On the Development of a National Spectrum Strategy

Docket Number: 230308-0068
United States Department of Commerce
National Telecommunications and Information Administration
Office of Spectrum Management

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High Tech Forum
Lakewood, Colorado

1. Introduction

The RFC poses approximately 70 questions in 21 groups under three pillars. The questions range from the particular ("What spectrum bands should be studied for potential repurposing…?") to the general ("How can federal and non-federal stakeholders best work together?).

Some are short term and immediate ("…what specific steps should be included in the Implementation Plan that could be taken in the next 12-24 months…?") and others are open-ended ("What are some recommendations for developing an enduring, scalable mechanism for managing shared spectrum access using the IIC or other similar mechanism, with the goal of increasing the efficiency of spectrum use?").

And, most interestingly, some questions are naïve ("What technologies are available to ensure appropriate interference protection for incumbents in adjacent bands?") while others are sophisticated ("What spectrum management capabilities/tools would enable advanced modeling and more robust and quicker implementation of spectrum sharing that satisfies the needs of non-federal interests while maintaining the spectrum access necessary to satisfy current and future mission requirements and operations of federal entities?").

Many of the issues in this inquiry reflect issues and concerns we raised in our 2013 TPRC paper, *Technical Principles of Spectrum Allocation*.[1] Much has changed since 2013, but much has not.

2. A Challenging Inquiry

Considering the breath, density, and brevity of the questions, the RFC is a very challenging inquiry. But that is perfectly understandable, given the need to create a baseline of consensus ground truths for an ongoing, quasi-judicial activity with tremendous implications for the nation's economy while mainly falling outside of NTIA's traditional role.

We deduce that NTIA seeks to distill principles for an enduring, scalable mechanism for managing shared spectrum access out of the compromises and tools needed to resolve the manifold controversies occasioned by the implementation of CBRS. Certainly, forecasts for new and emerging spectrum technologies play a large role in the inquiry.

If our assessment is correct (and it may not be), the CBRS-centric approach is problematic for two reasons:

1. NTIA's enthusiasm for CBRS is not broadly shared across the spectrum of wireless network engineers and operators;[2] and
2. CBRS woes aren't informative with respect to the larger set of controversies about spectrum rights between federal and non-federal users, let alone those pertaining to emerging and legacy non-federal users.

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[1] Richard Bennett, "Technical Principles of Spectrum Allocation," SSRN Scholarly Paper (Rochester, NY, 2013), https://doi.org/10.2139/ssrn.2240625.
[2] Richard Bennett, "Effective and Efficient Wireless Networks," *High Tech Forum* (blog), September 20, 2022, https://hightechforum.org/effective-and-efficient-wireless-networks/.

3. An Enduring, Scalable Mechanism for Managing Spectrum Access

Digital spectrum use, rights, and management practices also have a lot of history, dating back to 19th century work on mobile telegraphy. For several generations, spectrum rights were assigned by squatter's rights or relatively arbitrary regulatory beauty contests. Some users have reliance interests on spectrum bands that probably should not have been granted in the first place. And other rights holders are eager to sell or trade their rights for the right price.

Consequently, the United States has a problem with obsolete and less-than-optimal legacy spectrum allocations. This problem will certainly persist as long as the country assigns rights to particular spectrum bands, power levels, and beam forms in the future. The net result of obsolete rights assignments is fragmentation in the spectrum allocation table, where low-power and high-power allocations often neighbor each other. When this happens, potentially usable spectrum goes to waste in the form of guard bands.

Fragmentation in the spectrum rights table is similar to the problem that computer operating systems and high level languages have to manage in connection with dynamic memory allocation and storage space allocation on disk drives of various types. The computer science solution to this problem is a dynamic mechanism called "garbage collection" that frees up memory allocations no longer in use and compacts the remainder. As Microsoft describes this process in its technical literature.

> *A garbage collection has the following phases:*
>
> - *A marking phase that finds and creates a list of all live objects.*
> - *A relocating phase that updates the references to the objects that will be compacted.*

- *A compacting phase that reclaims the space occupied by the dead objects and compacts the surviving objects. The compacting phase moves objects that have survived a garbage collection towards the older end of the segment.*[3]

Spectrum garbage collection wouldn't add or subtract from the total pool of active allocations; rather, it would move allocations around in a rational manner such that interference potential between neighbors would be minimized. Interference potential is increased by power differential, but it can also increase or decrease because of spectrum properties such as bandwidth, beam direction (azimuth,) beam scatter, modulation, coding, interference temperature, and duty cycle. Primitive sharing mechanisms such as CBRS only concern themselves with duty cycle, the tip of the sharing iceberg.

Long-Term Value of Garbage Collection

In order to be enduring, the spectrum access mechanism needs to be dynamic. Spectrum fragmentation isn't the only problem to solve with the hoped-for "enduring, scalable mechanism for managing spectrum access," but is an important capability of said mechanism. We have numerous technical solutions to interference mitigation today and will have more in the future.

But we can't deny that interference potential is created in the first instance by allocation decisions. Rationalizing the interference potential baked-into our spectrum allocation history, policy, and practice goes a long way toward an interference-free future. Engineering can only provide regulators with tools; it's up to regulators to use these tools to their best advantage.

Garbage Collection in Pillar Two of the RFC

The RFC addresses this problem in Question 6 of Pillar 2 (P2Q6):

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[3] Microsoft, "Fundamentals of Garbage Collection," Microsoft Build, February 28, 2023, https://learn.microsoft.com/en-us/dotnet/standard/garbage-collection/fundamentals.

> *6. In considering spectrum authorization broadly (i.e., to include both licensed and unlicensed models as well as federal frequency assignments), what approaches (e.g., rationalization of spectrum bands or so-called "neighborhoods") may optimize the effectiveness of U.S. spectrum allocations?*

The question then devolves into minutiae. Spectrum garbage collection should be applied to all bands, across the board, in three phases:

1. Identify low value, lightly used bands for potential reassignment in return for license holder compensation (or other incentives.)
2. Identify licenses whose holders would be willing to undergo relocation in return for lower interference potential.
3. Auction or assign former guard bands and low-value assignments in larger (and more valuable) contiguous blocks than those formerly occupied.

This should be an ongoing process across all allocations triggered by supply, demand, and value. This procedure is capable of effectively creating more spectrum by eliminating inefficiency in the form of guard bands and obsolete licenses. Effectively, it would create a robust spectrum marketplace.

As appealing as it may be to rationalize spectrum rights into neighborhoods with low interference potential, this one idea is not the silver bullet that makes immediate sense out of 125 years of spectrum allocation. Federal parties, particularly those in the national security space, don't follow market incentives.

Risk-averse parties in general would probably prefer to leave the *status quo* in place unless they can be persuaded by a trusted voice that the benefits of a more rational spectrum management approach outweigh short-term inconvenience.

4. Pillar One: Building a Spectrum Pipeline

Question six in pillar one (P1Q6) also addresses the need of rights holders to "vacate, compress or repack some portion of their systems or current use to enable optimum utilization," a process that goes by the shorthand of "upgrade and repack" sometimes followed by "repeat forever."[4] This is how new spectrum comes to the market. As we wrote in 2012:

> *We free up spectrum for new services by improving the old ones. Almost every American adult is aware of the digital TV transition at some level, although most weren't affected by it. Before 2009, 500 MHz of RF spectrum was assigned to television broadcasting (not counting satellite TV):*
>
> - *54-72 MHz channels 2-4*
> - *76-88 MHz channels 5-6*
> - *174-216 MHz channels 7-13*
> - *470-896 MHz channels 14-83*
>
> *After the transition from analog to digital TV, 200 MHz formerly occupied by UHF channels 52-83 (698-896 MHz) was reassigned to a variety of uses, mainly cellular and public safety networks, and White Spaces networking and wireless microphones were permitted between allocated TV channels in local markets according to a database.*
>
> *On its face, the transition freed up 50% of the former allocation for analog TV (including the White Spaces allocation.) If we dig a little deeper, however, we find some more interesting implications.*

[4] Richard Bennett, "Upgrade and Repack; Repeat Forever," policy blog, High Tech Forum, August 8, 2012, https://hightechforum.org/upgrade-and-repack-repeat-forever/.

It was particularly easy for the US and other nations to capitalize on the spectrum dividend paid by replacing analog TV with a more efficient digital alternative because the case for transition was made by forces outside of government: international standards organizations, broadcasters, and technologists.

In fact, Direct Broadcast Satellite (DBS) systems made the transition from analog to digital before terrestrial TV broadcasters did. DirecTV's digital broadcast format enabled Philips and TiVo to build a consumer digital video recorder in 1999 that could time-shift television programming with no loss of quality.[5] Such ancillary benefits often come about from spectrum management upgrades.

The RFC asks about "upgrade and repack" in the context of spectrum sharing; it's also important to situate this question in the context of innovation more generally. Was DirecTV thinking about TiVo when its engineers decided to transition from analog to digital signal formats? Possibly, but it probably wasn't top of mind. Improving the efficiency of technical systems has myriad benefits.

Efficiency is Step One in the Pipeline

Pillar one focuses on sharing, beginning with the definition of the term. A definition is necessary because public discourse has corrupted the spectrum engineering vocabulary to a disturbing degree. The RFC correctly raises the interference-generating side effects of certain modes of "sharing."

In reality, all commercial uses of spectrum hinge on efficient sharing. Mobile carriers don't bid for spectrum licenses in order to communicate with themselves, their systems are all about the efficient sharing of spectrum among and between their customers. This isn't mere niggling with words.

Sharing among users of a managed service is efficient because the manager benefits from offering a reliable, high performance service to its users. Users benefit from these capabilities as well. Replacing a licensed spectrum service with an unlicensed one necessarily introduces interference and reduces

[5] "TiVo History," TiVopedia, accessed April 15, 2023, https://www.tivopedia.com/tivo-history.php.

efficiency. The greatest challenge for unlicensed services such as Wi-Fi is overcoming the loss of efficiency that necessarily comes about from contention between users as well as contention between operators.

Revising the Incentives

While the operator of a licensed service has full knowledge of the spectrum needs of its users moment by moment, unlicensed users have extremely limited knowledge of competing demands for spectrum. Similarly, unlicensed operators still have no better source of information about spectrum demand than the failure of certain attempts at communication. In some jurisdictions, operators are forbidden to share information with each other by privacy concerns.

Beam forming, beam coherence, Spatial Division Multiple Access (SDMA), OFDM, MIMO, MU-MIMO, Massive MU-MIMO, and frame aggregation are all attempts at improving the efficiency of unlicensed spectrum access. When these technical measures at isolating information from interference fail, the unlicensed spectrum industry beseeches regulators to grant it greater access to spectrum.

Improving technical efficiency is expensive: it requires more circuits, better software, costly redesign, better antennas, and, most of all, more power, a scarce resource for battery-operated mobile systems. It's no wonder that "more spectrum" has become a watchword for the unlicensed industry; all it costs is more lobbying.

Spectrum policy makers would be wise to demand efficiency improvements from unlicensed operators. Licensed operators already have such incentives because spectrum is a valuable resource to them. US spectrum regulators should refrain from granting additional allocations to Wi-Fi until they see evidence that it will be used responsibly.

Wi-Fi is meant to serve a small niche in the overall spectrum ecosystem: it's fundamentally a residential network that can be stretched to small businesses, hotels, cafes, and airports with management. We should never expect Wi-Fi to serve outdoor areas or to provide rapid mobility without a redesign. Current allocations in the 5, 6, and 60 GHz bands should be sufficient for the next ten years, if not longer.

In general, the unlicensed access model works best in enclosed spaces where signals are cabined by walls and windows. Limiting propagation facilitates spatial re-use across neighborhoods and in multiple dwelling units. Within dwelling units, walls can be overcome with simple repeaters that propagate signals between rooms. This approach is practical with high bands at 50 Ghz and above.

The desire of some portions of the unlicensed spectrum industry to seize midband spectrum suggests a desire to hobble licensed competitors by taking desirable bands off the table. 7 GHz is no better for unlicensed indoor use than 60 GHz, but it is vital for licensed services.

5. Pillar Three, Technology Development

Fixed Wireless Access (FWA) is a rapidly growing enabler of broadband service. We expect that LEO Constellations will play an increasingly important role in networking in the near future. It's perfectly conceivable that future growth in residential broadband service will predominantly be provided by FWA and LEO with wireline relegated to legacy connections and backhaul with unlicensed serving in-home and body area networks. Current trends in consumer choice signal this direction.

FWA FTW

ABI Research predicts: "5G Fixed Wireless Access (FWA) will be the fastest-growing residential broadband segment to increase at a CAGR of 71%, exceeding 58 million subscribers in 2026."[6] The Ericsson Mobility Report forecasts that FWA will account for more than 300 million connections

[6] ABI Research, "5G Provides Competitive Alternative to Wired Broadband and Will Account for 35% of Overall Fixed Wireless Subscriptions in 2027," company blog, ABI Research, March 23, 2023, https://www.abiresearch.com/press/5g-provides-competitive-alternative-to-wired-broadband-and-will-account-for-35-of-overall-fixed-wireless-subscriptions-in-2027/.

worldwide by 2028.[7] And the Wireless Infrastructure Association calculates the addressable market for FWA residential connections in the US is 35 million households.[8]

FWA reaches hard to serve areas at low cost by reducing the need for trenching and pole attachments. It also brings competition to markets served by one, two, or three wireline service. And it easily bundles with mobile wireless service, increasingly the most import communication mode of them all. FWA co-exists with both Wi-Fi and wired backhaul, but it limits the scope that these modalities need to serve.

FWA increasingly means 5G, with its 3GPP successor 6G on the horizon. FWA works best with midband spectrum from 3 GHz to 10 GHz. The BEAD program needs to embrace FWA as a legitimate, money-saving broadband technology that lends itself to speedy deployment and comfortably meets actual consumer needs. The race for first place in speed and capacity in the residential broadband market doesn't matter to consumers whose needs don't rival those of massive data centers.

LEO Set to Rule the Rural Space

The SpaceX Starlink service has played a pioneering role in residential LEO, especially in lightly populated rural areas with no broadband or poor broadband. SpaceX has become a victim of its own success as subscriber growth has exposed capacity limits and reliability issues.[9][10][11] The solution to these problems is more satellites in the sky, and probably more spectrum per satellite. As SpaceX is part of a portfolio of

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[7] Peter Jonsson, "Ericsson Mobility Report" (Ericsson, November 2022), https://www.ericsson.com/4ae28d/assets/local/reports-papers/mobility-report/documents/2022/ericsson-mobility-report-november-2022.pdf.

[8] iGR, "The Fixed Wireless Network Opportunity" (Wireless Infrastructure Association, Q4 2022), https://8967849.fs1.hubspotusercontent-na1.net/hubfs/8967849/WIA_WP_FixedWirelessNetworkOpportunity.pdf.

[9] Mashable SEA, "Elon Musk's Starlink Satellite Internet Might Be a Victim of Its Own Success," Mashable SEA, September 21, 2022, https://sea.mashable.com/tech/21436/elon-musks-starlink-satellite-internet-might-be-a-victim-of-its-own-success.

[10] Mark Anthony, "SpaceX Is a Victim of Its Own Success," Townhall, accessed April 16, 2023, https://townhall.com/columnists/markanthony/2019/03/02/spacex-is-a-victim-of-its-own-success-n2542457.

[11] Daniel Fraser, "Elon Musk's Starlink Satellite Internet Could Become a Victim of Its Own Success," *US Today* (blog), September 21, 2022, https://ustoday.news/elon-musks-starlink-satellite-internet-could-become-a-victim-of-its-own-success/.

companies suffering from reduced market valuations, it's unclear that it can or will spend the money needed to prop up the service.

But other companies are stepping into the LEO broadband market, such as Amazon's Project Kuiper:

> ***Los Angeles, Calif., March 1, 2023****--Given the media attention that it gets, you could be forgiven for thinking that Starlink is the only game in town, when it comes to low earth orbit (LEO) constellations for communications. Nothing could be further from the truth. There are many others, some of which remain on the drawing board and others that have at least got as far as flying demo satellites.*
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> *Of these companies, one of the most important to watch is Project Kuiper. So far nothing has been launched, but last year 83 launch contracts were signed. This is one of the largest ever commercial procurements of launch services; an ambitious statement from a company that has a zero track record in space. However, that company is Amazon, so financial resources are not the limiting factor that many new entrants have to contend with. It is also necessary to launch half of the 3,236 planned satellites by July 2026, in order to comply with the FCC deadline. In line with that contract, Amazon also acquired a new 172,000 square foot facility in Kirkland, Washington for satellite production. It is intended to produce 1-3 satellites per day. The customer antennas were designed in-house, reportedly, the components cost around US$ 400. Ultimately, the company says it expects to produce 10 million of these. The first two Kuipersat satellites are scheduled to launch during the first quarter of this year.*[12]

[12] Elisabeth Tweedie, "The LEO Satellites Market," Satellite Markets & Research, March 1, 2023, https://satellitemarkets.com/news-analysis/leo-satellites-market.

Other players in this sector include Telesat, OneWeb, Rivada Space Networks, and E-Space.

Military Applications of LEO Constellations

In addition to residential broadband, LEO constellations have obvious military applications, as we can see from Starlink's importance to Ukraine as it defends itself from a savage invasion. LEO constellations have obvious applications in purely military systems such as precision warfare, drone control, logistics, and surveillance. As we said to the Defense Department in its February Request for Information:

> *LEO constellations are showing their value for warfare in Ukraine, where a purely civilian system, Starlink by SpaceX, connects both civilians and warfighters to the Internet and to each other. SpaceX's erratic management also illustrates the pitfalls inherent in relying on a single-source commercial system for military needs.*[13]
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> *Anticipating these problems and opportunities, ARPA has launched the Blackjack program to explore LEO constellations better suited for warfare.*[14] *One significant output of Blackjack is the Arrow constellation created by the Airbus US Space and Defense company:*
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> - *IODA, the In-Orbit Demonstration Service provided by Airbus with the European Space Agency, facilitates in-orbit validation of new satellite concepts and technology demonstration systems to prove and derisk your new mission in LEO.*

[13] Matt Novak, "SpaceX Stops Ukraine's Ability To Use Starlink Internet For Drones," *Forbes*, February 9, 2023, https://www.forbes.com/sites/mattnovak/2023/02/09/spacex-stops-ukraines-ability-to-use-starlink-internet-for-drones/?sh=582fd07d2aba.

[14] "Project Blackjack: DARPA's LEO Satellites Take Off," Airforce Technology, July 23, 2020, https://www.airforce-technology.com/features/project-blackjack-darpas-leo-satellites-take-off/.

> - *In the Blackjack programme, Airbus will provide an architecture demonstration intended to show the military utility of global low-Earth orbit constellations and mesh networks of lower size, weight and cost. DARPA will use the ARROW satellite buses and pair them with sensors and payloads.*[15]

> *It's likely that LEO constellations will play an increasingly important role in future conflicts, but such networks have vulnerabilities. Hence, GEO satellites and ground-based wireless systems following future 3GPP standards and yet-to-be-created military approaches will still be necessary. 3GPP networks will become even more important than they are today.*

We believe that the LEO constellation market suffers from a lack of standardization. This isn't an insurmountable hurdle at the pioneer stage, but problems of cost and reliability generally yield to the efficiency of network standards. Once LEO providers have identified optimal solutions, standards will follow.

Complementary Space-Based Systems

LEO constellations are best seen as complements to GEO, FWA, and 3GPP networks. Two developments to watch in this space are backhaul in the sky and data centers in the sky. Starlink uses a combination of three technologies to bring about direct satellite-to-satellite communication:

> *The Starlink satellites use lasers to communicate with one another. Each satellite is equipped with a laser communication terminal that uses optical inter-satellite links (OISLs) to transmit data between satellites. This means that when two satellites are in line of sight of each other, they can transmit data directly to each other, bypassing*

[15] Airbus, "Arrow Brochure" (Airbus U.S. Space & Defense, Inc, 2020), https://airbusus.com/wp-content/uploads/2021/06/ARROW_Brochure-US-06.28.21.pdf.

> *the need to send data through a ground station. This allows data to be sent quickly and securely between satellites and ensures that the network is redundant and resilient.*
>
> *The Starlink satellites also use radio frequency links to communicate with each other. These links allow the satellites to share data across a wider area and beyond the line of sight of any particular satellite. This means that even if a satellite is blocked from direct communication with another, it can still send and receive data from other satellites in the constellation.*
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> *In addition to the use of lasers and radio frequencies, Starlink satellites also use other technologies to communicate with each other. For example, the satellites are equipped with a Global Positioning System (GPS) receiver to provide information about the satellite's location and altitude. This information is used to coordinate the satellite constellation and ensure that the network is optimized for maximum performance.*[16]

Radio frequencies used for satellite-to-satellite communication can be re-used on Earth without interference. This fact suggests that there are other applications for stacking spectrum rights by altitude and azimuth, a topic deserving of explication.

With inter-satellite communication, the shrinking of logic circuits enabled by Moore's Law progress, and photovoltaic efficiency, it is becoming practical to deploy storage and processing in space. In some instances, this may become a simple add-on to future satellites. The effect of data centers in space is

[16] Marcin Frąckiewicz, "Do Starlink Satellites Communicate with Each Other?," *TS2* (blog), March 5, 2023, https://ts2.space/en/do-starlink-satellites-communicate-with-each-other/.

reduction in the number of space-to-earth-to-space circuits needed to deploy entire applications out of the reach of hostile actors.

Space-based processing and communication is certainly an important research topic.

6. Industrial and Commercial Applications

The RFC's list of "spectrum reliant services and missions" includes this category (exemplified by manufacturing, agriculture, and utilities.) Smart factories, smart utilities, and precision agriculture share in the bounty of IoT and depend on spectrum rights. While farms and factories share some IoT devices – sensors and cameras – and the requirement for Quality of Service-capable networks, they differ insofar as one application is indoor and the other is outdoor. Hence, their propagation issues are distinct.

Agriculture and utilities appear to be exceptional candidates for FWA, LEO constellations, and GPS; manufacturing is more dependent on indoor antennas and is more susceptible to indoor sources of interference such as arc welders and electric motors. Factory automation networks are examples of a new market segment for LTE and LTE-Unlicensed that can be provided either by the factory operator itself or by a traditional carrier. Design services are important in all cases.

CBRS is often lauded as a solution to such use cases, but its primary advantage appears to be licenses limited to particular properties. IIC and duty-cycle sharing with Defense don't appear to offer any particular advantages to the spectrum users in these market segments.

The indoor applications are best served by high frequency bands, while the outdoor applications are better candidates for dynamic uses of mid-band, wherein farms are dotted by antennas installed and trenched by the farmer or a farming-oriented contractor adjust power levels to the proximity of active tractors.

Ongoing collaboration between industrial players and the spectrum rights agency are likely to produce good long term benefits.

One concern in this area is the tendency of lawmakers to simply cloak urban networking desires in agricultural and manufacturing garb.[17] Spectrum regulators should not fall for this ploy.

7. Transportation and Smart Cities

Transportation is a market segment characterized by an acute sense that its needs are special when they generally fall into the category of general-purpose networking. V2V and V2X systems don't share any special properties unknown to mobile broadband or peer-to-peer Wi-Fi. In reality, the automotive industry has proved itself to be less-than-competent at wireless networking in general and security in particular.[18]

These are general-purpose applications for general-purpose wireless networks.

8. Security

In general, wireless networks are more secure than wireline ones. This is because wireless engineers have known from the start that access restriction, authentication, and protection from eavesdropping must be designed into networks and not simply assumed to be solved problems as wireline operators have tended to do. All networks need zero-trust architectures because all networks are meant to provide access to information by particular parties.[19]

Security is not an issue unique to wireless systems and networks.

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[17] Richard Bennett, "Warren's Divisive Plan for Rural America," *High Tech Forum* (blog), August 8, 2019, https://hightechforum.org/warrens-divisive-plan-for-rural-america/.

[18] Richard Bennett, "How to Hack a Car," *High Tech Forum* (blog), July 23, 2015, https://hightechforum.org/how-to-hack-a-car/.

[19] Richard Bennett, "5G and the Zero Trust Security Model," *High Tech Forum* (blog), January 3, 2020, https://hightechforum.org/5g-and-the-zero-trust-security-model/; Richard Bennett, "Who Do You Trust? Zero-Trust Networks," *High Tech Forum* (blog), October 19, 2020, https://hightechforum.org/who-do-you-trust/.

9. Scientific Endeavors

Spectrum rights conflicts between NASA, NOAA, and the wireless industry are headline-grabbing issues but they're old hat to wireless engineers. Weather forecasting and radio astronomy need exclusive access to particular frequencies and inclinations because of the design specifications of the physical universe. The universe's demands are non-negotiable, obviously.[20]

Wireless standards often require exclusion of certain bands occupied of necessity by scientific systems. Despite such carveouts, complaints often persist when human-designed sensors lack filters on their receivers or the ability to distinguish between natural and artificial signals.

This is a case where receiver standards are beneficial. It would be wise for NTIA to continue its productive collaboration with FCC to develop meaningful, discernable, and enforceable receiver standards. We need standards that can be lab-tested. For too long, the discourse on receiver standards has consisted chiefly of handwaving. We need to get beyond the question of the desirability of such standards to the actual formulation.[21]

10. Overcoming Spectrum Deficits

According to Pentagon adviser and former Google CEO Eric Schmidt, China's 5G networks are four times faster than the ones we have in the US.[22] Schmidt fails to support his claim with evidence, but there is a gap. The Speedtest Global Index ranked China in the top 10 of median 5G download speeds in 2021 before falling out of the top 10 in 2022. According to Speedtest, China's three 5G networks deliver an average median download speed 86% higher than the US average median across T-Mobile, Verizon, and

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[20] Richard Bennett, "Will 5G Kill Weather Forecasting?," *High Tech Forum* (blog), June 5, 2019, https://hightechforum.org/will-5g-kill-weather-forecasting/.
[21] Richard Bennett, "Towards a DoD Spectrum Roadmap," policy blog, *High Tech Forum* (blog), February 21, 2023, https://hightechforum.org/towards-a-dod-spectrum-roadmap/.
[22] Graham Allison and Eric Schmidt, "China's 5G Soars Over America's," *Wall Street Journal*, February 16, 2022, sec. Opinion, https://www.wsj.com/articles/chinas-5g-america-streaming-speed-midband-investment-innovation-competition-act-semiconductor-biotech-ai-11645046867.

AT&T.[23] Even though the US leads the world in the deployment of 5G-capable devices while China is outside the top 10, the performance discrepancy is meaningful.[24]

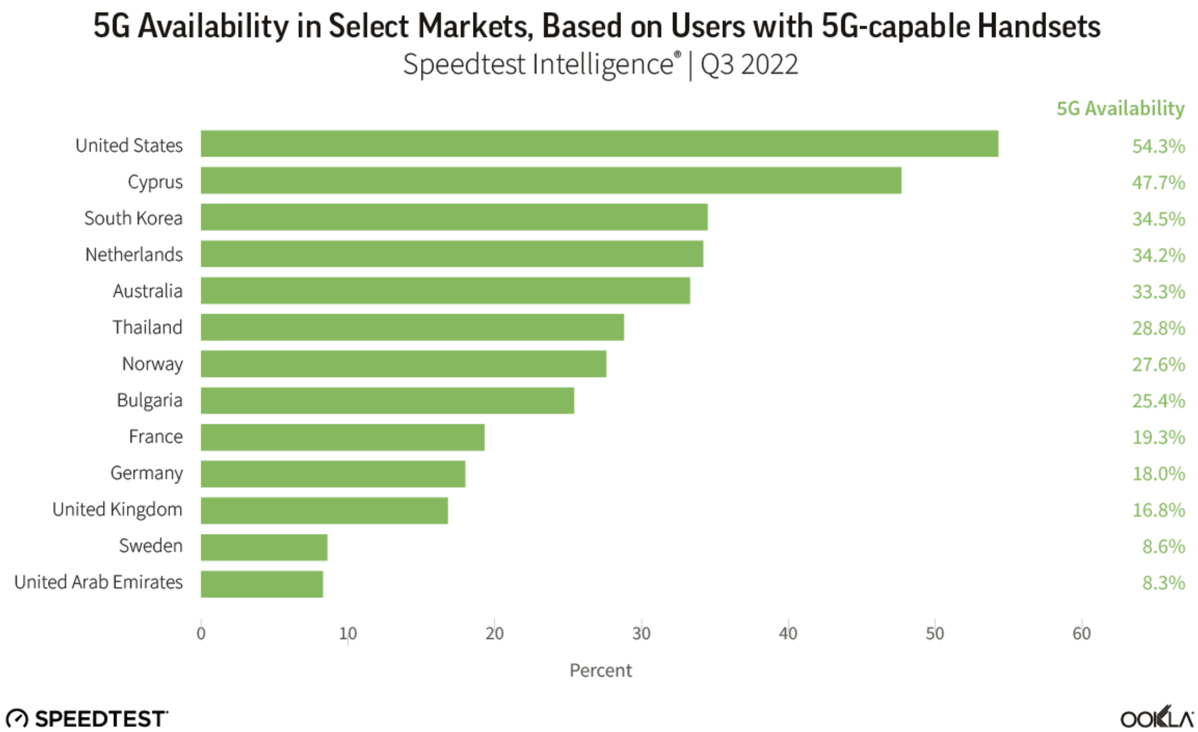

Figure 1 Source: Ookla, https://www.ookla.com/articles/state-of-worldwide-5g-2022[25]

So why does the nation with the highest rate of 5G device ownership and the most 5G coverage have a mediocre download score? After we rule out lack of device ownership, lack of network competition, and lack of network infrastructure, only one factor remains: lack of optimal spectrum allocation policy.

Former House Intelligence Committee Chair Mike Rogers pointed out in 2020 that the Pentagon regards itself as the ultimate arbiter of US spectrum policy, particularly with respect to the 3 GHz sub-bands

[23] "United States's Mobile and Broadband Internet Speeds Q1 2023," Speedtest Global Index, accessed April 17, 2023, https://www.speedtest.net/global-index/united-states#market-analysis; "China's Mobile and Broadband Internet Speeds Q1 2023," Speedtest Global Index, accessed April 17, 2023, https://www.speedtest.net/global-index/china#market-analysis.
[24] "Stable and Expanding: The State of 5G Worldwide in 2022," Ookla, December 18, 2022, https://www.ookla.com/articles/state-of-worldwide-5g-2022.
[25] "Stable and Expanding."

preferred for 5G by most national regulators.[26] In this instance, the Pentagon regarded its training exercises – which, in principle, could have been conducted over practically any frequency band – as more important than 5G's potential boost to the national economy. I needn't remind NTIA of the outcome of this painful exercise.

As long as the Pentagon sees itself as the country's *de facto* spectrum regulator, opportunities for innovation in the wireless space will be constrained by barriers unknown in the rest of the world. Therefore, we have a choice: cave into the Pentagon and accept its self-chosen status of spectrum rights overlord (as Schmidt recommends) or reform the purchasing policies that make the Pentagon irrationally incalcitrant. We propose the second path.[27]

Military systems need to be frequency-agile, such that no platform, capability, or system is hardwired for one particular frequency band. Replacing our 20th century military wireless modules with slightly more advanced tunable ones is bound to pay dividends when the military operates in hostile theaters where regulators are not extensions of our defense establishment. Every system should be capable of operating over a reasonable range of frequencies in order to facilitate reassignment and the "garbage collection" we described above.

We're aware that the Pentagon has gone down this road before, most embarrassingly with the $6B JTRS program.[28] We don't propose anything that ambitious; replace today's hardwired systems with modules that can be unplugged and replaced, as a commercial user would.[29] This approach will enable both

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[26] Mike Rogers, "Block the Pentagon's 5G Power Play," Defense One, November 13, 2020, https://www.defenseone.com/ideas/2020/11/block-pentagons-5g-power-play/169975/.
[27] Richard Bennett, "The End of 'Airplane Mode,'" *Washington Times*, December 14, 2022, https://www.washingtontimes.com/news/2022/dec/14/end-of-airplane-mode/.
[28] Richard Bennett, "The Pentagon's Spectrum Dilemma," *High Tech Forum* (blog), September 25, 2020, https://hightechforum.org/the-pentagons-spectrum-dilemma/.
[29] Sean Gallagher, "How to Blow $6 Billion on a Tech Project," tech blog, *Ars Technica* (blog), June 18, 2012, http://arstechnica.com/information-technology/2012/06/how-to-blow-6-billion-on-a-tech-project/2/.

training, defense, and invasion to be somewhat more feasible. Consider the range of frequency bands in any modern smart phone as the model for the design of each module and behave accordingly.

Out technologists need to have at least as much freedom of access to spectrum as that enjoyed by our allies, rivals, and competitors.

11. Research Initiatives

The RFC asks a number of questions about research spending. We're concerned that the research establishment, led by NSF, DARPA, and PCAST is underperforming, especially with respect to spectrum.[30] Spectrum innovation comes mainly from industry, as we see in the cases of Wi-Fi, 3GPP, DBS, and LEO. To the extent that there is a funding shortfall, it occurs on the applied side. We propose extending and increasing the R&D tax credit to close this gap.

The dearth of meaningful results suggests that there may be altogether too much cronyism in NSF networking programs.

12. Implementation

Conventional DC logic says we create a program today, implement it tomorrow, and end it never. We believe that the RFC should lead to something more like an algorithm for spectrum reassignment than to yet another point solution program solving a problem today that won't matter tomorrow.

The message is to create a spectrum reassignment algorithm that runs continuously. Feed it first with the most ancient spectrum authorizations, especially those that were made by regulatory fiat rather than commercial transactions. Convene regular gatherings of spectrum rights holders to review their progress on upgrades and rights transfers. Where there is no evidence of investment, improvement, or

[30] Richard Bennett, "Eric Schmidt's Spectrum Agenda," *High Tech Forum* (blog), May 5, 2022, https://hightechforum.org/eric-schmidts-spectrum-agenda/.

consideration of alternatives there may be opportunities for improvement. No agency or industry segment should be exempt. Every spectrum allocation has an opportunity cost and an externality, so all should be held to an improvement standard.

Spectrum is inherently dynamic, lending itself to a myriad of applications. Spectrum policy must be just as dynamic, constantly vigilant for better ways to accomplish better tasks with better technology.

The implementation of spectrum policy has been underway for 125 years, if not longer. We're already doing it and we need to do it better.

13. Conclusion

The search for a spectrum strategy leads us, perhaps inevitably, to the creation of an algorithm for spectrum management. When we undertook this journey in 2012 at ITIF we created a list of ten priorities:[31]

1. Sharing: Prefer assignments that serve multiple users, as commercial networks do, over those for single uses.
2. Application Flexibility: Prefer assignments that support a variety of applications over those that support a single application.
3. Dynamic Capacity Assignment: Prefer networks that allow capacity to be adjusted on demand to those that allocate capacity statically.
4. Technology Upgrade Flexibility: Permit technology upgrade without permission.
5. Aggregation Efficiency: Prefer large allocations over small ones to minimize guardband losses.

[31] Richard Bennett, "Powering the Mobile Revolution: Principles of Spectrum Allocation" (Washington, DC: Information Technology and Innovation Foundation, July 31, 2012), https://itif.org/publications/2012/07/31/powering-mobile-revolution-principles-spectrum-allocation/.

6. Appropriate Facilities-Based Competition: Seek an ideal number of networks, a number that is likely to be larger than two and smaller than six in most instances.
7. High-Performance Receivers: Favor systems of high-performance receivers over those that can't tolerate common sources of RF noise.
8. All Relevant Dimensions: Allocate "patches" of spectrum by frequency, power level, place, transmission direction, beam spread, modulation, coding, and time.
9. Promotion of New Technologies: Use rules modification rather than exclusive allocation as a means of enabling the next generation of spectrum technologies.
10. Maximize Redeployment Opportunities: When upgrades to existing systems free up spectrum for new ones, as was the case in the DTV transition, require the upgrade.

We revised the list the following year for TPRC after a number of discussions and reviews, to wit:[32]

> *A more rational system of spectrum assignment would respect the technical principles that are evident in the operation of actual high-demand, high-performance, and high-efficiency wireless networks today and in the near future. In brief, these principles are:*

1. **Upgrade and Repack:** When upgrades to existing systems will free up spectrum for additional uses, as was the case in the DTV transition, require the upgrade and reassign the excess.
2. **Strive for Sharing:** Prefer assignments that serve multiple users, as general-purpose commercial networks do, over those for single users, as some government systems do.
3. **Reward Application Flexibility:** Prefer assignments that support a variety of applications over those that support a single application.

[32] Bennett, "Technical Principles of Spectrum Allocation."

4. **Optimize Dynamic Capacity Assignment:** Prefer networks that allow capacity to be adjusted on demand to those that allocate capacity statically.
5. **Permit Technology Upgrade Flexibility:** Allow technology upgrades without permission and with a minimum of coordination.
6. **Recognize Aggregation Efficiency:** Prefer large allocations over small ones to minimize guard band losses.
7. **Create Facilities-Based Competition:** Allocate spectrum to multiple systems of the same general kind in order to create market competition and technical resiliency.
8. **Reward High-Performance Receivers:** Favor systems of high-performance receivers over those that can't tolerate common sources of RF noise and penalize low-performance receivers.
9. **Allocate in All Relevant Dimensions:** Allocate "patches" of spectrum by frequency, power level, place, transmission direction, beam spread, modulation, coding, and time.
10. **Promote New Technologies:** Use rules modification and market transactions rather than exclusive allocation as a means of enabling future generations of spectrum technologies.

These allocation principles flow from a particular vision of the empirical knowledge about radio frequency spectrum, the current state of the art in radio engineering, and the likely timeline of new developments in radio engineering.

The original lists suffer from omissions and shortcomings; we failed to mention that spectrum controversies are chiefly about the equipment that uses spectrum rather than spectrum technology itself. The Pentagon, for example, is loath to surrender rights in the 3450-3550 MHz band because it has purchased radar that only works on this band. It doesn't care about the band; it cares about the application.

We also didn't consider scientific spectrum needs because we considered them to be self-evident. We also over-emphasized mobile networks, and we didn't consider FWA, LEO, and many other advanced technologies. The list – which is simply elements of an algorithm – is best considered in light of current knowledge. Like everything in tech, it's subject to change.

We would like to suggest NTIA opens a further RFC on the elements of a spectrum assignment checklist. Understanding that the Administration needs an algorithm rather than a strategy may be a minor point, but it adds focus to the mission.

Technology policy, like technology itself, is always in a state of friction with respect to legal systems that emphasize tradition and precedent over change and progress. The enduring principle is best understood as the agreement that spectrum policy needs to be guided by a discernable algorithm. Once we accept that, the process of fleshing out the algorithm is a relatively simple task.

We appreciate NTIA's approach to this issue and the opportunity to offer our comments. The nation is already better on account of this inquiry and we're happy to have contributed.

Feel free to contact us for further clarification.

Sincerely,

[signed] Richard Bennett

President, High Tech Forum

Lakewood, Colorado

April 17, 2023