 10 years) (24K 3D)
Data Rate	120Mbps（2D） 200Mbps（3D）	1.40Gbps	3.36Gbps
Typical Round-Trip Time	10 msec.	5 msec.	5 msec.
Packet Loss	1 in 1 million	1 in 1 million	1 in 1 million

Current wireless networks assign equal priority to all third-party application traffic, regardless of the application type. An analogy is a freeway on which fast-moving cars and slow-moving trucks use all lanes equally. The Information Technology & Innovation Foundation (ITIF) states in a report, "To date, we have been able to muddle through with this 'best-effort' system, but many of the exciting innovations around the corner will increasingly require reliable low-latency connections. And while some applications affirmatively need prioritization or some kind of differentiation, other applications can easily tolerate delay or jitter."[3]

[2] GSMA, *Network Slicing, Use Case Requirements*, April 2018. Available at https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/NS-Final.pdf.

[3] Information Technology & Innovation Foundation, *Crafting a Grand Bargain Alternative to Title II: Net Neutrality with Net Adoption*, October 2015. Available at http://www2.itif.org/2015-alternative-title-ii.pdf.

The goal of intelligent traffic prioritization is to maximize the quality of experience across the largest number of users and application types possible, allocating higher priority for those applications that need it while not adversely affecting those that do not.

As ITIF states, “Traffic differentiation simply is not a zero-sum game.” Because applications have varying quality requirements, selective application of QoS results in higher average quality of experience across the subscriber base. The Broadband Internet Technical Advisory Group agrees, stating, “For example, some differentiation techniques improve the Quality of Service (QoS) or Quality of Experience (QoE) for particular applications or classes of applications without negatively impacting the QoE for other applications or classes of applications.”[4]

[4] Broadband Internet Technical Advisory Group, *Differentiated Treatment of Internet Traffic*, October 2015. Available at http://www.bitag.org/documents/BITAG_-_Differentiated_Treatment_of_Internet_Traffic.pdf.

> Differentiation is not a zero-sum game. Selective application of QoS increases the quality of experience across the subscriber base.

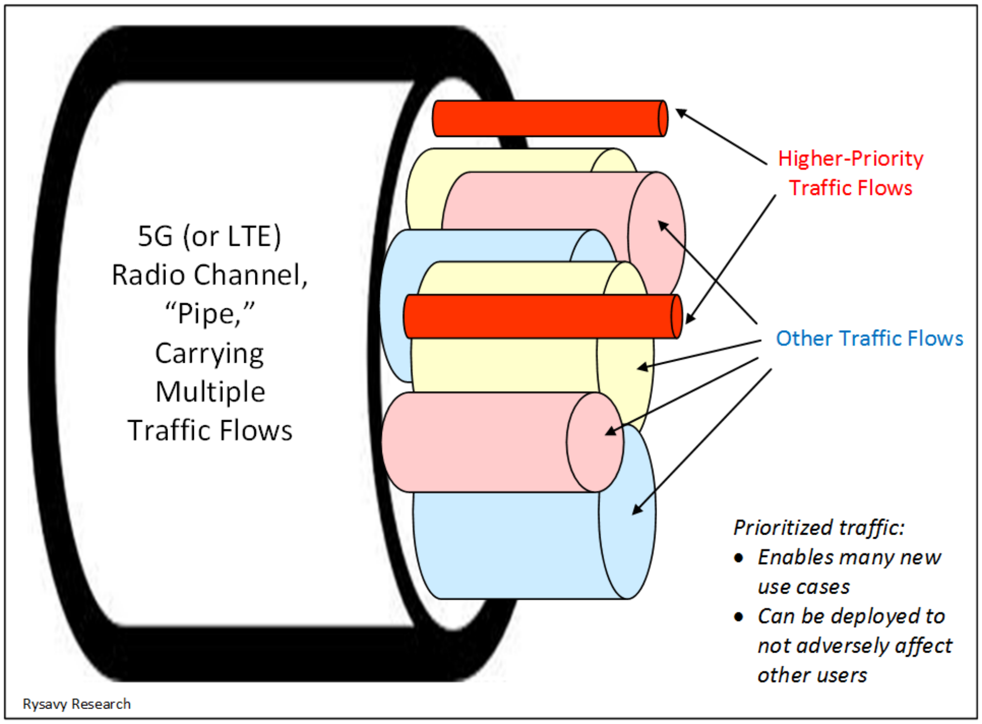
GSMA, representing the interests of 750 operators and 400 companies in the broader mobile ecosystem[5], states, “Mobile network operators must have the freedom to manage and prioritise traffic on their networks.”[6]

Figure 2 shows how a 5G wireless network could use QoS management to allocate different priorities to different traffic flows based on their urgency.

[5] GSMA, “About Us,” https://www.gsma.com/aboutus/, viewed May 16, 2019.

[6] GSMA, *Network Slicing, Use Case Requirements*, April 2018. Available at https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/NS-Final.pdf.

Figure 2: Radio Resource Management in a Wireless Network



How Title II Undermines 5G

Within any specific coverage area, a cellular network has a limited amount of aggregate capacity available to users. This capacity is determined by the amount of spectrum deployed and the spectral efficiency of the technology. When the amount of demand is less than the available capacity, applications function well for users in that coverage area. But when demand exceeds capacity, congestion results and applications suffer. The effect is analogous to too many cars traveling on a highway. Initially, cars simply slow down in the face of traffic ahead. If the traffic continues unabated, cars come to a halt. Similarly, in the face of network congestion, applications will initially operate more slowly; for example, a file download takes longer to complete. But as congestion gets worse, packet delays or dropped packets increase to the extent that network transactions time out and fail entirely. Even with the augmented capacity 5G will bring, new applications, such as virtual reality, will allow a relatively small number of users to consume available capacity.

Operators mitigate the worst effects of congestion by deploying more spectrum when possible, installing more cell sites, using more efficient technology, and offloading some traffic onto other networks such as Wi-Fi. But eliminating congestion entirely is impossible. Even a small number of users in the same geographic area simultaneously using high-bandwidth applications, such as video, can consume the entire capacity of a cell. Operators cannot predict how many mobile users will be present at any moment in any location, nor can they know what those users will be doing. Network investment can ensure a high quality of experience on average but cannot guarantee it for all users at all times.

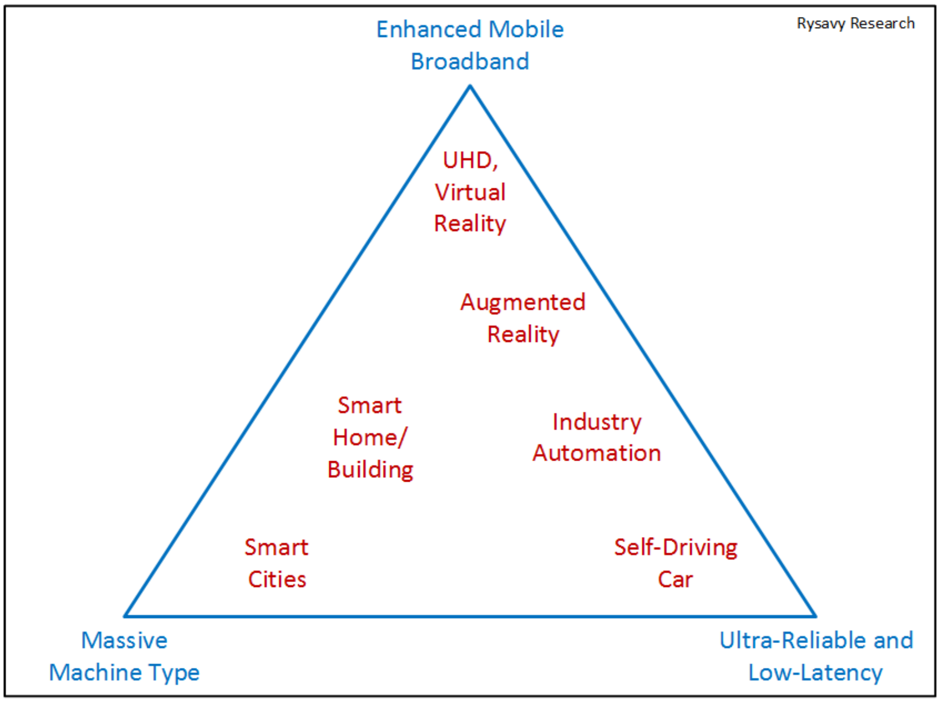
The effect of congestion is neither uniform nor consistent, meaning the degree of congestion can change moment by moment. Therefore, absent network tools to manage around congestion, no user can completely depend on the network for a critical operation. This was acceptable in years past, but consider the applications being developed for 5G: A medical device that has detected a possibly life-threatening event and is trying to send that data to a server for immediate evaluation could fail. A self-driving car may detect debris on the road but not be able to swerve in time. A surgeon operating remotely with robotics might lose connection at a critical moment.

A 5G network environment can ensure these critical connections are protected from congestion effects—but only if QoS and other tools built into the 5G standards are allowed to work.

5G Use-Case Models Depend on Ability to Provide QoS

The International Telecommunication Union is the organization charged with setting 5G objectives and approving final technical standards for how 5G networks interface with one another and enabled devices. The ITU's recommendation M.2083-0[7] defines use cases using the following model.

Figure 3: ITU 5G Use-Case Model



Enhanced mobile broadband is faster Internet, a turbo-charged version of today's LTE-Advanced networks. "Massive machine type" refers to millions of sensors and controls placed throughout cities, homes, and businesses to improve energy efficiency, transportation, and other logistics. But it is the new ultra-reliable and low-latency category, also referred to as "mission critical," that opens cellular networks to capabilities never before possible, such as advanced industry automation and autonomous vehicles. This category of 5G application will depend on the ability to deploy traffic prioritization.

Developers expect response times of less than a millisecond with 5G, ten times lower than with LTE, in which 10 msec. latencies are typical. But unprioritized and competing with other traffic, the latency (round-trip time in the network) can be ten times higher, for example, 100 msec. At 60 miles per hour, a car travels nine feet in 100 msec. versus only one inch in 1 msec. In a scenario of an intelligent highway

[7] Available at http://www.itu.int/rec/R-REC-M.2083-0-201509-I

warning a car of a pedestrian on the road at a blind curve, that could be the difference between life and death.

5G Networking Slicing and QoS Management

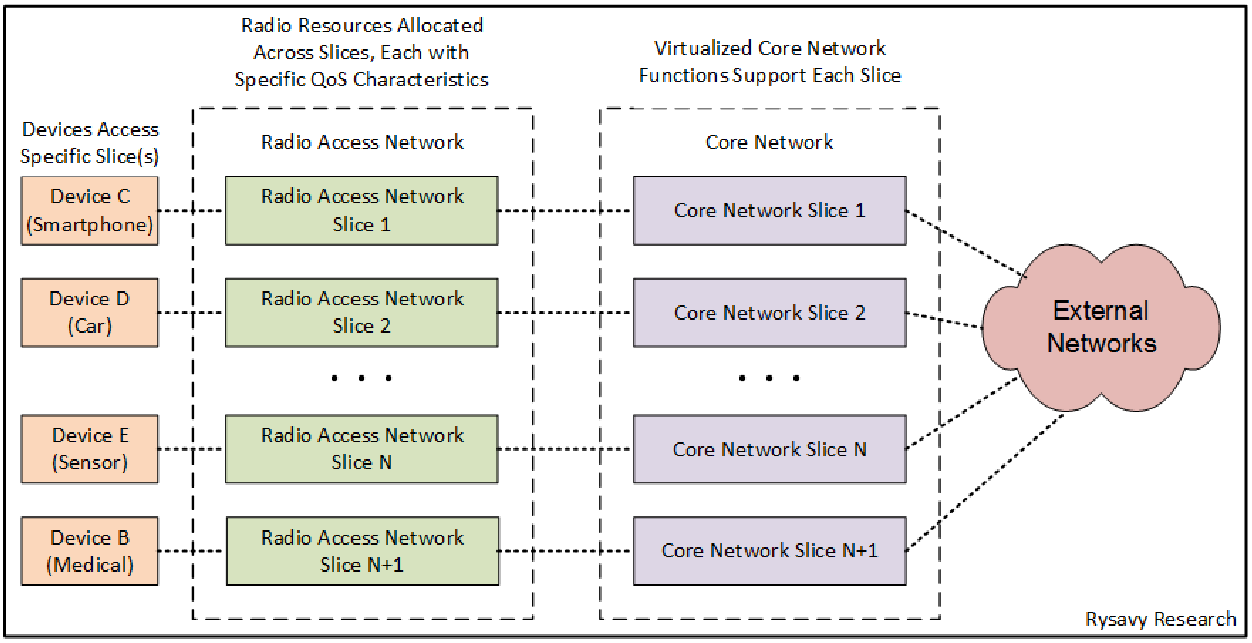
5G needs QoS management, not only for traffic prioritization to support mission-critical applications, but also to enable a fundamental capability in its architecture: network slicing. Network slicing, implemented through virtualization, will allow an operator to provide various services with different performance characteristics to address specific use cases. Each network slice operates as an independent, virtualized version of the network. For an application, the network slice is the only network it sees. The other slices, to which the customer is not subscribed, are invisible and inaccessible. The advantage of this architecture is that the operator can create slices that are fine-tuned for specific use cases. One slice could target autonomous vehicles, another enhanced mobile broadband, another low-throughput IoT sensors, and so on.

In essence, with network slicing, an operator can use a common physical infrastructure to create multiple logical networks, each operating as an independent business operation.

Figure 4 shows the network slicing architecture, with devices having access to only the slice(s) for which they have a subscription. Each slice has radio resources allocated, with specific QoS characteristics. As a 5G Americas report states, "Each slice is defined to meet different service/application requirements, which are represented in a certain QoS level."[8] Within the core network, virtualized core network functions support each slice and provide connections to external networks.

[8] 5G Americas, *Network Slicing for 5G Networks & Services*, November 2016. Available at: http://www.5gamericas.org/files/3214/7975/0104/5G_Americas_Network_Slicing_11.21_Final.pdf.

Figure 4: 5G Network Slicing Architecture



Operators will be able to provision devices through account configuration so the devices can access specific slices. For consumers, one slice might be for best-effort, unprioritized Web browsing, while another slice could support prioritized telepresence that needs low latency and high bandwidth. Meanwhile, a slice for smart meters could provide high reliability with low bandwidth.

GSMA has identified the following industry segments as ones that will benefit from network slicing:[9]

- Augmented Reality and Virtual Reality
- Automotive
- Energy
- Healthcare
- Manufacturing
- Internet of Things
- Public Safety
- Smart Cities

[9] GSMA, *Network Slicing, Use Case Requirements*, April 2018. Available at https://www.gsma.com/futurenetworks/wp-content/uploads/2018/04/NS-Final.pdf.

On a global basis, GSMA estimates that network slicing will provide operators a $300 billion revenue opportunity by 2025.[10]

Even with access to new spectrum and expected peak throughputs that will exceed 1 Gbps, 5G networks will need to manage latency, reliability, massive numbers of connections, and a mix of stationary and mobile users. Fundamental to this task will be managing QoS, which depends on traffic prioritization and will be undermined by Title II net neutrality rules.

Conclusion

The communications requirements of today's mobile network applications span a huge range. One application may need high throughput but can tolerate significant delay. Another may need to send only a small number of bits, but these must traverse the network with minimal delay. Future Internet of Things innovations, from intelligent highways to smart-grid monitoring, will only increase the rich variety of application diversity. QoS mechanisms in 5G provide for application developers and operators to specify needs and for the network to dynamically accommodate them.

Developers and operators have a financial stake in enabling a diverse range of services; empowering them to optimize networks to meet competing needs will result in the highest possible quality of experience for the largest number of users. The business case for massive 5G investment can only be made by being able to support all potential applications. Current simplistic views of network neutrality are blind to the fact that different types of applications have different network requirements.

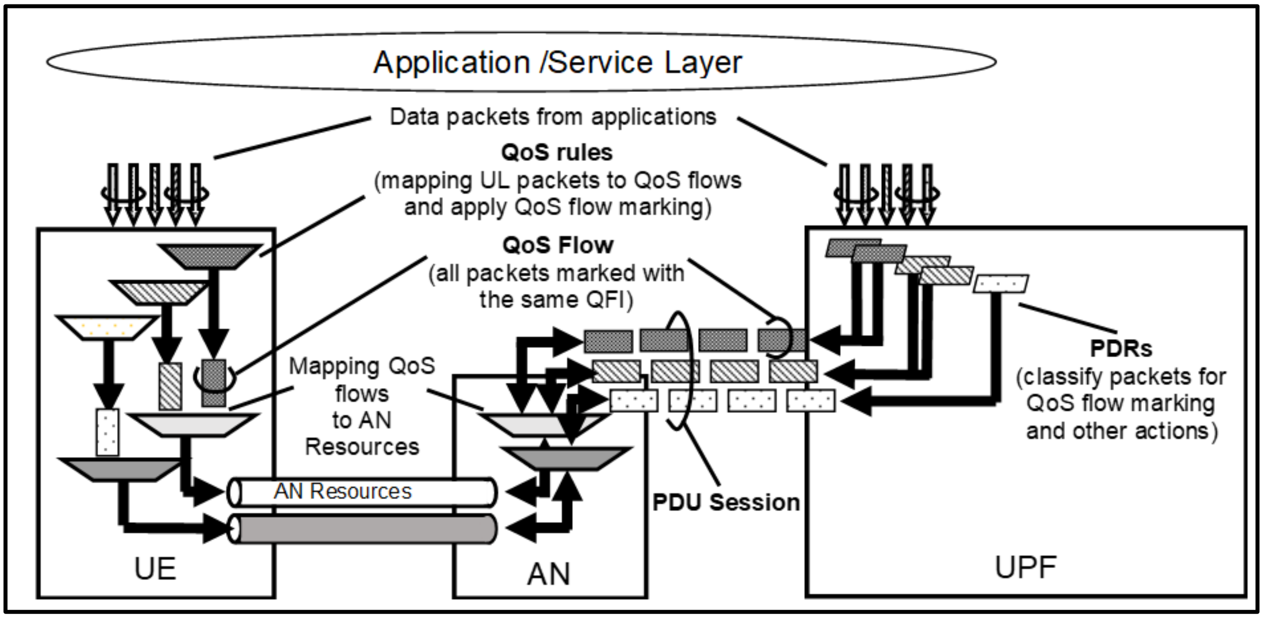
The U.S. wireless industry is at a critical juncture. The United States has assumed global leadership in 4G and enjoys deep 4G penetration, leading smartphone platforms, and a vibrant application ecosystem. Undermining 5G with Title II network neutrality would reduce both business investment in 5G networks and the economic gains from 5G applications. A diminished U.S. 5G market would also threaten the long-term viability of trusted 5G infrastructure vendors. Poor decisions on network neutrality will thus cede economic power to other countries, such as China, and threaten the ability of the United States to have the most advanced and most secure wireless infrastructure in the world.

[10] *Ibid.*

Appendix: 3GPP Specifications on 5G QoS and Network Slicing

3GPP technical specification, 23.501, *System Architecture for the 5G System*[11], covers both quality of service and network slicing. Section 5.7 covers the handling of QoS.

Figure 5.7.1.5-1 shows how a user's data session (PDU session) consists of multiple QoS flows, each with a particular QFI. If operating within a network slice, the slice determines the available QFIs.



5QI: 5G QoS Identifier
AN: Access Network
PDR: Packet Detection Rule
PDU: Protocol Data Unit
QFI: QoS Flow Identifier
UE: User Equipment
UPF: User Plane Function

Table 5.7.4-1 shows the mapping of 5QI values to specific QoS parameters.

[11] 3rd Generation Partnership Project, Technical Specification, *System Architecture for the 5G System; Stage 2, Release 16*, 3GPP TS 23.501 V16.0.2, Apr. 2019. Available at https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3144.

5QI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume (NOTE 2)	Default Averaging Window	Example Services
1	GBR (NOTE 1)	20	100 ms (NOTE 11, NOTE 13)	10^{-2}	N/A	2000 ms	Conversational Voice
2		40	150 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Conversational Video (Live Streaming)
3 (NOTE 14)		30	50 ms (NOTE 11, NOTE 13)	10^{-3}	N/A	2000 ms	Real Time Gaming, V2X messages Electricity distribution – medium voltage, Process automation - monitoring
4		50	300 ms (NOTE 11, NOTE 13)	10^{-6}	N/A	2000 ms	Non-Conversational Video (Buffered Streaming)
65 (NOTE 9, NOTE 12)		7	75 ms (NOTE 7, NOTE 8)	10^{-2}	N/A	2000 ms	Mission Critical user plane Push To Talk voice (e.g., MCPTT)
66 (NOTE 12)		20	100 ms (NOTE 10, NOTE 13)	10^{-2}	N/A	2000 ms	Non-Mission-Critical user plane Push To Talk voice
67 (NOTE 12)		15	100 ms (NOTE 10, NOTE 13)	10^{-3}	N/A	2000 ms	Mission Critical Video user plane
75 (NOTE 14)							
71		56	150 ms (NOTE 11, NOTE 15)	10^{-6}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])
72		56	300 ms (NOTE 11, NOTE 15)	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])
73		56	300 ms (NOTE 11, NOTE 15)	10^{-8}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])
74		56	500 ms (NOTE 11, NOTE 15)	10^{-8}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])
75		56	500 ms (NOTE 11, NOTE 15)	10^{-4}	N/A	2000 ms	"Live" Uplink Streaming (e.g. TS 26.238 [76])
5	Non-GBR (NOTE 1)	10	100 ms NOTE 10, NOTE 13)	10^{-6}	N/A	N/A	IMS Signalling
6		60	300 ms (NOTE 10, NOTE 13)	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.)
7		70	100 ms (NOTE 10, NOTE 13)	10^{-3}	N/A	N/A	Voice, Video (Live Streaming) Interactive Gaming
8		80	300 ms (NOTE 13)	10^{-6}	N/A	N/A	Video (Buffered Streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p

9		90					file sharing, progressive video, etc.)
69 (NOTE 9, NOTE 12)		5	60 ms (NOTE 7, NOTE 8)	10^{-6}	N/A	N/A	Mission Critical delay sensitive signalling (e.g., MC-PTT signalling)
70 (NOTE 12)		55	200 ms (NOTE 7, NOTE 10)	10^{-6}	N/A	N/A	Mission Critical Data (e.g. example services are the same as 5QI 6/8/9)
79		65	50 ms (NOTE 10, NOTE 13)	10^{-2}	N/A	N/A	V2X messages
80		68	10 ms (NOTE 5, NOTE 10)	10^{-6}	N/A	N/A	Low Latency eMBB applications Augmented Reality
82	Delay Critical GBR	19	10 ms (NOTE 4)	10^{-4}	255 bytes	2000 ms	Discrete Automation (see TS 22.261 [2])
83		22	10 ms (NOTE 4)	10^{-4}	1354 bytes (NOTE 3)	2000 ms	Discrete Automation (see TS 22.261 [2])
84		24	30 ms (NOTE 6)	10^{-5}	1354 bytes (NOTE 3)	2000 ms	Intelligent transport systems (see TS 22.261 [2])
85		21	5 ms (NOTE 5)	10^{-5}	255 bytes	2000 ms	Electricity Distribution-high voltage (see TS 22.261 [2])

NOTE 1: A packet which is delayed more than PDB is not counted as lost, thus not included in the PER.
NOTE 2: It is required that default MDBV is supported by a PLMN supporting the related 5QIs.
NOTE 3: This MDBV value is set to 1354 bytes to avoid IP fragmentation for the IPv6 based, IPSec protected GTP tunnel to the 5G-AN node (the value is calculated as in Annex C of TS 23.060 [56] and further reduced by 4 bytes to allow for the usage of a GTP-U extension header).
NOTE 4: A delay of 1 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN component of the PDB is used, see clause 5.7.3.4.
NOTE 5: A delay of 2 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN component of the PDB is used, see clause 5.7.3.4.
NOTE 6: A delay of 5 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. When a dynamic CN component of the PDB is used, see clause 5.7.3.4.
NOTE 7: For Mission Critical services, it may be assumed that the UPF terminating N6 is located "close" to the 5G_AN (roughly 10 ms) and is not normally used in a long distance, home routed roaming situation. Hence delay of 10 ms for the delay between a UPF terminating N6 and a 5G_AN should be subtracted from this PDB to derive the packet delay budget that applies to the radio interface.
NOTE 8: In both RRC Idle and RRC Connected mode, the PDB requirement for these 5QIs can be relaxed (but not to a value greater than 320 ms) for the first packet(s) in a downlink data or signalling burst in order to permit reasonable battery saving (DRX) techniques.
NOTE 9: It is expected that 5QI-65 and 5QI-69 are used together to provide Mission Critical Push to Talk service (e.g., 5QI-5 is not used for signalling). It is expected that the amount of traffic per UE will be similar or less compared to the IMS signalling.
NOTE 10: In both RRC Idle and RRC Connected mode, the PDB requirement for these 5QIs can be relaxed for the first packet(s) in a downlink data or signalling burst in order to permit battery saving (DRX) techniques.
NOTE 11: In RRC Idle mode, the PDB requirement for these 5QIs can be relaxed for the first packet(s) in a downlink data or signalling burst in order to permit battery saving (DRX) techniques.
NOTE 12: This 5QI value can only be assigned upon request from the network side. The UE and any application running on the UE is not allowed to request this 5QI value.
NOTE 13: A delay of 20 ms for the delay between a UPF terminating N6 and a 5G-AN should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface.
NOTE 14: This 5QI is not supported as it is only used for transmission of V2X messages over MBMS bearers as defined in TS 23.285 [72].
NOTE 15: For "live" uplink streaming (see TS 26.238 [76]), guidelines for PDB values of the different 5QIs correspond to the latency configurations defined in TR 26.939 [77]. In order to support higher latency reliable streaming services (above 500ms PDB), if different PDB and PER combinations are needed these configurations will have to use non-standardised 5QIs.

eMBB: Enhanced Mobile Broadband

GPR: Guaranteed Bit Rate

V2X: Vehicle to Anything (for example, Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I).

Network Slicing is also covered in the same specification in section 5.15.[12]

About Rysavy Research

Peter Rysavy is the president of Rysavy Research LLC, a consulting firm that has specialized in wireless technology since 1993. Projects include analysis of spectrum requirements for mobile broadband, reports on the evolution of wireless technology, evaluation of wireless technology capabilities, strategic consultations, system design, articles, courses and webcasts, network performance measurement, test reports, and acting as an expert in patent-litigation cases. Clients include more than ninety-five organizations.

Peter is a broadly published expert on the capabilities and evolution of wireless technology. He has written more than 160 articles, reports, and white papers, and has taught more than forty public wireless courses and webcasts. He has also performed technical evaluations of many wireless technologies, including cellular-data services, municipal/mesh Wi-Fi networks, Wi-Fi hotspot networks, mobile browser technologies, wireless e-mail systems, and social networking applications.

From 1988 to 1993, Peter was vice-president of engineering and technology at Traveling Software (later renamed LapLink); projects included LapLink, LapLink Wireless, and connectivity solutions for a wide variety of mobile platforms. Prior to Traveling Software, he spent seven years at Fluke Corporation, where he worked on data-acquisition products and touch-screen technology.

From 2000 to 2016, Peter was also the executive director of the Wireless Technology Association, an industry organization that evaluates wireless technologies, investigates mobile communications architectures, and promotes wireless-data interoperability. Peter Rysavy graduated with BSEE and MSEE degrees from Stanford University in 1979. More information is available at http://www.rysavy.com.

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[12] *Ibid.*