Securing the Future of U.S. Wireless Networks

The Looming Spectrum Crisis

U.S. wireless networks face a looming capacity crisis, risking material degradation in performance with dire implications for the broader economy if new spectrum cannot be made available for 5G. Networks will soon be unable to keep up with demand, creating a growing spectrum shortfall. The spectrum shortfall will start to impact consumers as early as 2026, and by 2027, networks will be unable to meet nearly a quarter of traffic demand in high-traffic areas during peak hours. Additional full-power mid-band spectrum must be licensed to enhance network capacity, enable enterprises to innovate and expand their services, and provide users with faster, more reliable, and secure connectivity.

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Contents

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Executive Summary

The U.S. faces a spectrum crisis, with long-term negative implications for U.S. economic growth. Rising demand on networks and constrained supply is pushing networks to their limit. Additional full-power mid-band spectrum must be licensed to enhance network capacity, enable enterprises to innovate and expand their services, and provide users with faster, more reliable, and secure connectivity to boost the U.S.' global technology leadership. Failing to do so would result in the U.S. losing out on $1.4T of potential GDP between 2025-2035[1]*.

Our previous paper, "The Case for Global Spectrum Harmonization", highlighted the core 5G bands that are either already globally harmonized or are on their way towards harmonization, and the opportunity for the U.S. to play a more active leadership role[2]. The U.S. has failed to make any harmonized bands or additional spectrum available for commercial use since 2022. Meanwhile, data consumption has been on pace to double every two years since 2021[3]. By 2027, the U.S. is expected to face a critical spectrum deficit, where the available spectrum will not be able to support connectivity demand in high-traffic areas during peak hours[4]. The U.S. must license additional spectrum to ensure reliable wireless networks, support 5G adoption growth, and sustain the productivity engine of the U.S. economy.

This paper examines the impact of the impending spectrum shortfall on U.S. wireless networks, businesses, consumers, and the country. Without additional spectrum, mobile networks will be unable to keep up with demand, risking material degradation in wireless network performance.

As connectivity demand overtakes spectrum supply, it will cause more frequent network congestion, reducing service quality, and hindering next generation use cases.

The spectrum shortfall will start to impact consumers as early as 2026, and by 2027 networks will be unable to meet nearly a quarter of traffic demand in high-traffic areas during peak hours[5]. This will worsen to only 27% of peak demand being met by 2035[6]. Without more spectrum, improving capacity will be challenging, as other levers besides spectrum yield significantly diminishing returns.

This strain on networks will harm U.S. businesses. Upstream manufacturers and ecosystem solution providers will lack the incentive and ability to innovate. Downstream enterprise end-users of advanced wireless technologies will then lose access to next-generation technology, limiting their digital transformation and productivity potential. Wireless use cases for smart cities and emergency response management will also degrade.

Consumers will be impacted as well. As networks are unable to keep up with expectations, user experiences with remote videoconferencing and mobile entertainment will worsen. Costs could rise, as cost-effective services like Fixed Wireless Access (FWA) are prevented from scaling and capacity buildouts become more costly for operators[7]. Next generation consumer use cases that have the potential to revolutionize daily life, including mobile AI applications, extended reality (XR) devices, and autonomous vehicles, will not reach the market. Studies show that wireless networks will struggle to meet mobile AI demands, with data traffic from AI-enabled devices outpacing capacity as soon as 2028 and growing to over a third of this AI demand being unmet by 2029[8].

Lastly, in the competitive race for 5G and beyond, the U.S. is in danger of losing its place as a global leader. Without additional licensed spectrum, the country risks losing $1.4T in potential GDP between 2025-2035[9]. Peer countries are also pulling ahead in spectrum availability and 5G innovation, putting U.S. national security at risk.

U.S. policymakers must address and resolve the spectrum crisis. This can be achieved by licensing additional mid-band spectrum for commercial use. This will provide enterprises, consumers and the country with the reliable wireless networks required to maintain the U.S.' global technology leadership in 5G and future wireless generations, and to sustain the productivity engine of the U.S. economy.

Impact on the U.S. Economy

The lost economic opportunity if the U.S. does not license more mid-band spectrum for 5G and beyond will be:

$300B

Annually to U.S. GDP by 2035[10]*

$1.4T

Cumulatively to U.S. GDP by 2035[11]*

Impact on wireless networks

Networks will only be able to meet

27%

Of expected traffic demand at peak hours by 2035[12]*

* See Appendix – Methodology.

Since 2022, the U.S. has not licensed additional mid-band spectrum

Spectrum supply is not keeping up with demand

By 2027, the amount of spectrum required to meet connectivity demand in the U.S. will exceed available spectrum by 401 MHz, assuming no additional new spectrum is licensed[13]. With demand for advanced wireless use-cases continuing to grow, this shortfall could more than triple to 1,423 MHz by 2032, leaving the U.S. in a precarious situation[14].

Global peers are taking the lead in licensed spectrum

As of 2022, the U.S. had 450 MHz of licensed mid-band spectrum available and has not licensed additional spectrum since[15]. By 2027, the U.S. is projected to trail China, Japan, South Korea, Saudi Arabia and the UK by an average of 520 MHz*, which puts U.S. global wireless leadership at risk, and threatens U.S. economic and security interests[16].

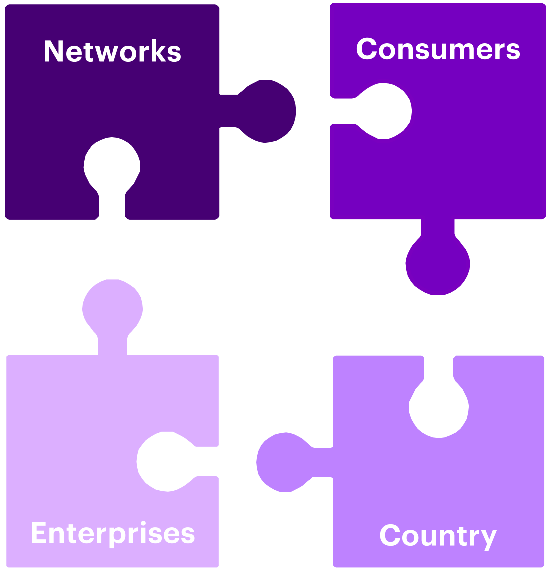
* Based on Analysys Mason's report issued in September 2022. By 2027, several countries with more licensed mid-band spectrum than the U.S. are projected to be China (1660 MHz), Japan (1100 MHz), the UK (790 MHz), South Korea (700 MHz) and Saudi Arabia (600 MHz).

There is an immediate need to act on forward-thinking spectrum policy

Wireless networks, consumers, businesses, and the U.S. economy will all face significant consequences without additional spectrum

Impact on networks

Lacking sufficient spectrum, wireless networks will become congested, affecting network performance and service quality[17]*. Network operators will struggle to add capacity and implement upgrades to address these issues, with few alternative courses of action should additional spectrum not be available**.



Impact on consumers

As network congestion accelerates, consumers will experience degraded wireless performance, impacting their quality of life[19, A]. Next-generation technological advancements will also be at risk, as they require high-bandwidth, low-latency environments that only additional spectrum can enable.

Impact on enterprises

Innovation from enterprises will be diminished, as active spectrum deployment and policy is correlated with increased product development and investment[18]. Enterprise end-users, who adopt and use next-generation wireless technologies, would miss out on the productivity gains these technologies offer.

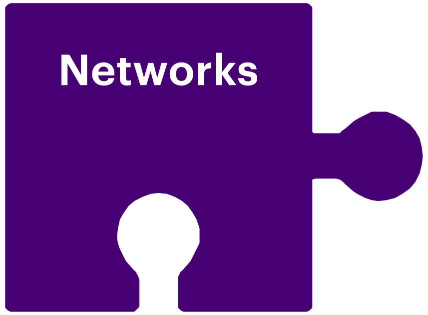
Impact on country

The spectrum shortfall will cause the U.S. to lose $300B of GDP growth annually by 2035[20, B]. The loss of U.S. wireless leadership would also threaten its ability to set global policy standards, potentially putting U.S. supply chains and national security at risk.

* Assuming no unforeseen breakthroughs in spectral efficiency or unforeseen enhancements to densification deployment strategies.
** Under the current scenario where diminishing returns are expected to cell densification and spectral efficiency gains.
A. Assuming that the aggregate consumer demand for connectivity is expected to grow substantially while available spectrum is expected to remain stagnant.
B. See Appendix - Methodology

As network congestion intensifies, operators face increasing challenges in addressing the fallout

If current trends continue, by 2027, networks will be unable to meet nearly a quarter of traffic demand during peak hours



Network performance and capacity upgrades will be significantly impacted

During periods where wireless network demands exceed spectrum supply, network congestion occurs. With network congestion comes higher latency and reduced bandwidth – two performance factors that deteriorate the user experience. If nothing is done to address growing demand, network capacity will only meet 77% of traffic demand during peak hours by 2027[21].* This deficit will worsen significantly by 2035, as networks will meet just 27% of demand at peak[22]. Taking definitive action to approve additional spectrum licenses will help mitigate congestion issues, enabling network operators to plan effectively for short-term needs while awaiting the new spectrum.**

Network congestion reduces network performance

- **Bandwidth per device,** or the amount of data that can be sent and received over the network per device, **will decrease**. This reduction lowers the amount of data transmitted and received for use cases such as video, voice, and text.
- **Latency,** or the time it takes for data to travel between devices and the network, **will increase.** The higher the latency, the longer the delay for data and signals to be transmitted, received, and synchronized between devices in the network.

Spectrum remains the best solution to add capacity

- **Spectrum is the only viable lever, both economically and physically, to add substantial network capacity.** Operators will add new cells but cannot do so fast enough or cost effectively in dense areas without additional spectrum. The other major lever, achieving spectral efficiency gains using existing equipment, has physical limitations as described by the Shannon Limit – making it an unsustainable solution to meeting future demand[23].

* See Appendix – Methodology. Analysis is based on of the relative growth of data demand and network capacity between 2025-2035 assuming the growth rate of peak demand is proportional to the growth rate of aggregate demand, and that prices for connectivity plans will not change between 2025-2035.
** See page 26 for additional analysis on what the implications of a definitive policy on spectrum licensing would have on short-term network congestion.

The wireless ecosystem depends on spectrum

Organizations across the wireless value chain will suffer economically and end-users will have less access to innovative wireless capabilities in the future

Enterprises

Innovation, investment and advanced use cases are at risk

Wireless networks, powered by licensed spectrum, enable organizational digital transformation that unlocks significant operational efficiency, productivity, and safety benefits for public and private enterprises. These efficiencies and benefits collectively serve to strengthen the U.S. economy.

Without spectrum, upstream Original Equipment Manufacturers (OEMs) and ecosystem solution providers will lack the incentive to innovate and build new products and services. In turn, industrial end-users lose access to next-generation wireless technology, reducing their operational efficiency and productivity. Smart city technologies, such as adaptive traffic signals that allow cities to reduce travel times for drivers, as an example, will be prevented from scaling due to network constraints.

Spectrum is critical for businesses across the wireless value chain

Upstream suppliers, such as OEMs, are incentivized to produce advanced chipsets and network equipment when more spectrum is made available, benefitting downstream technology providers[24].

Technology ecosystem providers rely on innovative upstream technologies and enough spectrum to support advanced products such as autonomous vehicle platforms and XR devices.

Enterprise end-users leverage advanced wireless products to increase efficiency and productivity, relying on adequate spectrum for these use cases to function.

Example: Utilities use 5G drones to monitor wildfire risks, saving at least 10% on operating costs. HD video feeds require high bandwidth, and piloting drones requires ultra-low latency to avoid collisions with trees and buildings[25].

Network congestion diminishes the consumers' quality of life

Consumers might soon face the risk of their mobile devices not functioning optimally in congested areas

Poor network performance has outsized effects on consumers' lives

Without additional spectrum, consumers will face the effects of network congestion. Network congestion leads to degraded service quality through lower bandwidth and higher latency, which ultimately leads to diminished quality of life for consumers. Additionally, U.S. consumers will have limited access to next-generation technologies, such as mobile AI applications, XR devices, and autonomous vehicles, compared to consumers in countries with greater spectrum availability.

~3X

Increase in **fair, poor, or bad** network experiences during peak hours by 2035*[26].

Consumers

Consumer quality of life will be affected in the following ways:

Lower bandwidth and higher latency lead to **lost productivity** at work, as users deal with lag and delay with virtual collaboration tools.

Long load times and buffering lead to **poor entertainment experiences** for users, as a lack of bandwidth contributes to slower and degraded services.

Critical services requiring low latency connectivity, such as remote healthcare or emergency response, will not be able to scale and reach their potential.

* See Appendix – The methodology assumes current quality levels using the Ericsson Mobility Report 2023. A proportional decrease ,based on the demand-supply gap, was applied to forecast how many more users will have the lowest level of network experience.

The U.S. will lose its position as a global technology and economic leader

$1.4T in cumulative economic opportunity is at risk over the next 10 years, in addition to U.S. technology leadership and national security

Economic Leadership

Advanced wireless networks are projected to provide a significant economic uplift in the U.S. over the next 10 years*. But a spectrum shortfall will constrain these benefits.

▼ **$300B**

Annual lost U.S. GDP opportunity by 2035[27]*

▼ **$1.4T**

Cumulative lost U.S. GDP opportunity by 2035[28]*

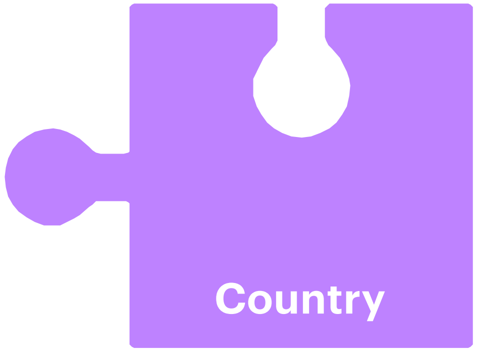
Technology Leadership

Peer countries will grow their influence in setting international standards.

Next-generation connectivity platforms and marketplaces will emerge abroad.

National Security

As international peers begin to lead in setting standards, manufacturing equipment, and developing next-generation products and software; U.S. consumers and enterprises will become more vulnerable to potential foreign threat actors.

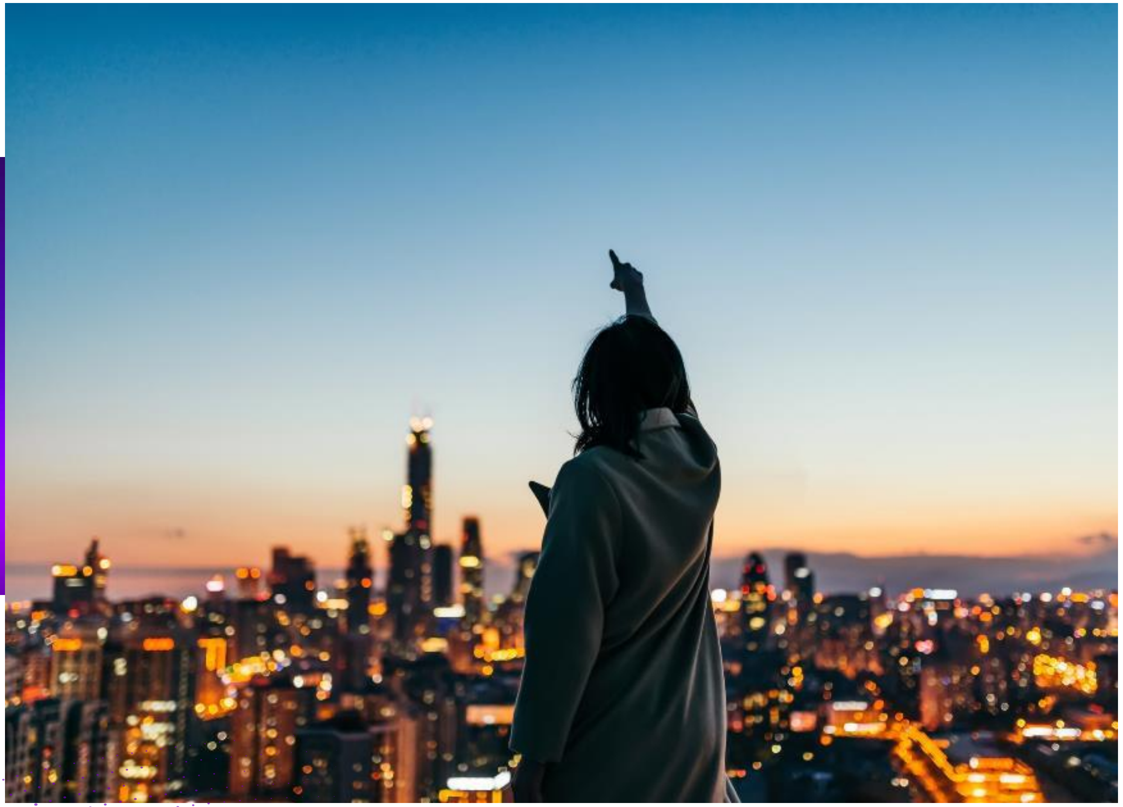


* See Appendix – Methodology. A baseline expected GDP benefit from advanced wireless networks had been identified using a range of previously published figures on 5G GDP benefits. Key drivers of economic uplift from advanced wireless networks include greater enterprise productivity, capital investment, job creation, and tax revenue for governments.

Call to action: The time to act is now

Policymakers must urgently license additional commercial mid-band spectrum to address the U.S.'s looming spectrum deficit

The U.S. faces an imminent spectrum shortfall. To avoid downstream impacts, policymakers must license more full-powered commercial mid-band spectrum. Without spectrum, the quality and reliability of wireless networks will fail to meet consumer and enterprise expectations, the U.S. will miss out on economic growth potential, and national security interests will be threatened. Of greatest utility would be globally harmonized spectrum in the 3.3-8.5 GHz range, which will set the U.S. back on track to unlock $300 billion in annual economic opportunity, address the urgent wireless needs of the U.S. public and commercial sectors, and strengthen the U.S.'s strategic interests.



1 Introduction

Spectrum overview

What is Radio Spectrum?

Radio spectrum - or spectrum - is the invisible raw natural resource that facilitates wireless data transmission. Without spectrum, mobile internet, phone calls, emails, and satellite communications would not be possible[29].

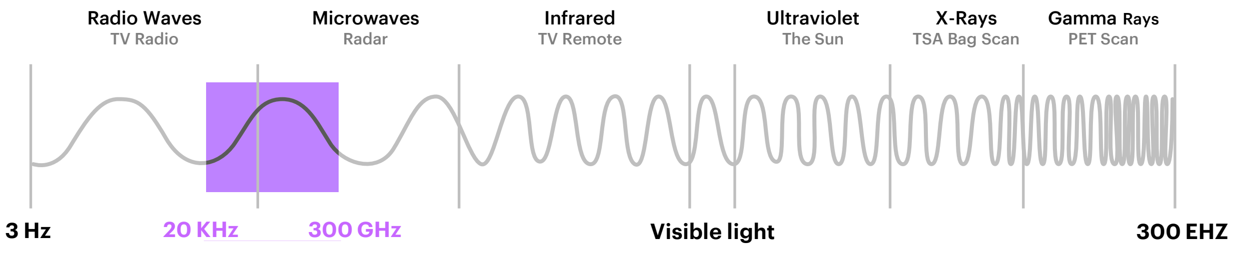
The electromagnetic spectrum encompasses the radio spectrum, which consists of various frequencies (refer to Electromagnetic Spectrum and Radio Spectrum, right[30]). These frequencies are segmented into numerous bands, each with a unique technical application based on its coverage and capacity characteristics.

This paper focuses on parts of the lower mid-band, characterized as the range of spectrum between 3GHz and 8.5GHz. These bands are currently being used by most 5G networks and are being made available for future 6G networks as well[31].

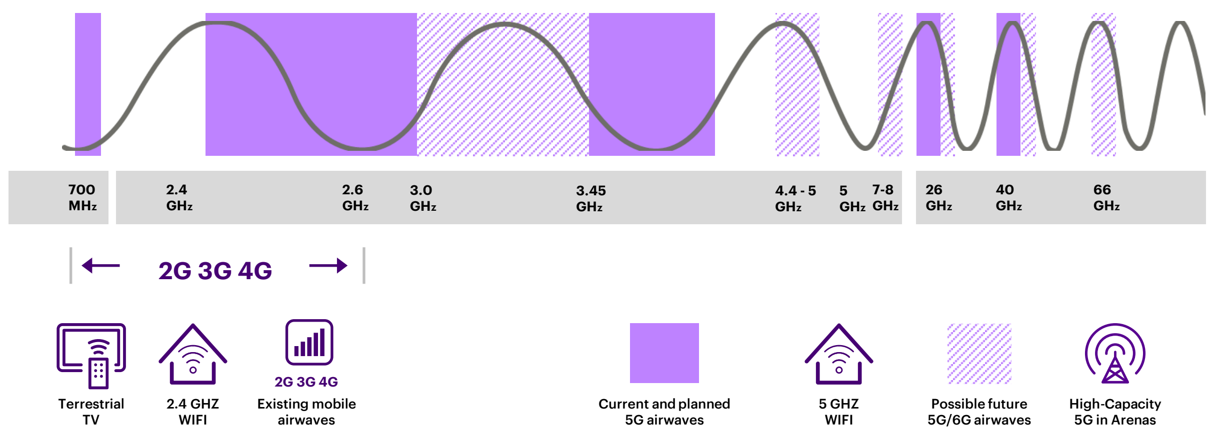
How is Spectrum Regulated?

To prevent interference between users, government agencies oversee the regulation of spectrum usage in their respective countries. In the U.S., the Federal Communications Commission (FCC) issues commercial usage licenses for specific bands. The National Telecommunications and Information Administration (NTIA) manages federal spectrum assignments.

Electromagnetic Spectrum[32]



Radio Spectrum



Spectrum underpins cellular network performance

Illustration: Low-, Mid- and High-Band Spectrum[33]

Low-Band 0.3-3 GHz	Mid-Band 3-24 GHz		High-Band 24-50 GHz
	Lower Mid-Band 3-8.5 GHz	Upper Mid-Band 8.5-24 GHz	
Required for its range and ability to propagate through obstacles, low-band is critical for ensuring that the benefits of 5G/6G are accessible to all. Low-band helps maximize network coverage.	Lower mid-band balances coverage and capacity. It is the band of choice globally for most 5G applications and emerging 6G standards[34].	Upper mid-band spectrum will be critical to meeting the network challenges associated with rapidly growing data traffic. It has higher capacity which can enable data-intense use cases and can help realize unfulfilled enterprise 5G/6G applications.	Spectrum in the mmWave range (e.g., 26, 28, or 40 GHz) supports high-capacity throughput in crowded environments, delivering the low latencies and high reliability required by many future enterprise use cases. Propagation of high-band spectrum remains limited at scale.

More Coverage ←→ **Higher Capacity**

***Note**: While there is no set rule for differentiating between low-,mid-, and high-band spectrum we have chosen to do so based on recent assignment decisions made by policymakers in relation to 5G service deployments.*

U.S. networks need more spectrum to unlock 5G and future wireless generations

Mobile Generation	2G	3G	4G	5G and beyond...
Capabilities[35]	*Voice, Basic data services*	*Internet Higher data rates*	*Mobile apps, Video HD streaming*	*Autonomous vehicles, XR, industrial Internet of Things (IoT)*
Bands[36]	900 MHz 1900 MHz	800 MHz 1700 MHz 1900 MHz 2100 MHz	700 MHz 800 MHz 1700 MHz 1900 MHz 2100/2300/2500 MHz	Previous Bands (700 – 2500 MHz) 3000 MHz 4000 MHz 7000 MHz Higher Bands > 24 GHz
Bandwidth[37]	64 kbps	2 Mbps	200 Mbps	> 1 Gbps

The U.S. has failed to license more spectrum for networks

The previous whitepaper, ‘Spectrum Allocation in the United States’, examined how additional licensed spectrum in the U.S. would enable wireless providers to continue expanding 5G connectivity and unlock 5G-enabled innovation[38]. We identified three bands that offer the greatest potential for meeting the needs of additional 5G deployments by wireless operators: the lower 3 GHz, mid 4 GHz, and 7 to 8.4 GHz bands.

We then published ‘The Case for Global Spectrum Harmonization’, where we explored how those core bands are either already globally harmonized or are on their way towards harmonization, and the opportunity for the U.S. to play a more active leadership role[39].

But since 2022, the U.S. has failed to license any additional spectrum[40]. In this paper, we will explore how this hold-up in spectrum licensing will become a serious problem for wireless networks in the U.S. as demand for connectivity continues to grow.

!

The U.S. has not licensed additional mid-band spectrum for commercial use since 2022

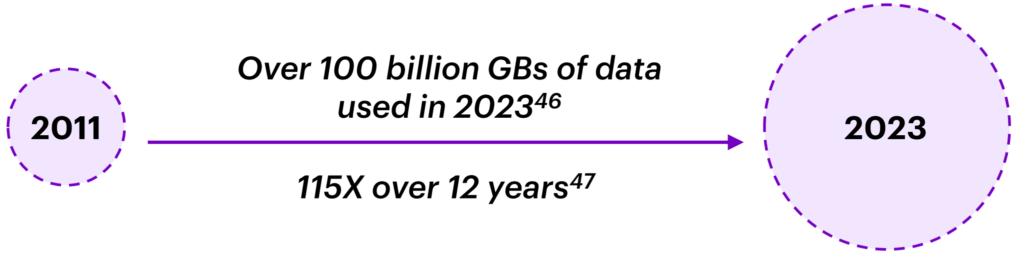
Consumers rely on wireless connectivity now more than ever

U.S. data consumption is growing at an increasing rate as networks become more capable

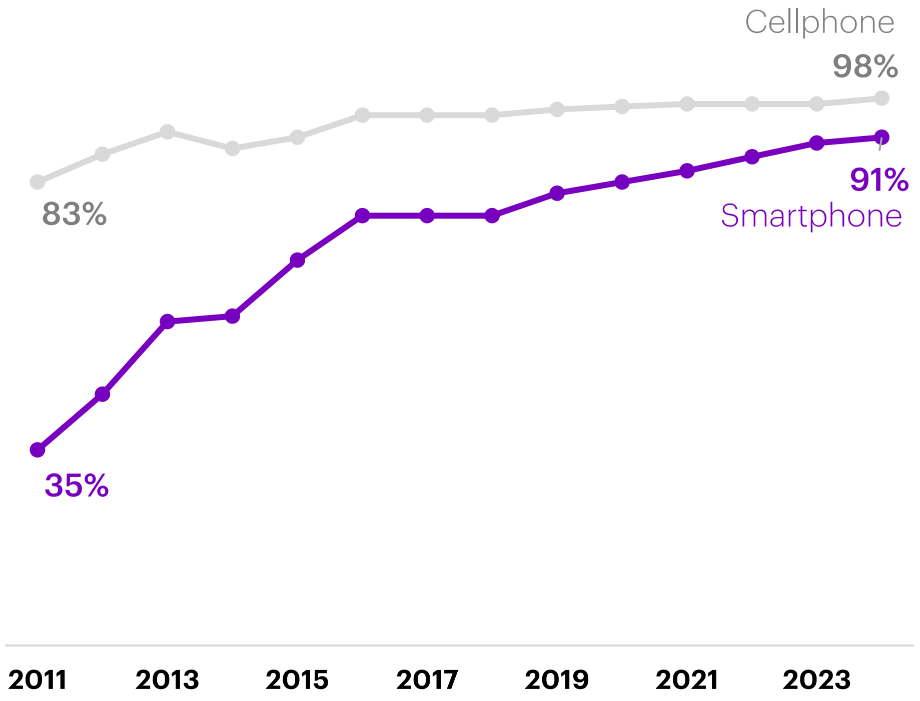
U.S. consumers depend on mobile connectivity for critical aspects of everyday life, using more data than ever before. In 2023, U.S. consumers used more than 100 billion GBs of mobile wireless data, nearly double the amount used only two years prior[41]. Over 91% of U.S. adults own a smartphone[42]. This includes 15% of adults who are "smartphone-only" internet users, meaning they own a smartphone, but do not subscribe to fixed broadband[43]. Whether consumers have fixed broadband at home or not, they rely solely on mobile networks when out-of-home. 67% of U.S. adult smartphone owners, including 80% of those aged 18-29, use their phone for navigation and transit[44]. Consumers have an insatiable demand for mobile connectivity, with growth that will soon begin to outstrip supply of network resources and capacity.

Today, consumers are only just beginning to benefit from new 5G-enabled products that did not previously exist during the 4G/LTE era. AI applications, XR technologies, and autonomous vehicle networks are beginning to emerge, thanks to the progression of 5G network technical capabilities, but have not yet reached their scaled potential[45].

Historical increase in wireless data consumption



Percentage of U.S. adults who say they own the following[47]:



U.S. spectrum allocations are behind both in terms of meeting domestic demand, as well as in keeping up with global peers

1 Spectrum shortage

U.S. connectivity demand will exceed spectrum supply

401 MHz
By 2027

1423 MHz
By 2032

Projected spectrum deficit in the U.S. based on aggregate connectivity demand and available spectrum supply[48]

Impacts

- Network congestion and degraded user experience
- Limited network capacity expansion
- Mobile applications and use cases not functioning
- Reduced wireless innovation

2 Competitive lag

U.S. will lag behind global peers in terms of licensed spectrum availability

520 MHz
By 2027

Average amount by which the U.S. will trail select global peers in licensed spectrum availability[49]*

Impacts

- Loss of U.S. global wireless leadership
- National security risks

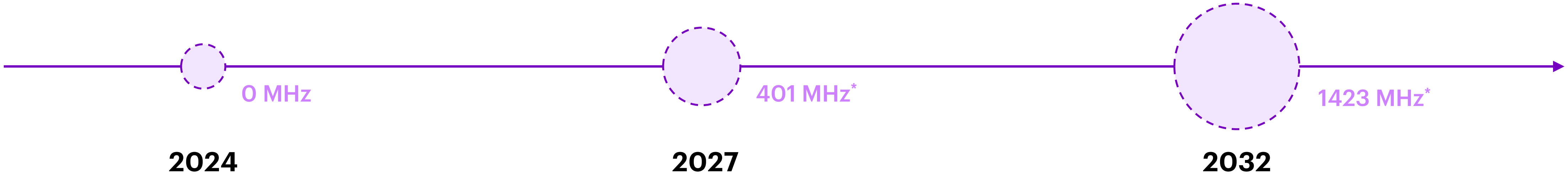
Both sets of impacts will be explored throughout this paper

* Based on Analysys Mason's report issued in September 2022, by 2027 several countries with more licensed mid-band spectrum than the U.S. are projected to be China (1660 MHz), Japan (1100 MHz), the UK (790 MHz), South Korea (700 MHz) and Saudi Arabia (600 MHz),

1 **Spectrum shortage**

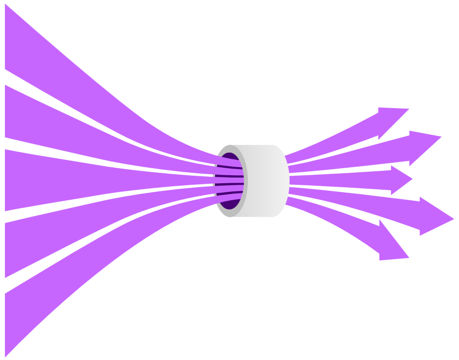
U.S. connectivity demand will exceed the supply of available spectrum

The U.S. will reach an available spectrum deficit of 401 MHz by 2027 and 1423 MHz by 2032[50].



Demand continues to grow

- In 2023, Americans used more than 100 billion gigabytes of mobile data, nearly double the amount used in 2021[51]
- Data traffic per smartphone is expected to increase over 2.5X by 2029[52]
- New wireless services such as Fixed Wireless Access (FWA) and emerging use cases like AI applications, XR devices, and autonomous vehicles will be key drivers of this growth



Available spectrum remains stagnant

- The FCC has not auctioned new commercial spectrum licenses since 2022[53]
- The FCC authority to hold and conduct spectrum auctions expired in March 2023, and has since not been renewed by congress[54]
- Congress has been unable to come to an agreement on re-authorizing FCC spectrum auctions[55]

* Forecasted spectrum deficit is normalized to a lower mid-band equivalent (exclusive use, with undue power restrictions)

2 **Competitive lag**

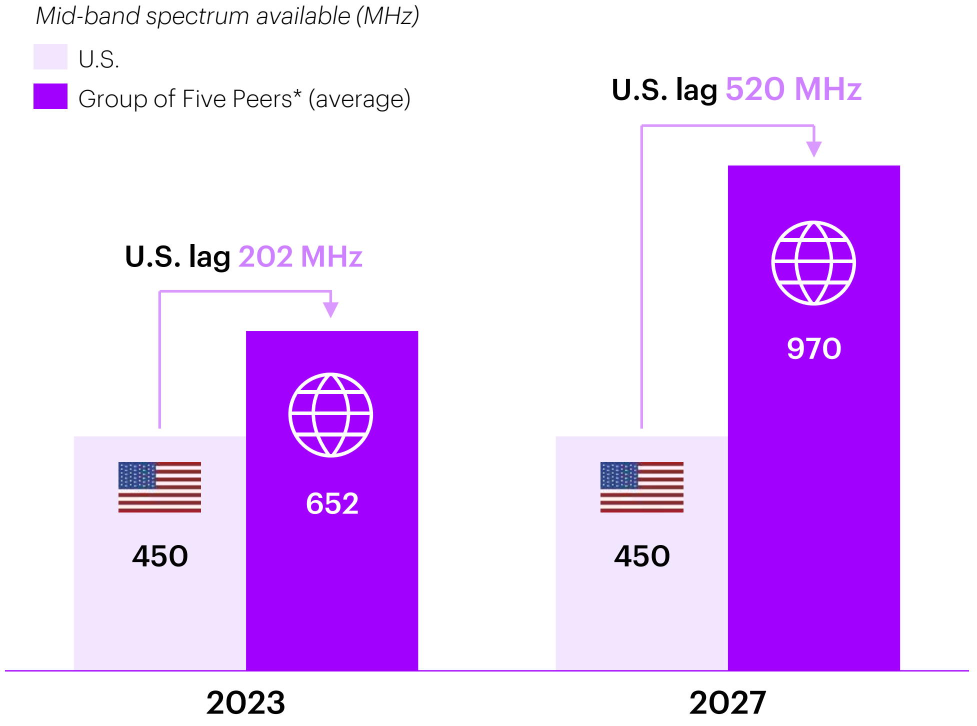
Meanwhile, peer countries are leaping ahead in terms of spectrum availability

While the U.S. has stopped licensing additional spectrum, peer countries are pushing ahead. **If this trend continues, the U.S. will lag significantly behind leading nations, in terms of licensed spectrum availability, by 2027.**

In 2023, the U.S. trailed five leading nations – Japan, UK, France, China, and Saudi Arabia* – by an average[56] of 202 MHz in available spectrum. This deficit is expected to more than double by 2027, with the U.S. expected to trail five projected leading nations – China, Japan, UK, South Korea and Saudi Arabia** – by an average of 520 MHz of available spectrum.

The threats to U.S. productivity, global technology leadership, and national security will be explored in the subsequent sections of this paper.

Leading countries will significantly outpace the U.S. in mid-band spectrum availability if U.S. spectrum policy remains as it is today[57]



* Based on Analysys Mason's report issued in September 2022, several countries (listed in current order of spectrum advantage) with more licensed mid-band spectrum than the U.S. included Japan (1100 MHz), the UK (790 MHz), France (510 MHz), China (460 MHz), and Saudi Arabia (400 MHz)

** By 2027, several countries (listed in order of projected spectrum advantage) with more licensed mid-band spectrum than the U.S. are projected to be China (1660 MHz), Japan (1100 MHz), the UK (790 MHz), South Korea (700 MHz) and Saudi Arabia (600 MHz).

The looming crisis: The U.S. cannot afford to delay further spectrum allocation

As U.S. spectrum demand outpaces supply and global peers pull ahead in terms of licensed spectrum, the effects on the U.S. will be significant

This paper explores the impact of the impending U.S. spectrum shortage on wireless networks and key stakeholders:

Section 2

Impact on Networks

- Limited bandwidth per device and high latency
- Inability of networks to meet future demand
- Constrained capacity upgrades

Section 3

Impact on Enterprises

- Reduced incentives for upstream OEMs and ecosystem providers to innovate
- Hindered productivity due to lack of access to industrial wireless use cases

Section 4

Impact on Consumers

- Reduced quality of life
- Lack of access to next-generation consumer technology

Section 5

Impact on Country

- Constrained GDP growth
- Loss of global technology leadership
- National security risks

2 Spectrum Shortfall Impacts on Wireless Networks

A lack of spectrum will constrain network performance and limit capacity upgrades in the U.S.

When connectivity demand exceeds spectrum supply, it will cause more frequent network congestion that reduces service quality for users and hinders next generation use cases. Additionally, network operators will be faced with limited options to improve capacity, as other levers besides spectrum yield significantly diminishing returns.

1 **Impact on Network Performance**

A spectrum shortage will lead to more frequent network congestion

Relationship between lack of spectrum and congestion

Wireless data is encoded and transported through radio waves, and the quantity that a network can modulate each second is known as bandwidth[58]. The more spectrum a network can use, the greater the network's bandwidth can be[59]. When networks have less spectrum available, less bandwidth can be allocated to each cell site.

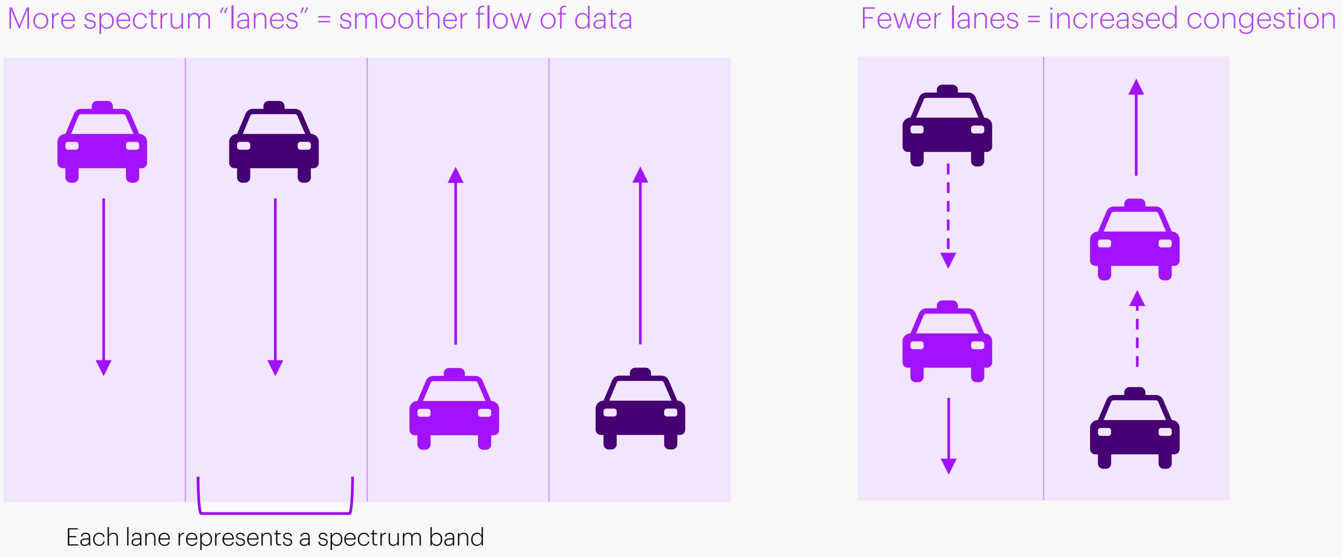
Network congestion describes when the amount of data packets demanded exceeds the amount of bandwidth available[60]. When networks have limited amounts of bandwidth available at a given cell site, congestion is inherently more likely.

During times of network congestion, network operators must ration data packets served between users over the network[61]. This will reduce bandwidth allocated per user. It will also impact latency - the time it takes for data to travel from its source to its destination – as data packets must wait in queues before the network can transmit them[62]. This will degrade the experience of all network users with slower download speeds, video stream buffering, and other performance degradation effects.

Illustrative Example: Spectrum as "Highway Lanes"

Imagine a highway with multiple lanes, with each lane representing a frequency channel within a spectrum band. More lanes (spectrum) mean more cars (data) can travel at the same time, just like higher bandwidth allows more data to be transmitted simultaneously. Additionally, with free flow of traffic, cars (data) can travel quickly to their destinations without backing up (low latency).

Now, consider the same highway, but with fewer lanes. This is what a limited spectrum scenario looks like. As more cars (data) try to pass through, congestion builds. Cars must wait longer to move forward (higher latency). Fewer cars can pass through at any given time, effectively reducing the number of cars that can travel per unit of time (reduced bandwidth).



1 **Impact on Network Performance**

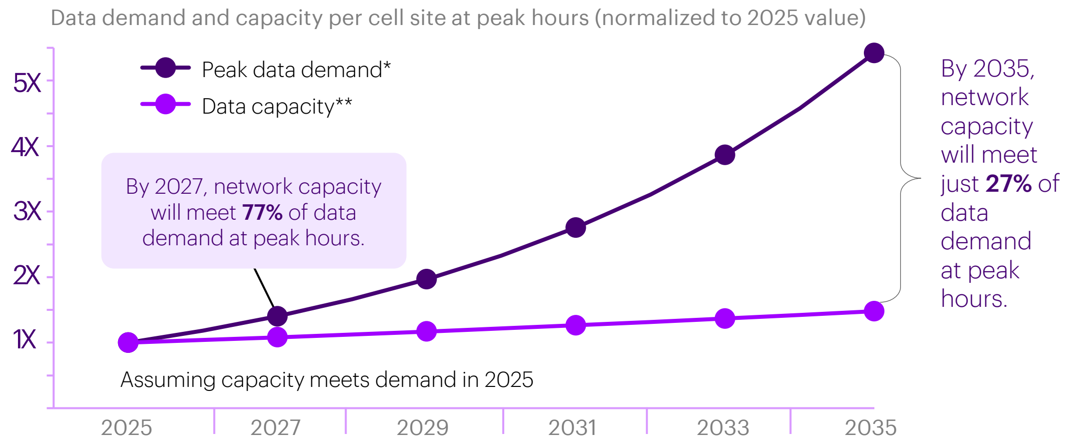
Networks will significantly underperform expectations during peak hours

Spectrum shortage will lead to significant congestion as demand continues to grow

Aggregate consumer demand for connectivity is expected to grow substantially over the next ten years[63], while available spectrum is expected to remain stagnant. We forecast that network capacity will meet only 77% of data demand during peak hours by 2027, and this will worsen to networks meeting only 27% of peak demand by 2035. When data demand exceeds supply to this level, the network suffers significantly, as operators must reduce bandwidth per device to prevent connection failures entirely.

While operators are dedicated to providing the best service at low cost, this supply-demand deficit will make them unable to deliver on this promise, resulting in either raised prices or performance degradation over time. In subsequent analysis throughout this paper, we assume that prices are held constant and illustrate how user experience specifically will suffer.

Traffic demand is projected to significantly outpace capacity at peak hours



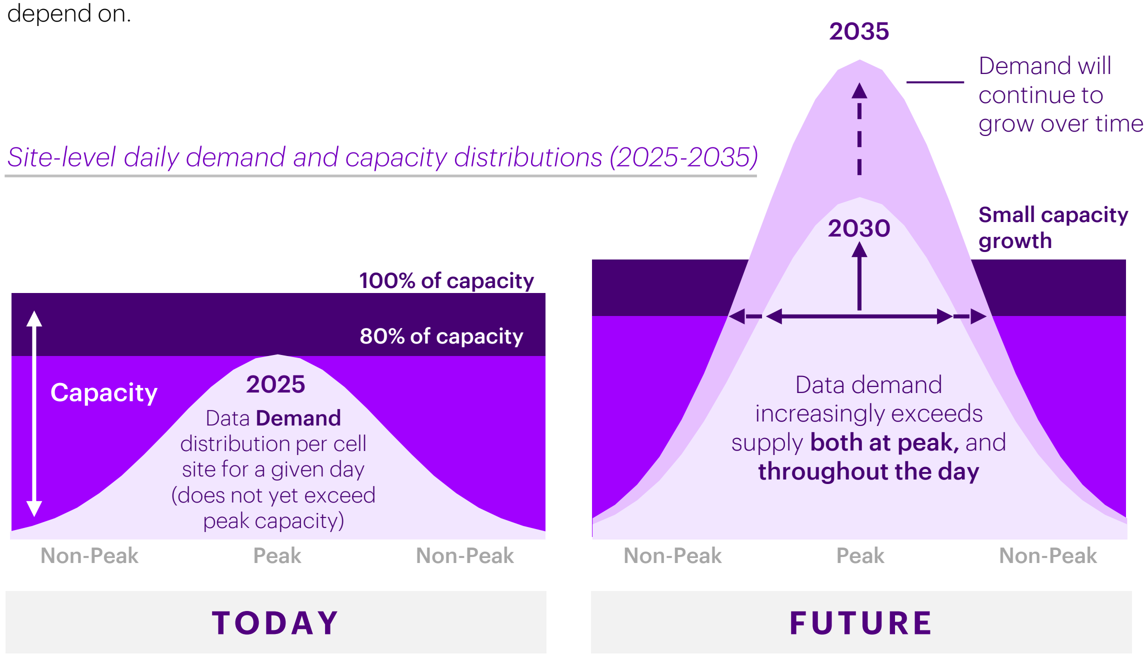
* Assuming that the growth rate of peak demand is proportional to the growth rate of aggregate demand
** Relative to data demand. Assuming that in 2025 data demand is equal to network capacity, and data capacity grows according to spectral efficiency estimates in the CTIA-Brattle 2023 report.

This will cause the greatest issues at peak hours, though as demand rises, more parts of the day will be increasingly congested

At first, this overutilization and performance degradation will be most prominent at peak hours, which can vary based on location. For example, a cell site in an urban center will typically have peak utilization at 1pm[64]. If future traffic rises proportional to this same pattern, the highest amount of congestion and quality issues will occur during these hours.

Over time, however, this will affect a wider part of the day, even during non-peak hours. Users will feel the impacts of congestion throughout daily life, severely limiting the applications that they depend on.

Site-level daily demand and capacity distributions (2025-2035)



Data Demand & Capacity Patterns for a particular time period in the day (illustrative)

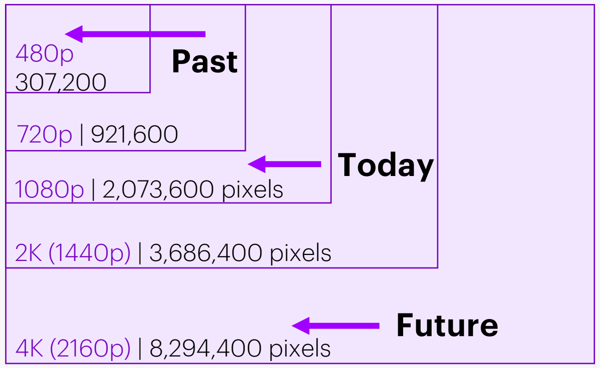
1 **Impact on Network Performance**

Congestion at peak hours will significantly impact user experiences

Video streaming is a key benchmark for network quality, driving rapid growth in bandwidth expectations

There are many use cases that account for demand growth, but one of the most significant is video streaming, which accounts for three quarters of mobile traffic today[65]. Each generation of mobile networks has brought us closer to the full HD streaming experience consumers currently expect. In the future, consumers will demand networks to deliver even higher video quality.

Each evolution of mobile streaming has required significantly more throughput



In the early 2010s, 480p was the peak resolution for mobile video streaming.

Today, consumers expect at least 1080p quality which requires nearly 7X more data throughput.

Soon, 2K-4K will become the quality consumers expect.

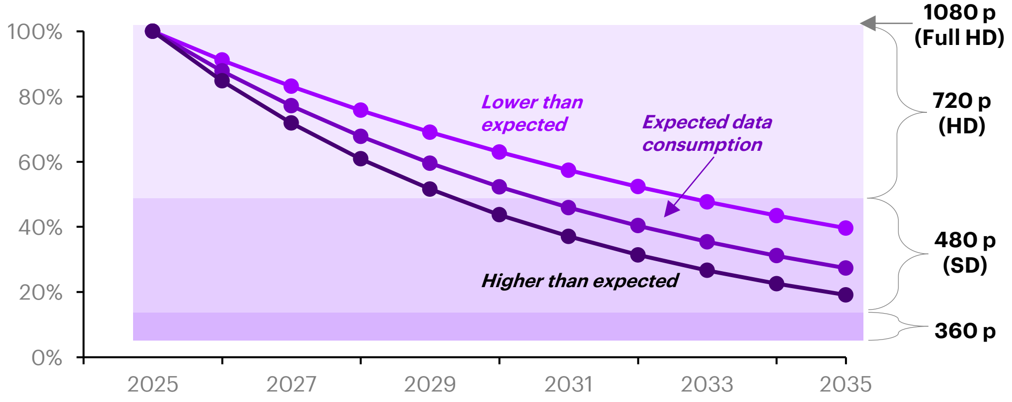
As mobile networks evolve, one trend remains: **Mobile streaming resolution that was considered exceptional a decade ago is no longer regarded as high-quality.**

Networks will soon fail to meet user expectations due to the supply-demand gap

As consumer demand for high-quality video outstrips the ability of networks to deliver, consumers will be stuck in the past - the equivalent of only being able to watch videos in SD, rather than HD today.

Perceived quality* levels in 2035 will be like streaming in 480p today instead of 1080p

Achievable level of video quality during peak hours** (in terms of 2025 expectations) under different scenarios



Note: While data demand growth rate is expected to be 23.5%, we have considered higher & lower possibilities as well

~3X

Increase in **fair, poor, or bad** network experiences during peak hours by 2035[A]

The proportion of consumers with fair, poor, or bad experience will also triple, due to inability to meet rising demand. What is currently considered exceptional quality will not meet expectations in 2035, and U.S. consumers will be left behind compared to those in other countries.

* Perceived quality is determined on a relative basis compared to growing consumer expectations; absolute streaming resolution may not decrease significantly (depending on portion of demand growth is coming from additional devices), but users would perceive the quality similar to how 480p is viewed today.
** Assumes that prices do not increase to dampen demand and rise in demand is distributed across users.
A. Assumes current quality levels using the Ericsson Mobility Report 2023, with a proportional decrease based on the demand-supply gap to forecast how many more users will have the lowest level of network experience.

1 **Impact on Network Performance**

Network congestion will limit future wireless technologies even more significantly

Advanced use cases have significantly higher bandwidth and latency requirements than 4K video streaming, meaning that without more spectrum, their experience will be even more restricted

Networks will struggle to support the following complex use cases due to their connectivity requirements:

Remote Robotics

Remote robotics necessitates ultra-low latency and high-bandwidth to ensure real-time, precise control and seamless data transmission[66]. For example, remote surgery leverages these capabilities to allow surgeons to perform emergency procedures from afar, providing high-quality, urgent care to patients regardless of their location.

Connectivity requirements

~6X	**More bandwidth** required than 4K streaming*[67]
<50ms	**Latency** required[68]

XR Devices

Extended Reality (XR) devices require low latency to quickly process video feeds and sensor data, and enough bandwidth to generate visual content at high frame rates to ensure a seamless user experience[69].

Connectivity requirements

~16X	**More bandwidth** required than 4K streaming*[70]
<20ms	**Latency** required[71]

Autonomous Vehicles

Autonomous Vehicles require high bandwidth and low latency wireless connections to rapidly process data from sensors, high resolution cameras, and human interfaces to navigate traffic and obstacles[72].

Connectivity requirements

<30ms	**Latency** required[73]

* Using the benchmark that ~25 Mbps is required to stream a 4K video74

Lack of spectrum will also significantly hinder network capacity upgrades

In addition to impacting current network performance, a lack of additional licensed spectrum will reduce network operators' ability to expand and upgrade the network in the future. In the current state of network rollout, additional spectrum is the most effective lever to improve network capacity. Approving additional spectrum licenses is not only the most efficient option but also provides network operators with the confidence that short-term mitigation efforts will be supported by a long-term solution. Knowing that new spectrum will become available allows operators to manage current resources more effectively, reducing the impact of spectrum shortages and ensuring a smoother transition with minimal disruption.

At the beginning of U.S. 5G buildouts, network operators utilized three tools to add network capacity: densifying the Radio Access Network (RAN) with cellular infrastructure, improving spectral efficiency, or utilizing additional spectrum[75].

Spectrum Utilization

Utilizing additional spectrum allows carriers to increase the capacity of RAN clusters without needing to densify cellular infrastructure or invest in spectral efficiency solutions[76]. Bandwidth, coverage, and latency can be maximized through the optimal use of spectrum and cellular infrastructure[77].

RAN Densification

Densification is the process of increasing the concentration of cells that constitute a Radio Access Network (RAN) within a designated area. These RAN clusters, together, provide continuous and reliable network coverage to the area in which they're deployed[78].

Spectral Efficiency

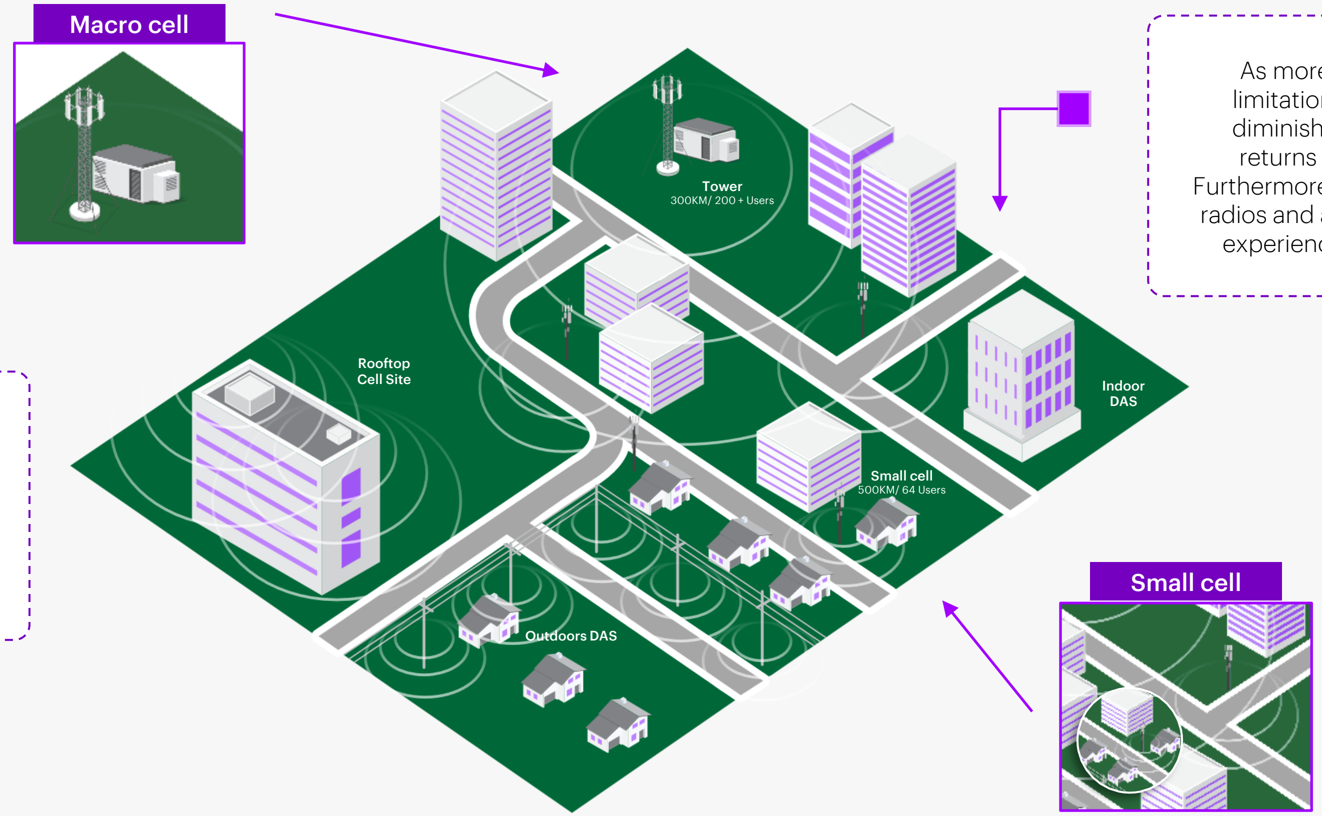
In collaboration with RAN equipment providers, network operators can develop ways to transit and receive data more efficiently into existing network channels[79]. A key example in the 5G era are MIMO antennae (multiple-input, multiple-output), which utilize multiple antennae at both the transmitter and receiver ends to maximize data throughput[80].

2 Impact on Network Capacity

RAN densification yields diminishing marginal returns

While Radio Access Networks (RANs) are a vital lever for increasing network capacity, further densification presents diminishing returns to coverage, bandwidth, and latency. Operators will continue to densify, but it is not sufficient to keep up with rapid growth

Macro cells, which are larger and used in conjunction with small cell sites, provide broad, spectral coverage over a wider area than small cells.



As more cell sites are built, there are physical limitations – in the form of limited space – that diminish the coverage, bandwidth and latency returns as each radio is deployed to the RAN. Furthermore, as the proximity between high powered radios and antennae starts to reduce, RANs begin to experience electromagnetic interference (EMI)*.

Small cells, which are smaller than macro sites, are utilized by network operators to provide coverage in dense urban areas and help add capacity in more targeted ways than macro sites.

*Electromagnetic Interference (EMI) is like unwanted noise that disrupts wireless signals, causing issues like dropped calls and slow connections. In this context, this occurs when high powered radio equipment, placed close together, interfere with each other's signals

2 Impact on Network Capacity

Radio equipment is reaching physical peak performance; spectrum is the only answer

There are logistical, physical, and cost limitations to densification and spectral efficiency

Until now, network operators have successfully utilized a combination of RAN optimization tools to cover the U.S. with 5G service[81]. However, these tools have hard physical and economic limits, making reliance on RAN densification and spectral efficiency improvements unreliable approaches to expanding network capacity.

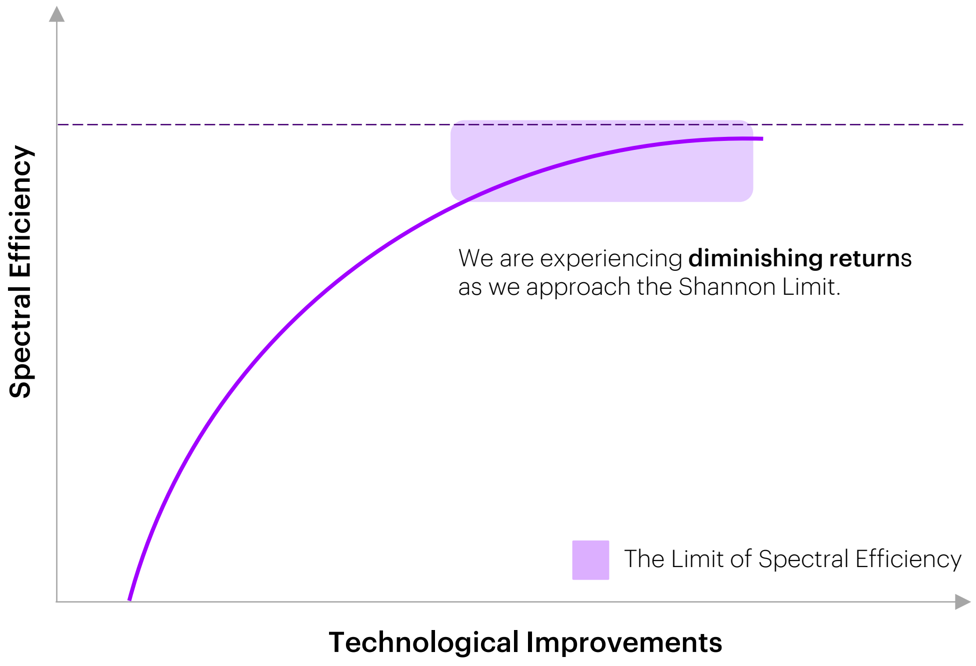
Network operators have already exhausted the feasibility of RAN densification in many areas. In urban areas, constituting over 80% of the population, operators must deploy small cells[82], which GSMA forecasts to carry a 3-5x increase in total network costs due to equipment and regulatory expenses[83]. In addition, cities have strict regulations regarding power density and emissions from communications equipment, which can further limit the ability to deploy new equipment[84].

Spectral efficiency improvements will also become more difficult to reach. Recently, 5G equipment innovations have delivered unprecedented levels of spectral efficiency that has allowed carriers to economically build 5G networks that provided wide coverage, higher bandwidth, and lower latency[85]. But at a physical level, spectral efficiency has a natural limit. Technology providers will eventually approach the Shannon limit – a fundamental theorem that defines the maximum data transmission rate possible within a spectrum channel, considering its bandwidth and noise characteristics (see visual on the right)[86].

Overall, network operators have exhausted network densification and spectral efficiency for their buildouts. If the U.S. is to reverse the imminent threat of network demand exceeding capacity by 2027, spectrum allocation is the only remaining answer[87]. In the meantime, spectrum constraints will severely limit the ability of network operators to upgrade their networks, posing a grave threat to enterprises, consumers, and the nation. This paper will explore the threats to each stakeholder in detail in the subsequent sections.

The marginal benefit of improving technology to increase spectral efficiency will eventually reach an asymptote threshold.

Technological Improvements vs Spectral Efficiency Growth



3

The Risk to Enterprises Without More Spectrum

The impending spectrum shortage will have a cascading effect throughout the wireless enterprise value chain

Without spectrum, the wireless enterprise value chain, defined as **upstream original equipment manufacturers** (OEMs, e.g. chipset, device, and network equipment manufacturers), **ecosystem solution providers** (e.g. cloud/edge providers), **and enterprise end-users** (e.g. manufacturing, utilities, and healthcare services), will all be adversely affected.

Upstream manufacturers and ecosystem solution providers will lack the incentive and ability to innovate. Downstream enterprise end-users of advanced wireless technologies will then lose access to next-generation technology, affecting their overall productivity potential.

Enterprises, across the wireless connectivity value chain, depend on spectrum

A lack of available spectrum will affect organizations across the wireless technology value chain. Chipsets, device, and network equipment OEMs will face subdued market demand, giving them limited incentive to innovate for the U.S. market. Ecosystem solution providers will also have reduced innovation capabilities and incentives to participate. In turn, U.S. end-users of advanced wireless technologies will not have access to the world's most advanced products, such as IoT connected devices, AI, and smart grids. Collectively, a lack of access to technology and spectrum will impact the productivity and market development opportunities for all U.S. businesses across the connectivity value chain.

Upstream OEMs

Upstream OEMs - such as chipset, device, and network equipment manufacturers, produce the components, materials, and devices that enable wireless connectivity. Companies such as Ericsson, Nokia, Qualcomm, and Broadcom supply the processors, modems, routers, and switches that power our connected world.

Technology Ecosystem Providers

Ecosystem providers, like cloud platforms, extended reality developers, and autonomous vehicle platforms, amplify the wireless technology value chain by deploying innovative products and services within the connectivity ecosystem. Companies such as Amazon, Microsoft, and Google deliver computing efficiencies through cloud solutions that power the digital economy, while organizations like Meta, Apple, and Snap Inc. are pioneering advanced XR hardware, shaping the future of productivity and entertainment.

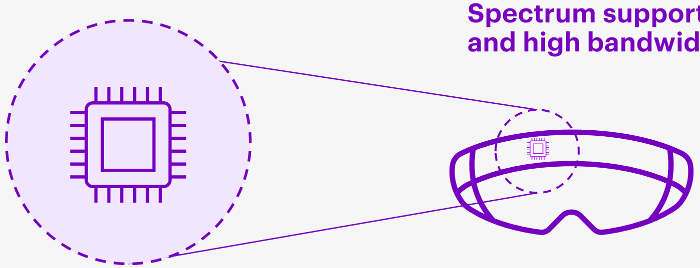
Enterprise End Users

Industries including (but not limited to) utilities, manufacturing, and public services provide essential services and products for the U.S. consumer and economy. These services enable daily life to function smoothly and ensure the seamless operation of critical systems. These sectors stand to unlock significant operational efficiencies and productivity and safety benefits through digital transformation that are only possible when there is sufficient spectrum to support an application ecosystem.

Illustrative example of enterprise participants in the connectivity value chain contributing to a spectrum-enabled industry use

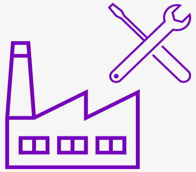
Spectrum incentivizes R&D for technology inputs

New spectrum bands enable new wireless use cases, and OEMs will be incentivized to produce the inputs.



Spectrum supports low latency and high bandwidth use cases

Use cases help optimize operational efficiency



Smart factories implement use cases like augmented-reality (AR) to support maintenance and reduce error rates.

1 **Upstream OEMs**

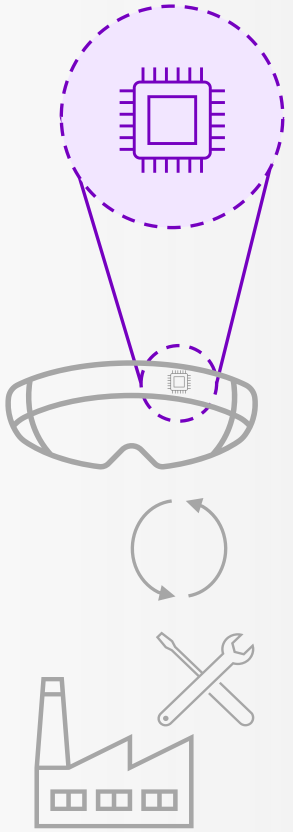
Lack of spectrum will reduce incentives for upstream OEMs to develop new products

Forward-looking and decisive spectrum policy creates markets for upstream OEMs to enter

A lack of spectrum will impact chipset and network equipment OEMs, including Ericsson, Nokia, Qualcomm, and Broadcom, by dampening market demand for technology inputs. This reduction in demand will, in turn, decrease their product investments and constrain their development efforts.

Historically, spectrum licensing has been closely linked to R&D investment, product development, and patent registration by OEMs[88, 89]. For instance, Nokia's announcement of its C-Band compatible products (including radios, antennae, and small cell solutions) followed the allocation of new spectrum in the US. Similarly, in Japan, Qualcomm introduced new chipsets tailored to the newly licensed mid-band and mmWave 5G spectrum bands[90]. Investments in R&D and future products from enterprises have helped form the basis of major technological advances in the past, which have benefited both enterprises across the connectivity value chain and consumers alike[91].

While there has been some investment from upstream OEMs in the U.S. market for 5G advanced wireless use cases, this is now being threatened by a lack of additional licensed spectrum[92]. OEMs will no longer have an incentive to create new technology inputs, and this will diminish their market potential, potentially pushing them to focus on non-U.S. markets. But while this clearly effects the OEMs and their employees, the downstream effects will be significantly farther reaching. Next, we will explore how US technology ecosystem providers will suffer without access to advanced inputs, in addition to the inability of the network itself to support advanced wireless use cases without more spectrum.



Spectrum incentivizes R&D for technology inputs

New spectrum bands enable new wireless use cases, and OEMs will be incentivized to produce the inputs

Spectrum supports low latency and high bandwidth use cases

Use cases help optimize operational efficiency

Technology ecosystem providers will have reduced capabilities to innovate

Next generation technologies will not be able to flourish without more spectrum

The deployment of 5G networks has ushered in a new era of advanced wireless use cases that have the potential to revolutionize the daily lives of Americans. Companies are leveraging the advanced capabilities of 5G connectivity, including enhanced mobile broadband, low latency and massive internet-of-things (IoT) to develop new, futuristic products such as XR headsets, autonomous vehicles, and smart cities[93].

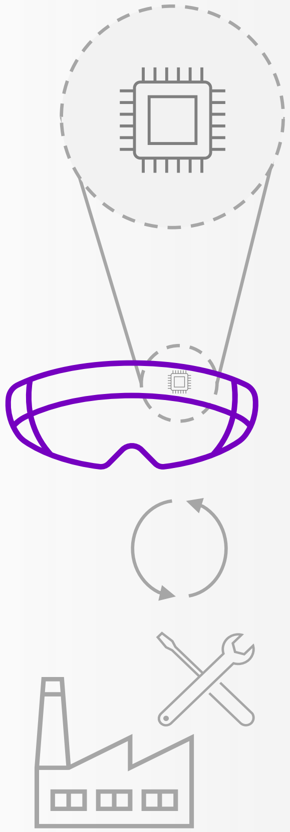
Key industries are emerging in the U.S.: the 5G devices market has reached $45 billion in total revenue with a 38% estimated CAGR between 2025-2030[94]. Use cases such as XR are gaining footholds in the enterprise and consumer markets, with the US extended reality market size reaching $22 billion in 2024 with a projected 34% CAGR between 2024-2029[95].

Regardless of the progress that ecosystem providers have made with existing cellular networks, they will continue to rely fully on quality connectivity, as well as the availability of upstream technology inputs, for their products to function. Without additional spectrum, a lack of upstream OEM innovation, and network congestion, will prevent ecosystem providers from launching new advanced wireless products in the future.

Ecosystem technology providers depend on chipset manufacturers to develop the technology inputs that enable 5G connections. For example, Qualcomm has developed the Snapdragon XR2 5G chip that enables direct 5G connectivity for XR devices[96]. But additional upstream innovation may not be feasible if spectrum availability remains stagnant – meaning XR companies might not have new chips for next-generation products.

As we have explored, 5G-supported use cases, such as telerobotic surgery, XR, and autonomous vehicles will all require high-bandwidth and low-latency connectivity[97]. Low power alternatives, such as WiFi, are not an adequate substitute as these use cases will require full-power, wide area networks. Given that by 2027 networks will already be unable to meet nearly one quarter of peak traffic demand, and by 2035 it will fail to meet nearly three quarters of peak demand, there will not be enough available bandwidth for these use cases to flourish.

While ecosystem providers will be affected firsthand by the inability of the network to support their products, there will be an even more widespread impact on the downstream users of these technologies. To conclude our analysis of the enterprise value chain, we will first explore how enterprises will not be able to reach their digital transformation potential when the network can no longer support the expansion of advanced wireless use cases. Then in the following section, we will discuss the impact on US consumers, and what they stand to lose without these technologies.



Spectrum incentivizes R&D for technology inputs

Spectrum supports low latency and high bandwidth use cases

Advanced AR headsets for ultra low latency & high-resolution applications

Use cases help optimize operational efficiency

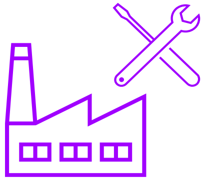
Smart factories implement use cases like augmented-reality (AR) to support maintenance and reduce error rates

3 **Enterprise End-Users**

Lack of innovation and network capacity will limit enterprise use-cases and benefits

U.S. industries will be less productive and effective without access to advanced wireless technologies

If upstream suppliers and ecosystem technology providers do not develop new products for the U.S. market, industrial end-users of these advanced wireless technologies will not have access to the world's most advanced technologies, limiting their ability to digitally transform and compete. Additionally, even if the technology becomes available, a spectrum shortage will severely impact the performance of existing enterprise wireless use cases that require low latency and high bandwidth within the macro cellular network.



Use cases help optimize operational efficiency

Examples of at-risk enterprise use cases due to a lack of spectrum*

Wireless use case	Benefits	Latency requirements	Bandwidth requirements
Utilities | Drones equipped with high-quality cameras can help technicians monitor the grid and identify wildfire risks, such as equipment contact with vegetation[98]	Proactive real-time remote monitoring could save utilities operators 10% or more in operating costs[99]	Remote technicians require ultra-low latency to pilot the drones around obstacles such as trees and buildings[100]	Technicians depend on high quality video streams to identify potential risks from the air[101]
Shipping & Logistics | Autonomous driving technology enables shipping companies to address driver shortages by operating trucks independently of humans[102]	Autonomous trucks can effectively double revenue per truck, as drivers are limited to 11 hours of driving per day. Additionally, by optimizing driving performance, companies can reduce fuel consumption by 10%[103]	Autonomous vehicles require extremely low latency to identify and respond to potential collisions before they happen[104]	Autonomous vehicles rely on sending high quality video and sensor data to the network to maintain their routes and identify obstacles[105]
Healthcare | Remote surgery, in time sensitive and emergency cases, allows surgeons to perform life saving procedures on a patient from a distant location using robotic systems and wireless connections[106]	Remote surgery allows surgeons to respond to emergencies and time-sensitive procedures, and address surgeon shortages by allowing them to practice across geographical boundaries[107]	Surgeons depend on low-latency connections to perform remote surgeries with a high level of robotic control[108]	Surgeons need high quality video streams to adequately see what they are doing during remote surgery[109]
Smart Cities | Adaptive traffic signals use real-time wireless camera feeds at intersections to help cities optimize traffic flows[110]	Deployment of smart traffic lights can lead to a 40% reduction in vehicle wait time, 26% faster commute, and 21% decrease in emissions[111]	Traffic management systems must analyze video for vehicles, bicyclists, and pedestrians in real-time to adjust traffic signals[112]	Adaptive traffic signals require live video streams to track the presence of vehicles, bicyclists, and pedestrians at intersections[113]

*Non-exhaustive illustrations

4 Downstream Consequences for Consumers

Consumers will feel the downstream effects of spectrum limitations

Network congestion during peak hours will impact use cases that have become integral to the ways Americans work, spend leisure time, and consume critical services. Current connectivity affordability will be threatened as networks (including FWA) are unable to further scale in a cost-effective manner.

A lack of enterprise innovation will also leave U.S. consumers without access to the future technologies that have the potential to revolutionize daily life, including mobile AI agents, virtual reality devices, and autonomous driving platforms.

1 **Reduced Quality of Life**

Widespread network congestion will impact everyday quality of life

From productivity and entertainment, to emergency services, poor network quality has real-world impacts

Poor network performance caused by a spectrum shortage will impact regular users in both everyday and critical scenarios. Out-of-home network congestion has a direct impact on the functionality of mobile applications, which are becoming an increasingly integral part of daily life. As network congestion increases, users will experience a range of issues, including device connection failures, call drops, packet loss, and video buffering. These disruptions will be particularly harmful during special events and emergencies, when reliable connectivity is most critical.

Productivity

Network congestion, which contributes to latency and bandwidth issues, hampers productivity by slowing down the completion of online tasks.

Work-related activities like video conferencing, file transfers, cloud-based document editing, and virtual collaboration will become inefficient[114].

This will lead to time wasted, missed deadlines, and reduced work quality, ultimately impacting users' abilities to perform efficiently in a remote/hybrid workspace

Entertainment

Entertainment options, such as video streaming and mobile gaming, are affected when consumers have insufficient bandwidth[115].

Buffering, long load times, and poor streaming quality will degrade the viewing experience, and games will become less responsive[116].

As highlighted in the impact to network section, three times* as many consumers will have a fair, poor, or bad quality of video experience by 2035[117], when compared to currently reported consumer levels.

Critical Applications**

In critical applications like remote healthcare or disaster relief activities, sufficient bandwidth and low latency are paramount.

For remote healthcare, poor video quality during virtual consultations can prevent physicians from making an accurate diagnosis.

In disaster relief scenarios, latency & bandwidth issues reduce the efficiency of digital tools such as drone-based video monitoring or real-time GPS navigation. These can lead to misdirected aid or delayed emergency response[118].

* This analysis assumes current quality levels using the Ericsson Mobility Report 2023. We then applied a proportional decrease based on the demand-supply gap to forecast how many more users will have the lowest level of network experience.
** Typically, traffic for Emergency 911 calls will be prioritized, though the supply-demand gap will ultimately affect and limit the scalability of other potential applications.

1 Reduced Quality of Life

Connectivity costs will rise, and consumers will be left with fewer broadband options

Lack of spectrum will raise costs to serve customers for network operators, and prevent the expansion of fixed wireless access

Costs to serve customers will increase for operators

As previously explored, a lack of spectrum will prevent network operators from upgrading capacity efficiently and economically. Network densification and spectral efficiency advancements are costly alternatives to spectrum, and they will force operators to incur heavy capital costs for necessary upgrades. This can ultimately increase cost for consumers, Mobile operators have already recognized the need to address rising consumer data demands, stating that mobile service prices may increase if no additional spectrum is licensed[119].

Expansion of an affordable broadband alternative will be limited

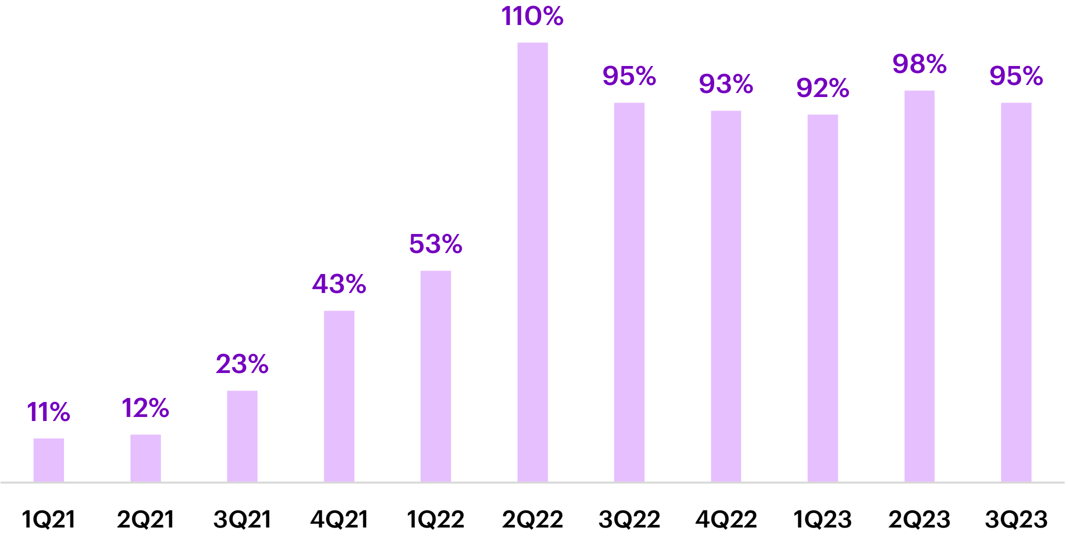
Fixed Wireless Access (FWA) provides high-speed internet connectivity to users over cellular networks instead of traditional wired connections. FWA is emerging as a key service, as its relatively low cost of deployment enables affordable pricing plans. Traditional fiber deployment cost per household ranges from $800 - $6,000 in urban to rural areas, compared to $200 to $1,800 for FWA, representing a material relief in installation costs[120]. Overall, FWA has accounted for most of the U.S. broadband subscriber growth since 2022[121].

However, operators can only offer FWA in locations where they can balance fixed and mobile traffic on their cellular network[122]. As a result, many consumers are still faced with fewer options to access reliable, and essential broadband access, diminishing their quality of life[123].

Lack of spectrum will limit the expansion of FWA, which has become an essential driver of net broadband growth in the US.

FWA has accounted for virtually all new subscribers in recent years, even as other access technologies have lost share[124]

FWA's share as a percentage of new broadband subscriptions in U.S. (Q1 2021 – Q3 2023)



2 **Lack of Access to Next-Gen Tech**

Consumers will not have access to next-gen technologies that would benefit their lives

Commercial deployment of AI, autonomous vehicles and XR will be at risk due network congestion

The next-generation of wireless consumer technology is arriving. These products have the potential to revolutionize the daily lives of American consumers. For example, extended reality (XR) headsets will help nursing and medical students simulate medical procedures in a safe environment[125]. Autonomous driving platforms provide mobility solutions for those who cannot drive themselves, greatly improving their independence[126].

However, these advanced wireless use cases all depend on a combination of high bandwidth and low latency to function suitably over cellular networks. As previously discussed, a spectrum shortage will limit the ability to meet these network requirements, leaving users unable to reap the full potential of these technologies.

To illustrate the benefits that American consumers stand to lose without these use cases, we will explore three advanced technologies in detail – mobile AI applications, autonomous vehicles, and XR devices – and their benefits to users while noting their dependence on high bandwidth and low latency.

Consumer use cases that cannot be supported without high bandwidth and low latency:

Mobile AI Applications

Offer users enhanced productivity tools, such as real-time visual and audio interfaces that analyze and respond with contextual insight in real time.

Autonomous Vehicles

Reduce injury-causing accidents by 85% compared to human drivers and give disabled Americans more independence[99].

XR Devices

Provides users with immersive experiences that boost safety, education and learning, such as surgical training on XR stimulations, and overlays for road assistance and navigation.

2 **Lack of Access to Next-Gen Tech**

The future of mobile AI depends on spectrum

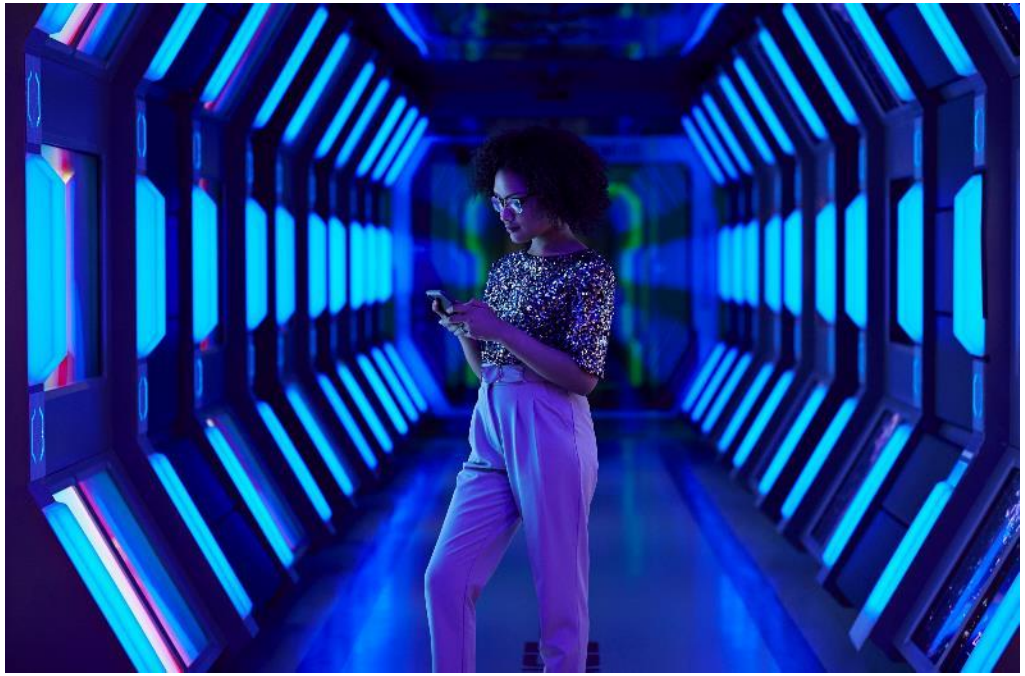
To achieve the rich potential of AI, a high-capacity network, backed by sufficient spectrum, will be essential

AI is poised to become an integral part of daily life, transforming how consumers interact with technology. Instead of the text-based interfaces increasingly[127] used today, future AI agents will allow users to engage through video, voice, and 'always on' interfaces[128]. These advancements will enable AI agents to offer contextual insights and assistance seamlessly throughout daily activities, without the need to pause to type. This trend is evident with the introduction of new AI-driven tools that offer real-time voice and video conversations[129].

Future AI tools will be able to take in surroundings captured by wearables or the user's device, and process queries in real-time, while producing video or audio responses back tailored to the user's situation[130]. Companies have already begun to introduce immersive, 'always on' models that illustrate this approach, with features such as real-time language translation and instant video generation and response. Users will be able to listen and speak in their native language, while instantaneously responding back in voiced-over foreign languages to another user, as the AI consistently communicates with its servers in real-time[131]. This effectively allows users to communicate in a foreign language seamlessly, adding significant value to user experience and productivity.

While powerful, these tools will put a high amount of stress on wireless networks, requiring rich bidirectional data transfer[132]. These future AI interfaces, alongside other data-rich AI use cases including real-time AI-assisted image and video editing, will drive up consumer data usage[133, 134]. AI applications are projected to drive uplink traffic 20% higher than it would be with existing applications[135]. Mobile operators will not have the uplink capacity to match in high-traffic areas, and uplink traffic is expected to outpace capacity as soon as 2028. By 2029, only two-thirds of uplink demand will be met if spectrum availability remains constant[136].

Over time, wireless networks will struggle to sustain required bandwidth levels without additional spectrum, ultimately leaving consumers at risk of losing access to AI applications that otherwise have the potential to transform daily life..



2 **Lack of Access to Next-Gen Tech**

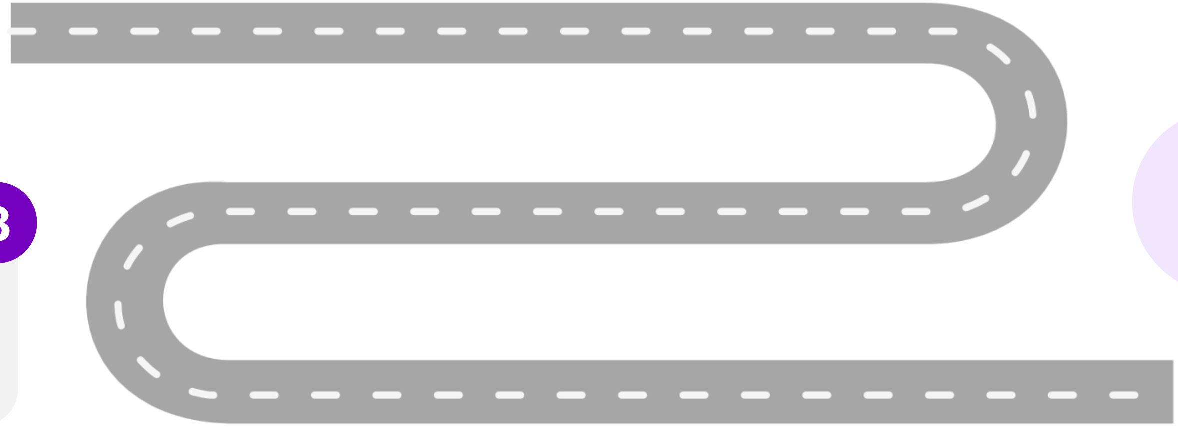
The future of mobility depends on spectrum

Low latency is critical for the future of autonomous vehicles, ensuring safety and reliability for all

Autonomous vehicles will revolutionize road hey can also change the lives of disabled Americans by helping them access essential services, attend medical appointments, and participate in social activities without relying safety in the US. They are 6.8 times less likely to be involved in a crash resulting in injury compared to human drivers, giving them the potential to save thousands of lives annually[137]. Ton others. For autonomous vehicles to operate safely, they require ultra-low latency communications to ensure real-time data processing and immediate response to dynamic driving conditions. This high level of reliability and low latency is crucial to prevent accidents and ensure the safety of all road users and won't be possible if wireless networks don't receive additional spectrum to address rising levels of network congestion.

1 Real-time communication between autonomous vehicles and its driving platforms help guide vehicles to their destinations, with spectral networks providing ultra-low latency connections (20-30 millisecond) to enable this feed[138].

2 Local cell sites provide wireless network and coverage that enables connectivity in an area.



3 Autonomous vehicles communicate with connected smart meter lights and traffic data, providing an extra level of integrated safety and security.

4 Disabled patients organize direct pickups from autonomous driving applications on their smart phones, unlocking mobility access for anytime use.

2 Lack of Access to Next-Gen Tech

The future of Extended Reality (XR) depends on spectrum

Virtual, augmented, and mixed reality technologies can revolutionize user experiences, enabling immersive education, remote collaboration, and enhanced retail experiences for consumers

Extended Reality (XR) technology offers transformative benefits for consumers. XR can help create immersive learning environments, making education more engaging and effective[139]. XR can also provides real-time information overlays, improving shopping experiences and navigation. In the workplace, XR can help make training more engaging, improve collaboration with virtual meetings, and simplify tasks with helpful real-time information[140]. In healthcare, XR technologies enable advanced simulations for medical training and remote surgeries, which improve patient outcomes[141].

To fully realize these benefits, wireless networks need to be able to handle the data demands and needs of XR technology[142]. XR applications require real-time data transmission to create immersive and interactive experiences, which is only possible with networks that provide latency of under 10-20 ms[143]. Without additional spectrum, network congestion will cause networks to struggle with providing the necessary bandwidth and latency requirements for these use cases to operate effectively. This limitation would hinder the adoption of XR, preventing consumers from leveraging its full potential.

Extended Reality (XR)

AR
Augmented Reality
Real world enhanced with 3-D digital objects overlaid or placed within the real-world environment

MR
Mixed Reality
Blended real & digital world combined, enhanced with interactive & spatially-aware 3D holograms

VR
Virtual Reality
Full immersion in a virtual environment, completely replacing the real world, brought to life with simulation

5

Impact of Spectrum Inaction on the U.S.

A lack of available spectrum will pose risks to U.S. global economic leadership and national security

The U.S. held a wireless leadership position throughout the 3G and 4G eras, realizing large productivity and economic benefits. Companies such as Apple, Google, Meta and Uber emerged as clear winners of 4G, supported by forward-looking spectrum policies and a robust investment environment.

In the competitive race for 5G and beyond, the U.S. is in danger of losing its place as a global leader. Without additional licensed spectrum, the country risks losing $1.4T in economic benefits between 2025-2035[144]. As peer countries pull ahead in spectrum availability, U.S. national security is also at risk.

The U.S. thrived on its pioneering leadership during the 4G era

A combination of proactive spectrum policies and network investment paved the way for significant innovation and growth

The U.S. emerged as the global leader in 4G/LTE network deployment during the 2010s, thanks to a combination of spectrum allocation and industry policy from policymakers, alongside significant investments from network operators[145]. U.S. 4G leadership enabled the creation of a new mobile technology ecosystem that was largely driven by U.S. companies such as Meta, Apple, Microsoft, and Google. By 2016 the U.S. had gained $100 billion in additional annual GDP compared to its prior 3G trajectory, due to the investment in and deployment of 4G connectivity[146]. Subsequently, the U.S. took an early lead in 5G deployment, utilizing the same model of spectrum allocation by policymakers and investments by network operators[147, 148].

4G leadership also contributed to 84% of all U.S. wireless-related jobs from 2011-2014[149]. This growth was fueled by disruptive ecosystem providers like well-known U.S.-based application marketplaces, social media, logistics, and media organizations, who all harnessed enhanced 4G mobile broadband to create the new mobile application economy.

At the beginning of the 5G era, starting in 2017, approximately $186 billion was invested into networks by U.S. carriers, including approximately $113 billion spent on spectrum acquisitions alone[150, 151]. The combined efforts of policymakers and carriers enabled the U.S. to reach 99% 5G coverage as of mid-2023[152].

$100B

In Annual Economic Benefits Created by 4G between 2010 - 2016[153]

84%

Of All Wireless Jobs Created from 2011 – 2014 tied to 4G Leadership[154]

U.S. Companies Defined the Global 4G Era

1 **Impact on U.S. Economy**

Lack of spectrum will prevent the U.S. from capturing the economic opportunity offered by 5G and future generations of wireless technology

The U.S. is projected to realize significant GDP gains over the next decade as advanced wireless networks evolve and enable new technologies that increase national productivity.

However, if enterprises and consumers are restricted by a lack of spectrum, then these future GDP benefits will become significantly limited.

The lost economic opportunity if more spectrum is not licensed will amount to $300B in annual GDP by 2035 ($1.4T cumulatively over the next 10 years*)[155].

Lost Economic Opportunity from Spectrum Inaction

$300B lost annual GDP opportunity by 2035[156]

$1.4T cumulative lost GDP opportunity (2025-2035)[157]

GDP impact based on estimates for 5G and beyond benefits over a 10-year period.

* See Appendix – Methodology. We identified a baseline expected GDP benefit from advanced wireless networks using a range of previously published figures on 5G GDP benefits. Key drivers of economic uplift from advanced wireless networks include greater enterprise productivity, capital investment, job creation, and tax revenue for governments.

2 **Impact on Global Tech Leadership**

The U.S. risks losing its global technology leadership if it continues to lag global peers in spectrum availability

As previously established, the U.S. is projected to lag behind global peers in licensed mid-band spectrum by an average of 520 MHz* by 2027. As peer countries allocate more licensed spectrum to their technology ecosystem players, those companies will be well-positioned to capitalize on 5G and future opportunities – putting the U.S. at a severe competitive disadvantage. The U.S. became the global leader in wireless technology during the 4G/LTE era thanks to its early spectrum deployment and network investments[158] , but now risks losing this position.

China is now following the same blueprint in the 5G era – leading the world in licensed spectrum availability and deploying more 5G-enabled technologies than the U.S.[159, 160]. China aims to position itself to lead the next major wireless ecosystem that emerges. Chinese technology provider Huawei is currently leading the world, in terms of quantity in 5G patent families and contributions to 3GPP standards[161]. If the U.S. does not maintain leadership in the next advanced wireless generation, it will risk depending on foreign providers for critical technology[162]. Additionally, the importance of spectrum to the United States' ability to set wireless standards can be seen in its approach during the 4G period, where its leadership in deploying spectrum and participation in setting global standards setting bodies gave birth to 5G policy setting organizations[163]. Other nations have now adopted a global model in licensing spectrum intentionally, leading to a louder voice at the standards setting table, and thus influencing global standards in their image.

* Based on Analysys Mason's report issued in September 2022. By 2027, several countries with more licensed mid-band spectrum than the U.S. are projected to be China (1660 MHz), Japan (1100 MHz), the UK (790 MHz), South Korea (700 MHz) and Saudi Arabia (600 MHz).

2 **Impact on Global Tech Leadership**

Case Study: Semiconductor Industry

The semiconductor industry illustrates what happens with U.S. inaction, as peers invest and innovate in vital, next-generation infrastructure. Spectrum allocation is just as critical, as it is the door opener for 5G+ innovation and the next wave of the AI economy

In the late 1980s, Taiwan Semiconductor Manufacturing Company (TSMC) was founded, which solely focused on manufacturing chipsets for semiconductor design companies[164]. Through constant reinvestment in R&D, TSMC eventually became one of the only companies capable of manufacturing the most advanced chipsets[165, 166].

Today, the rest of the world is years behind TSMC in terms of chipset manufacturing capabilities, meaning companies have little choice but to depend on TSMC to produce the most advanced chips used for cutting edge technologies, such as AI microprocessors[167].

The recent CHIPS Act passed by Congress addresses these issues, through targeted incentives and policies for OEMs invest in critical infrastructure within the United States[168]. The goals of this policy are to increase domestic production, strengthen semiconductor supply chain resiliency, enhance U.S. R&D , and build a robust workforce base for the semiconductor industry.

If high quality, scaled semiconductor fabrication facilities form the foundation for microprocessor technology leadership, then innovatively deployed wireless spectrum forms the foundation for wireless technology leadership.

The AI economy is coming, and policymakers are duly addressing the semiconductor side of the equation. Similar attention should be paid to the connectivity infrastructure that will supercharge the AI application marketplace. Connectivity will prove to be a key enabler in driving widescale adoption of the AI economy[169].

Semiconductor Industry			Connectivity Industry
The CHIPS Act recognizes semiconductor manufacturing as the foundation for strategic technological, economic, and security objectives which can impact multiple stakeholders[170]			**Similar opportunities exist for the wireless connectivity value chain that can be unlocked by forward-looking spectrum policies**
Grow domestic fabrication of semiconductors and microprocessors	**Foundries**	**Networks**	Additional spectrum helps alleviate network congestion and unlock connectivity to advanced wireless use cases, such as autonomous vehicles
Improve enterprise innovation and productivity gains by enabling low-cost-to-serve compute workflows	**Enterprises**	**Enterprises**	Enterprises will increase investment in the domestic production of wireless and communication equipment
Enhance the consumer experience with low-cost-to-serve semiconductor technology in consumer devices	**Consumers**	**Consumers**	Consumers benefit from quality-of-life improvements across productivity, entertainment and critical services
Secure domestic supply chains and labor market demand	**Country**	**Country**	Spectrum enables the U.S. to capture economic benefits and secures supply chain resiliency in critical communications equipment

3 **Impact on National Security**

U.S. national security will be at risk without additional spectrum

Lagging peer countries in spectrum availability also poses U.S. national security concerns

If the U.S. loses its global wireless technology leadership, it will depend on foreign companies for critical technology – creating national security risks

Dependence on foreign technology means that the U.S. will have less control over its own communications infrastructure, making it more difficult to ensure the security and reliability of networks[171]. Additionally, foreign suppliers could use their critical position to exert economic or political pressure on the U.S., potentially compromising national interests[172]. Global wireless standards - which the U.S. helped shape in the 3G and 4G eras – played a critical role in developing widespread technological adoption[173]. If the U.S. loses the ability to set future wireless standards, it could open the door for new disruptive nation-states to drive the global technology agenda.

Furthermore, this will serve to exacerbate the risk of allied nations increasingly adopting non-U.S. technologies into their connectivity ecosystem, posing international security concerns[174].

Lastly, reliance on non-U.S. suppliers would mean that any supply chain disruptions would disrupt the U.S. economy, infrastructure and communication and security protocols while exposing the country to foreign threat actors[175].

6 Call to Action

A Call to Action:

Policymakers must urgently license additional commercial mid-band spectrum to address the U.S.'s looming spectrum deficit

U.S. policymakers should license additional, full-powered commercial mid-band spectrum to prevent detrimental effects to enterprises, consumers, and the country. Without immediate action, the U.S. will be forced to reckon with a crippling spectrum shortage domestically, as well as lost spectrum leadership globally. This position jeopardizes the benefits from investment in **wireless infrastructure**, the everyday needs of **consumers**, the productivity of its **economy**, and even **national security**. The path forward is to license **additional commercial mid-band spectrum between 3.3 – 8.5 GHz**, which helps unlock an additional **$300B of economic benefits** annually and helps to alleviate the pressing needs of the U.S. public, its commercial industries, and the nation's strategic interests.[176]

Why Spectrum Matters

- Improves Wireless Network Performance and Connectivity
- Provides Next-Generation Technology Access for Consumers
- Secures U.S. Global Wireless Leadership

Conclusion:
There is no time to waste on crucial spectrum policy

The U.S. stands at a pivotal moment where licensing additional spectrum is crucial to maintaining technology and wireless leadership. Immediate action is necessary to prevent the negative impacts of a spectrum shortage on enterprises, consumers, and the U.S. economy. By licensing more spectrum, the U.S. can ensure reliable wireless infrastructure, support advanced wireless technology use cases, and enhance the quality of life for its citizens.

The urgency of these issues will be felt as spectrum shortfall becomes a reality. Significant lead time will be required to implement an accelerated deployment to meet this timeline. This includes evaluating a new candidate band for use, seeking and incorporating key stakeholder feedback for review, as well as holding a spectrum auction. These activities will need to be completed within 2025 to have any realistic way of addressing the shortfall in time for 2027. By these measures, the U.S. is already behind schedule and there is no time to waste in implementing policy.

This strategic approach will enable the U.S. to capture significant economic benefits, attract talent and investment, and maintain its global leadership in wireless technology. Failure to act could lead to network degradation, economic losses, and a diminished role in setting global standards, allowing other nations to shape the future of wireless connectivity and the next wave of innovation.

Licensing more mid-band spectrum will ultimately elevate and boost the U.S.'s technology and connectivity leadership. This leadership will bring positive impacts to enterprises, consumers, the economy, and national security.

Appendix

Model Methodologies

Connectivity supply-demand model

Network capacity will meet 27% of data demand during peak hours by 2035

To quantify network capacity relative to demand between 2025-2035, we assumed that in 2025, network capacity equals demand during peak usage hours[A].

To estimate network capacity for each year, we assumed that the amount of available mid-band spectrum will remain fixed in the U.S. between 2025-2035. We then assumed a small amount of growth to network capacity each year[B].

Our projections for annual connectivity demand at peak hours were based on aggregate mobile wireless data traffic in 2023, sourced from the CTIA *Wireless Indices Report*, with an applied CAGR based on a range of published sources[C]. We assumed demand will be spread evenly throughout the network and across users, and we normalized demand to the projected number of cell sites each year[D]. Additionally, we assumed that the growth rate of peak demand is proportional to the growth rate of aggregate demand, and that prices for connectivity plans will not change between 2025-2035.

When demand exceeds network capacity, we assume that operators will reduce allocated bandwidth per device evenly to avoid needing to drop device connections entirely.

A. Based on the CTIA-Brattle estimate that the U.S. will reach a spectrum supply-demand gap by 2027. "Capacity" is defined as the level of utilization that the network can tolerate before it becomes congested – this may occur between 80% to 100% utilization.

B. We made the conservative assumption that spectral efficiency increases mildly over time, based on estimates in CTIA-Brattle 2023.

C. We derived a range of mobile traffic growth rates from previously published figures (Ericsson, CTIA).

D. Cell site growth estimates were based on CTIA's *Wireless Indices Report*. Assuming that demand will be spread evenly throughout the network is a conservative assumption, as 20% of cell sites carry approximately 50% of traffic.

Video streaming experience model

Perceived quality levels in 2035 will feel like streaming in 480p today instead of 1080p

Perceived quality is determined on a relative basis compared to growing consumer expectations; actual streaming resolution may not decrease significantly (depending on how much demand growth is coming from additional devices). Relative to growing expectations, perceived quality in 2035 would be comparable to how we regard 480p today.

We assumed that 1080p is the resolution that consumers expect for an 'excellent' experience today, per standards outlined in the *Ericsson Mobility Report 2023*. To put the degradation of perceived network quality by 2035 in terms of today's standards, we multiplied the necessary data throughput for 1080p (in terms of pixel count) by the proportion of demand that will be met by network capacity at peak utilization in 2035.

Fair, poor, or bad network experiences during peak hours will triple by 2035

We assumed current network experiences using the *Ericsson Mobility Report 2023*. We then applied a proportional decrease based on the demand-supply gap to forecast how many more users will have the lowest level of network experience.

For each year, we assumed that the video resolution necessary to provide an 'excellent' experience will scale proportionately with demand. To project the network's ability to deliver each level of experience at peak hours by 2035, we calculated how experiences would change today if capacity met 27% of demand (see supply-demand model finding on the left). We multiplied this 27% portion by the number of pixels[E] needed to deliver an 'excellent,' 'good', and 'fair' experience today. We then derived the relative number of additional users that would fall below the 'good' service threshold.

E. Using pixels as a proxy for data throughput needed for video streaming.

Model Methodologies

Economic impact model

The U.S. stands to lose $300B in annual GDP opportunity by 2035, and $1.4T cumulatively between 2025-2035, if demand for spectrum is not met

To calculate the economic opportunity that the U.S. will lose due to a spectrum shortfall, we first identified the baseline expected GDP benefit from advanced wireless networks. We aggregated a range of previously published figures on 5G GDP benefits (including GSMA, Nokia, and IHS Markit), normalizing them over a 10-year period (accounting for, in part, future wireless generations beyond 5G[A, B]).

We then applied an estimate of the percentage of GDP benefits that would specifically be driven by mid-band spectrum, sourced from GSMA's *The Socio-Economic Benefits of Mid-Band 5G services*.

Lastly, we projected the percentage of this baseline GDP benefit that is at risk each year due to a national spectrum deficit – specifically the amount of spectrum required that will be unfulfilled by availability[C].

A. We assumed that the 2025-2035 "5G and beyond" baseline benefit is proportional to 2020-2030 5G estimates. Key drivers of published 5G GDP impacts include greater enterprise productivity, capital investment, job creation, and tax revenue for governments

B. To estimate the growth curve of benefits between 2025 and 2035, we used the growth trajectory of GDP benefits during the 4G era, as calculated in the CTIA-Recon Analytics report *The 4G Decade: Quantifying the Benefits*.

C. Based on CTIA-Brattle estimates for spectrum required versus available in 2027 and 2032. Assuming lost economic opportunity is proportional to the amount of unfulfilled spectrum demand in the U.S.

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