Spectrum Economics and Market Tools

Curriculum for the National Radio Astronomy Observatory, National Science Foundation

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1 Syllabus

This course examines spectrum economics and market tools such as auctions, secondary markets, unlicensed bands, and experimental licenses. Course material will cover the foundations of spectrum valuation, allocation methods, and economic concepts. This undergraduate course should assist in improvement of your analytical skills, particularly with regards to current advances in wireless technology.

Course Description:
The course will address the following topics: licensed vs. unlicensed spectrum; auctions and government allocations; policy challenges; and other topics in spectrum economics. We will also discuss current events in spectrum policy.

Class Format and Expectations:
The course is primarily a lecture course, with a student presentation component. Students will also give five-minute presentations on a current event related to radio spectrum economics. Presentations can extend upon any of the "Headlines" sections in the course syllabus, or other technology event in the readings. Detailed instructions on expectations for the student presentations will be provided in a separate handout. Students can sign-up first come, first serve, for their preferred week, two students per week.

Students will also write a short research paper on one of the spectrum auctions listed in the handout. Papers should include an explanation of one of these auctions with U.S. data from the U.S. Federal Communications Commission. Detailed instructions on expectations for the paper are provided below.

Course Requirements and Grading:
Scores on the research paper, presentation, and final exam will determine final grades for this course module. The final exam will cover material from the lecture material and readings.

Schedule:

Lecture	Topics	Assignments
1	Introduction to Spectrum Economics and Market Tools: Spectrum in the News; Nobel Prize Winners	
2	Spectrum Economics: History of Auctions; Valuation Methods and Factors	
3	Market Tools Part A: Reallocation Challenges and Secondary Markets	*Paper Due*
4	Market Tools Part B: Incentive Auctions and Other Tools	*Student Presentations (5 minutes each)*
5	New Developments: Satellite Constellations, Local Governance	*Student Presentations (5 minutes each)*
6	Conclusion	*Final Exam*

Paper Assignment:
Students will write a ten-page paper describing one U.S. spectrum auction since 1994. The paper should be based on information from news articles and the U.S. Federal Communications Commission website.

The objective of this assignment is to understand how the U.S. holds spectrum auctions. First, the FCC announces that an auction will take place. Second, a process is established to create rules for the auction. Third, the auction is conducted and bidders bid for the spectrum licenses. Last, the results are announced and bidders have buildout requirements.

Step 1. Students should select one auction from the auctions section of the FCC website. Each student should select a different auction and sign-up on the online schedule. Interesting papers will likely address new technologies such as "5G" or "television band" or "C-Band" or "satellite" band.

Step 2. In a few paragraphs, explain the frequency band that was selected for auction. List any technical constraints on the usage of the band and the terms of the license. Briefly describe features of the auction based on information posted to the FCC auction page.

Step 3. Include an Introduction, Background, Auction Rules, Auction Results, International Comparisons, Conclusion, and References sections. Provide background information on your particular spectrum auction, perhaps with news headlines on the importance of that auction to the economy. If you can find out how the auction impacts new innovation, that is a very important question, but may take time to research. Provide international comparisons if any other countries have conducted auctions on that same frequency band. Find appropriate economics and financial news sources and make sure to discuss with citations. Consider whether other countries have had difficulty in auctioning this band.

Student Presentation Instructions:
Students will give five-minute presentations on a topic related to course material, cited in the readings or with instructor permission. Presentations can extend upon any of the "Headlines" sections in the syllabus, another event cited in the readings, or a current event. Students should sign-up first come, first serve, on an online schedule for their preferred week and should try to select different topics. Grades will be based on an average score of 1 (low) to 5 (high) for these criteria:

1. Powerpoint slides with the headline story, from WSJ, FT, etc.
2. Explanation of the headline story to the class
3. Background information on the spectrum news event
4. Background information on frequency band at issue
5. Current state of the situation since the headline

Students should style their presentations as an objective briefing to their classmates on a particular spectrum dispute or other international spectrum event. Students should aim for clarity, simplicity, but also depth of understanding.

2 Introduction to Spectrum Economics and Market Tools

An introduction to spectrum economics and market tools begins with a discussion of current events and news headlines. In this introduction, we review a few recent events through news headlines that provide a spotlight on important features of spectrum economics and market tools of interest.

Next, students of spectrum economics may find that an accessible way to learn about the more challenging areas of policy development is to first start with an overview of notable economists who have been recognized for contributions and advances in the understanding of spectrum policy. Innovations such as auctions, secondary markets, unlicensed bands, and experimental licenses have been implemented in part due to the work of these scholars and researchers.

2.1 Spectrum in the News

2.1.1 C-Band Auction and Satellite Relocations

The Federal Communications Commission held a spectrum auction for "C-Band" spectrum that amounted to $81.11 billion in auction proceeds, with $45.45 billion from Verizon's Cellco Partnership, $23.41 billion from AT&T, and $9.34 billion from T-Mobile in February 2021.[1]


CNBC

TECH

Companies have bid $81 billion for the airwaves to build 5G, and winners will be revealed soon

PUBLISHED SUN, JAN 31 2021·9:30 AM EST

Kif Leswing
@KIFLESWING

WATCH LIVE

Figure 1. Headline on C-Band Auction[2]

The C-Band auction, or Auction 107, had an average price of $0.94 per MHz/pop for the parcels of spectrum rights across the United States.[3] The C-Band is a spectrum band from 3.7 GHz to 4.2 GHz which is considered mid-band 5G spectrum which is used around the world in at least 58 markets for 5G service.[4]

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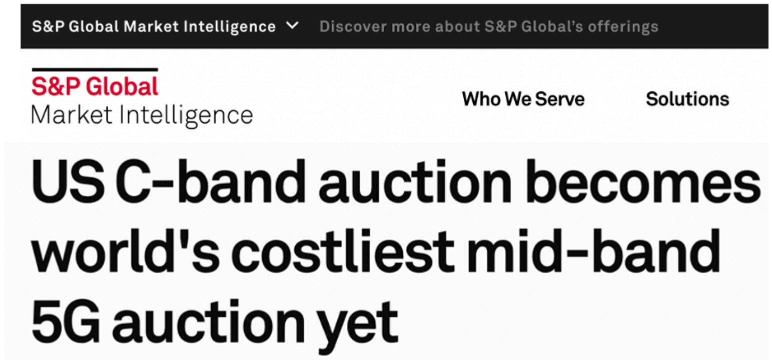
[1] Julber Osio, "U.S. C-Band Auction Becomes World's Costliest Mid-Band 5G Auction Yet," S&P Global Market Intelligence, Apr. 22, 2021, https://www.spglobal.com/marketintelligence/en/news-insights/research/us-c-band-auction-becomes-worlds-costliest-mid-band-5g-auction-yet.

[2] Kif Leswing, "Companies Have Bid $81 Billion for the Airwaves to Build 5G, and Winners Will Be Revealed Soon," CNBC, Jan. 31, 2021, https://www.cnbc.com/2021/01/31/5g-spectrum-auction-bids-total-80point9-billion-winners-revealed-soon.html.

[3] Julber Osio, "U.S. C-Band Auction Becomes World's Costliest Mid-Band 5G Auction Yet," S&P Global Market Intelligence, Apr. 22, 2021, https://www.spglobal.com/marketintelligence/en/news-insights/research/us-c-band-auction-becomes-worlds-costliest-mid-band-5g-auction-yet.

[4] *Id.*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US C-band auction becomes world's costliest mid-band 5G auction yet

Figure 2. Headline on C-Band Auction[5]

The spectrum is low enough on the frequency dial for communications to travel long distances with the benefit of being wide enough for download speeds.[6] The auction was well subscribed, with 97 rounds of bidding, and total proceeds higher than the range that was anticipated from prior auctions. The auction design had a first phase and second phase, where the bidders bid how much spectrum that would want followed by specific blocks and regions of assignments.[7]

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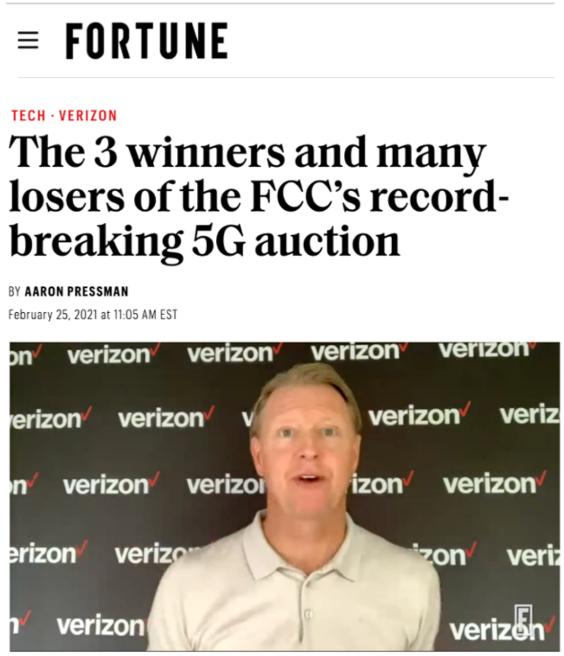
[5] Julber Osio, "U.S. C-Band Auction Becomes World's Costliest Mid-Band 5G Auction Yet," S&P Global Market Intelligence, Apr. 22, 2021, https://www.spglobal.com/marketintelligence/en/news-insights/research/us-c-band-auction-becomes-worlds-costliest-mid-band-5g-auction-yet.
[6] Aaron Pressman, "The 3 Winners and Many Losers of the FCC's Record-Breaking 5G Auction," Fortune, Feb. 25, 2021, https://fortune.com/2021/02/25/fcc-5g-auction-t-mobile-version-att/.
[7] *Id.*



FORTUNE

TECH · VERIZON

The 3 winners and many losers of the FCC's record-breaking 5G auction

BY AARON PRESSMAN

February 25, 2021 at 11:05 AM EST

Figure 3. Headline on C-Band Auction[8]

The C-Band auction also includes a relocation component where satellite operators are compensated for clearing out of the bands.[9] In an FCC proceeding prior to the auction, satellite operators negotiated and agreed to clear out a portion of the C-Band in exchange for monetary compensation of $13 billion. To relocate satellite operations, Intelsat and SES ordered 13 new satellites in 2020 and Eutelsat and Telesat moved operations to existing fleets.[10]

[8] Aaron Pressman, "The 3 Winners and Many Losers of the FCC's Record-Breaking 5G Auction," Fortune, Feb. 25, 2021, https://fortune.com/2021/02/25/fcc-5g-auction-t-mobile-version-att/.

[9] Debra Werner, "FCC C-Band Auction Raised Nearly $81 Billion So Far," Space News, Jan. 15, 2021, https://spacenews.com/c-band-raises-81-billion/.

[10] *Id.*

Figure 4. Headline on Satellite Talks Prior to C-Band Auction[11]

The satellite industry negotiated the price for its 200 MHz of spectrum in a spectrum repurposing plan that won out over alternative proposals put forth in the rulemaking proceeding.[12] The valuation process of determining that price was not an easy task. "'Spectrum values are very badly understood by equity investors,' Fred Turpin, JP Morgan's global head of media and communications, said Sept. 9 at the World Satellite Business Week conference here."[13] The determination of a price for the satellite spectrum requires investors to "understand a number of unfamiliar but nonetheless influential variables, ranging from specific regulatory policies to the spectrum clearing process and the impact of the timing of an FCC decision."[14]

In determining the price of the satellite spectrum, the C-Band Alliance, a trade group that includes the satellite operators with spectrum licenses, put forth its own estimates of the value of the spectrum, while other trade groups like ACA Connects, a trade group of cable and internet providers put out its own. Wall Street analysts and other telecom executives put forth their own estimates as well. An analyst with Jefferies Financial Group estimated $3.3 billion for Intelsat and SES each with "time discounted and post all clearing costs,"[15] while ACA Connected estimated $60 billion for the full 500 MHz if it were to come onto the market.[16] A television broadcast executive that leases capacity from the satellite operators estimated $34 billion in compensatory value from the spectrum.[17]

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[11] Caleb Henry, "Satellite C-Band Is Worth Billions, But How Many?" Space News, Sept. 16, 2019, https://spacenews.com/satellite-c-band-is-worth-billions-but-how-many/.
[12] *Id.*
[13] *Id.*
[14] *Id.*
[15] *Id.*
[16] *Id.*
[17] *Id.*

Figure 5. Headline on Defense Department Review of the C-Band[18]

The satellite industry was not the only other industry that had to be involved in C-Band clearing. There is also controversy in the C-Band with the aviation industry. With the rolling out 5G in October 2021, the Federal Aviation Administration released a bulletin with concerns from the aviation industry about radar altimeters experiencing interference from 5G towers around airports. The defense sector was also asked to look into C-Band impacts on its mid-band operations.[19] Leaders from the Department of Defense, Department of Homeland Security, and various task forces were called upon by the FAA to discuss findings and impacts from their reports on 5G interference.[20] The next section describes the news headlines related to the aviation industry in more detail.

2.1.2 FAA and 5G Interference Dispute

The White House became involved to mediate a dispute between the wireless and aviation industries about harmful interference between new 5G wireless towers and radar altimeters in airplanes. In the winter of 2021 and through spring and summer of 2022, lobbying and letters were flying back and forth between the agencies and industry representatives.[21]

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[18] Valerie Insinna and Aaron Mehta, "The Military is Scrambling to Understand the Aviation Crash Risk from a New 5G Sale," Defense News, Dec. 21, 2020, https://www.defensenews.com/2020/12/21/the-military-is-scrambling-to-understand-the-aviation-crash-risk-from-a-new-5g-sale/.

[19] Valerie Insinna and Aaron Mehta, "The Military is Scrambling to Understand the Aviation Crash Risk from a New 5G Sale," Defense News, Dec. 21, 2020, https://www.defensenews.com/2020/12/21/the-military-is-scrambling-to-understand-the-aviation-crash-risk-from-a-new-5g-sale/.

[20] *Id.*

[21] Peter Elkind, "Inside the Government Fiasco that Nearly Closed the U.S. Air System," ProPublica, May 25, 2022, https://www.propublica.org/article/fcc-faa-5g-planes-trump-biden.

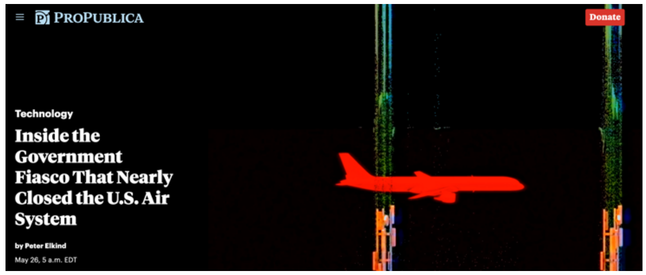

Figure 6. Headline on FAA and 5G Interference Dispute[22]

Verizon and AT&T agreed to delay rollout for 1 month to and lower power levels near runways.[23] The Department of Transportation also got involved alongside the Federal Aviation Administration, Federal Communications Commission, and National Telecommunications and Information Administration in the Department of Commerce to sort through the conflict between spectrum licensees.

[22] Peter Elkind, "Inside the Government Fiasco that Nearly Closed the U.S. Air System," ProPublica, May 25, 2022, https://www.propublica.org/article/fcc-faa-5g-planes-trump-biden.
[23] *Id.*


POLITICO

TECHNOLOGY

How Washington flew into a 5G mess

The saga of squabbling agencies, warnings of plane crashes and billions of dollars in spectrum has been years in the making.

Passenger flights land and take off at Reagan Washington National Airport in Arlington, Va., across the Potomac River from Washington, D.C., on Wednesday. | J. Scott Applewhite/AP Photo

By JOHN HENDEL
01/19/2022 07:10 PM EST

Figure 7. Headline on Conflict between Federal Agencies in Washington D.C.[24]

Flight cancellations and haggling about the scope of 5G rollout around specific airports occurred as short-term solutions, but a long-term solution has not yet been determined.[25] The airplanes will need to be retrofitted with new equipment to replace radar altimeters that are not able to filter 5G transmissions.[26]

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[24] John Hendel, "How Washington Flew into a 5G Mess," Politico, Jan. 19, 2022, https://www.politico.com/news/2022/01/19/5g-flights-spectrum-mess-washington-527425.

[25] Peter Elkind, "Inside the Government Fiasco that Nearly Closed the U.S. Air System," ProPublica, May 25, 2022, https://www.propublica.org/article/fcc-faa-5g-planes-trump-biden.

[26] David Shepardson, "FAA Wants U.S. Airlines to Retrofit, Replace Radio Altimeters," Reuters, May 3, 2022, https://www.reuters.com/business/aerospace-defense/faa-wants-us-airlines-retrofit-replace-radio-altimeters-2022-05-03/.

REUTERS

World Business Legal Markets Breakingviews Technology Investigations More

Aerospace & Defense

3 minute read · May 3, 2022 7:57 PM EDT · Last Updated 5 months ago

FAA wants U.S. airlines to retrofit, replace radio altimeters

By David Shepardson

A commercial aircraft approaches to land at San Diego International Airport as U.S. telecom companies, airlines and the FAA continue to discuss the potential impact of 5G wireless services on aircraft electronics in San Diego, California, U.S., January 6, 2022. REUTERS/Mike Blake

Figure 8. Headline on Replacement of Radar Altimeters[27]

One possible solution is to place the burden on the owners of legacy receivers to upgrade their equipment, rather than the new technology. Because interference is such a probabilistic occurrence, for example, a 5% chance of out-of-band emissions on certain weather days, the bright line rules for radio borders are far from bright or observable. The Federal Communications Commission reopened an inquiry into how it could place standards on receiver quality,[28] but the probabilistic nature of interference events will continue to be a physical phenomenon that makes bright line rules difficult to define ex ante and costly to enforce ex post.

[27] Peter Elkind, "Inside the Government Fiasco that Nearly Closed the U.S. Air System," ProPublica, May 25, 2022, https://www.propublica.org/article/fcc-faa-5g-planes-trump-biden.

[28] Jon Brodkin, "FCC Considers Crackdown on Bad Wireless Receivers After 5G/Altimeter Debacle," Ars Technica, March 3, 2022, https://arstechnica.com/tech-policy/2022/03/fcc-considers-crackdown-on-bad-wireless-receivers-after-5g-altimeter-debacle/.

ars TECHNICA

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STAY IN YOUR LANE —

FCC considers crackdown on bad wireless receivers after 5G/altimeter debacle

Receivers that ignore spectrum boundaries are a problem for new wireless services.

JON BRODKIN - 3/3/2022, 3:19 PM

Figure 9. Headline on FCC's Receiver Standards Proceeding[29]

Clarity on the scope of each of the spectrum licenses and burden of mitigating or avoiding interference has been the request of the wireless and aviation industries.[30] When a new technology enters the airspace, the neighboring users may need to upgrade its technology to accommodate more airwave traffic.

AINonline

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AIR TRANSPORT

Airlines Clamor for Clarity on Altimeter Upgrades for 5G

by Gregory Polek - August 12, 2022, 7:10 AM

Cellular providers plan to increase 5G signals to full power by next July. (Photo: Pixabay)

Figure 10. Headline on the Need for Clarity on Interference Disputes[31]

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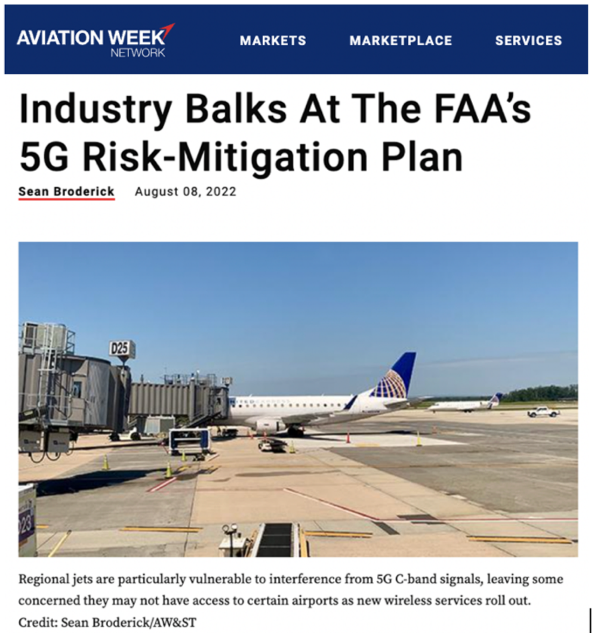
[29] Jon Brodkin, "FCC Considers Crackdown on Bad Wireless Receivers After 5G/Altimeter Debacle," Ars Technica, March 3, 2022, https://arstechnica.com/tech-policy/2022/03/fcc-considers-crackdown-on-bad-wireless-receivers-after-5g-altimeter-debacle/.

[30] Gregory Polek, "Airlines Clamor for Clarity on Altimeter Upgrades for 5G," AINOnline, Aug. 12, 2022, https://www.ainonline.com/aviation-news/air-transport/2022-08-12/airlines-clamor-clarity-altimeter-upgrades-5g.

[31] Gregory Polek, "Airlines Clamor for Clarity on Altimeter Upgrades for 5G," AINOnline, Aug. 12, 2022, https://www.ainonline.com/aviation-news/air-transport/2022-08-12/airlines-clamor-clarity-altimeter-upgrades-5g.

The institutional wrinkle here, however, is that, at the time of the C-Band auction and decades of research and development, and notice and comment, and rulemaking where the aviation industry could have raised harmful interference concerns, they did not. The process and escalation of the interference dispute is a study in political economy and reforms are actively being considered to better anticipate the need for engineering studies that encompass relevant concerns in a timely fashion.


AVIATION WEEK NETWORK MARKETS MARKETPLACE SERVICES

Industry Balks At The FAA's 5G Risk-Mitigation Plan

Sean Broderick August 08, 2022

Regional jets are particularly vulnerable to interference from 5G C-band signals, leaving some concerned they may not have access to certain airports as new wireless services roll out.
Credit: Sean Broderick/AW&ST

Figure 11. Headline on Ongoing Negotiations on 5G Risk Mitigation[32]

The aviation industry and wireless industry are still determining how to resolve the interference concerns, while the federal agencies that are supposed to mediate and determine spectrum allocations, are constrained in how much they can do under administrative law in the Executive Branch and statutory authority granted by Congress.

2.1.3 Starlink and 5G in the 12 GHz Band

The 12 GHz band, also known as the "Ku-band," has been in the news recently with proposals

[32] Gregory Polek, "Airlines Clamor for Clarity on Altimeter Upgrades for 5G," AINOnline, Aug. 12, 2022, https://www.ainonline.com/aviation-news/air-transport/2022-08-12/airlines-clamor-clarity-altimeter-upgrades-5g.


SPACENEWS

SpaceX says 5G plan could disrupt Starlink more than previously thought

by Jason Rainbow — October 5, 2022

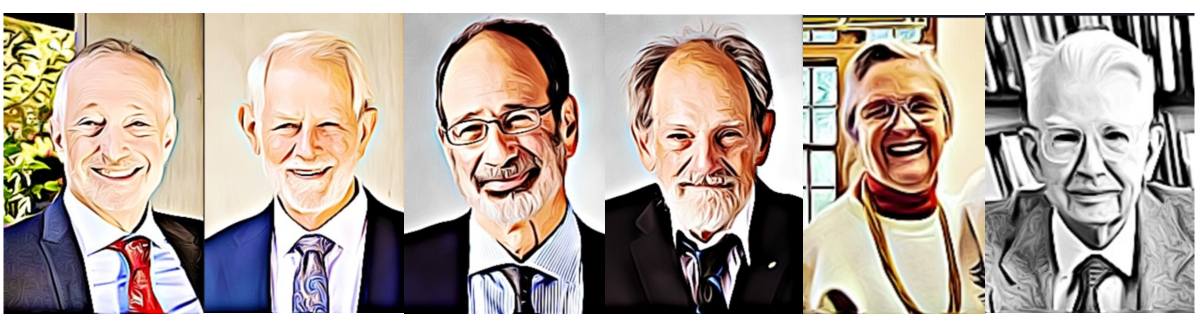
An antenna for Starlink, which says its users would also be subjected to harmful interference in the U.S. if a plan to deploy 5G in the 12 GHz band goes ahead. Credit: Starlink

Figure 12. Headline on Starlink and 5G in the 12 GHz Band[33]

2.2 Nobel Prizes in Economics Related to Spectrum Auctions

The Nobel Prize in Economics has been awarded several times to economists who have made significant contributions and advances to the understanding of auctions, matching markets, economic governance, and transaction costs and property rights. The effort of these professors to study the economics of spectrum has been the groundwork that has enabled the acceptance of market mechanisms to allocate spectrum rights around the world.

In this section, we review prizes awarded to Paul Milgrom and Robert B. Wilson in 2020, Alvin Roth and Lloyd S. Shapley in 2012, Elinor Ostrom in 2009, and Ronald Coase in 1991.



[33] Jason Rainbow, "SpaceX Says 5G Plan Could Disrupt Starlink More Than Previously Thought," Space News, Oct. 5, 2022, https://spacenews.com/spacex-says-5g-plan-could-disrupt-starlink-more-than-previously-thought/ .

Figure 13. Nobel Prize Economists with Contributions to Spectrum Economics[34]

2.2.1 Paul Milgrom and Robert B. Wilson (2020)

Paul Milgrom and Robert B. Wilson were awarded the Nobel Prize in Economics in October 2020 "for improvements to auction theory and inventions of new auction formats."[35]

Figure 14. Paul Milgrom[36]

Paul Milgrom[37] and Robert Wilson applied game theory to develop new auction types, and studied how people behave in auctions.[38] In his own words, he describes his contribution to auctions and economic theory:

> My auction research began as part of the work originated by Bob Wilson, who wanted to understand where prices came from. Economic analysis before that time focused on so-called "market-clearing" prices, a theory that posits that prices are determined through competition among buyers and sellers when the supply of something is equal to the demand and there are no leftovers. But what is the nature of that competition and how does it affect prices and allocations of goods? We studied the competition in auctions to begin to answer that question, but it led to lots more questions.
>
> One early puzzle was how bidders would respond to the "winner's curse," in which the bidder who wins an auction is more likely to be someone who has overestimated the value of the item they won and is thereby "cursed" by having paid too much.

[34] Photo Credit: https://www.nobelprize.org, © The Nobel Foundation. Photo: U. Montan.
[35] Press Release: The Prize in Economic Sciences 2020, The Nobel Prize, October 12, 2020, https://www.nobelprize.org/prizes/economic-sciences/2020/press-release/.
[36] Source: https://en.wikipedia.org/wiki/Paul_Milgrom
[37] Paul R. Milgrom – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 29 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/2020/milgrom/biographical/; https://en.wikipedia.org/wiki/Paul_Milgrom.
[38] Jason Stoughton, "'The Greatest Auction Ever' – Q&A with Paul Milgrom, 2020 Nobel Laureate," Science Matters, National Science Foundation, Oct. 23, 2020, https://beta.nsf.gov/science-matters/greatest-auction-ever-qa-paul-milgrom-2020-nobel.

> Related to the winner's curse, another of my models studied how information comes to be incorporated in security prices, such as stocks and bonds, in a "specialist" market. Such a market is created by intermediaries like financial institutions who both buy and sell a security and thereby "make" a market for it. These "market makers" compete to serve customers, who want to buy and sell at different times, always quoting a higher price to buyers than they offer to sellers. On some of its trades, the market maker suffers a winner's curse: It loses money on average to privately informed buyers when the security is underpriced and to sellers when it is overpriced, but it covers those losses from profits earned from uninformed traders.
>
> We showed that the prices at which transactions actually take place come to reflect the information of the informed traders, explaining the puzzle of how privately held information is eventually reflected in competitive prices. As my collaborators studied this and other examples, we realized that auction rules could have important effects on the auctioneers' revenues, the efficiency with which goods are allocated, and the kinds of strategies available to bidders. And there was an opening for improved designs.
>
> Still, more work was needed before we could suggest valuable new designs for some real problems. Mechanism design theory — dealing with how institutions can best set up methods and incentives to cope with individual self-interest and incomplete information — had mostly focused on solutions in which bidders bid just once, offering one price for any combination of goods that they may win.
>
> But, that approach can pose daunting practical challenges for both the bidders and the auctioneer. Imagine an auction of 100 separate goods, where there are 2 to the one-hundredth power possible combinations of goods to bid on. Even if the buyers could make such bids, computing the highest price the seller could get from combining bids would be virtually impossible! It's what computer scientists call an "NP-hard" problem. For those kinds of applications, my collaborators and I worked on practical mechanisms that call for revealing just enough information in an auction system and doing computations that are actually feasible.[39]

Professor Milgrom recounts in his biographical essay for the Nobel Prize committee the personal influences that shaped his economics scholarship,

> Unsure about what to do next, I asked an advanced graduate student, Bengt Holmström, who told me: "The secret is to get Bob Wilson to be your dissertation adviser." So, I signed up for Wilson's class in "Multi-person Decision Theory," which involved reading new research in economic theory. The readings included one paper of Wilson's, about auctions. Hoping to get Wilson's attention, I wrote a term paper extending Wilson's work. He was excited by the results, telling me that the paper could be the main chapter of my doctoral dissertation. Holmström became a lifelong friend, colleague, and co-author, as well as a Laureate in economic sciences in 2012. Wilson, now a friend and neighbor, became my co-Laureate in 2020.[40]

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[39] *Id.*

[40] Paul R. Milgrom – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 29 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/2020/milgrom/biographical/.

Figure 15. Robert Wilson[41]

Robert B. Wilson[42] laid the groundwork for the game theory applications in auctions in his three papers in the 1960s and 1970s. As described in a news article on the Nobel prize award,

> In three influential papers in the 1960s and 1970s, Wilson showed how rational auction bidders can overestimate the value of an item they are bidding on. This was the first auction theory framework to look at a "common value" scenario where the bidders collectively hold the same value for the object being auctioned, but without full information of its value. In these papers, Wilson examined the "winner's curse," which is the tendency for the winning bid to exceed the true worth of the item. The winner's curse can also lead cautious bidders to undervalue an item – to avoid the curse – and becomes especially problematic when bidders have different private information about an item's true value.[43]

Professor Wilson, with Professor Milgrom, then went on to develop a new auction format, called the Simultaneous Multiple Round Auction:

> To address this issue, Milgrom and Wilson invented a new auction format, called Simultaneous Multiple Round Auction (SMRA). In these auctions, all biddable items are offered simultaneously and bidders can bid on any portion of the items. The bids start low, in order to avoid the winner's curse, and the auction ends when no bids are placed in a round. The first SMRA auction in 1994 sold 10 licenses over 47 rounds, fetching $617 million.
>
> Many governments around the world adopted SMRA auctions for their own purposes and further refinements have resulted in additional new auction formats. Among these new formats was the incentive auction, which Milgrom took the lead in developing in order to help the government repurpose radio spectrum from television to wireless broadband. The incentive auction has two parts: a reverse auction to procure the spectrum-usage rights and a forward auction to sell that spectrum. The incentive auction design was the foundation of the largest-ever spectrum auction in 2016, which resulted in the sale of 70 MHz of wireless internet licenses for $19.8 billion.[44]

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[41] Robert B. Wilson, Photo Gallery, The Nobel Prize, https://www.nobelprize.org/prizes/economic-sciences/2020/wilson/photo-gallery/.
[42] Robert B. Wilson – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 29 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/2020/wilson/biographical/; Robert B. Wilson, https://en.wikipedia.org/wiki/Robert_B._Wilson.
[43] Taylor Kubota, "The Economic Science Behind Wilson's and Milgrom's Nobel Prize," Stanford News, Oct. 12, 2020, https://news.stanford.edu/2020/10/12/economic-science-behind-wilsons-milgroms-nobel-prize/.
[44] *Id.*

On his background that led to his interest in economics, Professor Wilson describes his childhood in Nebraska in his biographical essay for the Nobel Prize committee,

> We mail-ordered pigeons (white kings, Russian trumpeters, pygmy pouters) that we raised with pride, and won prizes at the York County Fair. I raised angora rabbits to shear for wool, a ferret that eventually bit our mother, and families of orphaned opossums and owlets; and once I brought home a skunk that I mistakenly trapped while trying to catch mink, but alas it sprayed me thoroughly. We lived a carefree existence, rather like Tom Sawyer and Huck Finn. I always had a job. From age 7, I delivered newspapers (even in blizzards), mowed grass, shoveled snow, bagged groceries, swept businesses' walkways, and for two summers toiled in a bottling plant. One summer I managed the golfers' clubhouse for my grandpa Leonard who had the concession. I excelled in football, basketball, and track until my right leg broke in a football game, but I continued basketball and golf to win a letter. The local schools were good, and I was always at the top of my class.[45]

He continued working through university at Harvard,

> I worked as library page, sold milk and donuts in the residence halls, and entered data at the computer center; and in summers, I sold ice cream and then insurance before real jobs as engineer on the Regulus missile and then actuarial trainee.[46]

His tenure at Stanford for 56 years, of which 52 years were spent teaching Multiperson Decision Theory, has been notable for the legacy of scholars that have studied with him, including Nobel Prize winners Alvin Roth, Bengt Holmstrom, and Paul Milgrom. His work on auctions started with an interest in offshore exploration leases for oil companies and the U.S. Department of Interior. This interest in auctions evolved alongside his more consequential work in game theory as he describes,

> My research in economics can be summarized by saying that I studied the effects of private information in markets, especially auctions, at a time when this was novel. My lasting contributions, neither about auctions, were co-authored with David Kreps and Srihari Govindan, on whom I relied for their superior skills and deep insights.[47]

Paul Milgrom and Robert B. Wilson shared the Nobel Prize for their work that contributed to what we know today about auction theory.

[45] Robert B. Wilson – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 29 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/2020/wilson/biographical/.
[46] *Id.*
[47] *Id.*

Figure 16. Paul Milgrom and Robert Wilson[48]

Figure 17. Robert Wilson[49] and Paul Milgrom

2.2.2 Alvin Roth and Lloyd S. Shapley (2012)

Alvin Roth and Lloyd S. Shapley were awarded the Nobel Prize in Economics in October 2012 "for the theory of stable allocations and the practice of market design."[50]

[48] Interview with Robert B. Wilson, February 2021, The Nobel Prize, https://www.nobelprize.org/prizes/economic-sciences/2020/wilson/167537-robert-wilson-interview/.
[49] Paul Hannon and David Harrison, Nobel Prize in Economic Sciences Is Awarded to U.S. Academics, Oct. 12, 2020, Wall St. J., https://www.wsj.com/articles/nobel-prize-in-economic-sciences-is-awarded-to-u-s-academics-for-invention-of-new-auction-formats-11602496403.
[50] Press Release: The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 2012, October 15, 2012,
https://www.nobelprize.org/prizes/economic-sciences/2012/press-release/.

Figure 18. Alvin Roth[51]

Alvin Roth[52] is an expert at the art of designing markets, which include auctions of radio spectrum.[53] He helped create a new field of economics known as "market design," which involves understanding the different features of different markets in order to design rules and procedures that make these markets work better. In his own words in an article, Professor Roth describes the development of market design,

> Two developments in economics came together to form the field of market design. One was game theory—the study of the "rules of the game" and the strategic behavior that they elicit. By the 1990s it had matured to the point where it could offer practical guidance. In this it was helped by another new methodology, experimental economics, which provided tools both for testing the reliability of game theory's predictions and for testing market designs before introducing them into operating markets. A primary motive for market design is the need to address market failures. To function properly, markets need to do at least three things.
>
> 1. They need to provide *thickness*—that is, to bring together a large enough proportion of potential buyers and sellers to produce satisfactory outcomes for both sides of a transaction.
>
> 2. They need to make it *safe* for those who have been brought together to reveal or act on confidential information they may hold. When a good market outcome depends on such disclosure, as it often does, the market must offer participants incentives to reveal some of what they know.
>
> 3. They need to overcome the *congestion* that thickness can bring, by giving market participants enough time—or the means to conduct transactions fast enough—to make satisfactory choices when faced with a variety of alternatives.[54]

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[51] Stanford Engineering, Engineering Alum Awarded 2012 Nobel Prize in Economics, October 19, 2012, https://engineering.stanford.edu/news/engineering-alum-awarded-2012-nobel-prize-economics.

[52] Alvin E. Roth – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Fri. 30 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/2012/roth/biographical/; Alvin E. Roth, https://en.wikipedia.org/wiki/Alvin_E._Roth; Alvin E. Roth, The Economist As Engineer: Game Theory, Experimentation, and Computation as Tools for Design Economics, Econometrica Vol. 70, No. 4 (July 2002), 1341-1378.

[53] Alvin E. Roth, "The Art of Designing Markets," Harvard Business Review, Oct. 2007, https://hbr.org/2007/10/the-art-of-designing-markets.

[54] *Id.*

He discusses labor and spectrum markets as different from each other but also traditional in the sense that they use money, as opposed to "marketlist allocation procedures" that do not involve money or prices.[55]

His interest in markets started in graduate school. Professor Roth describes his graduate school experience after failing one of his Ph.D. qualifying exams and having Bob Wilson as his advisor at Stanford,

> I decided to do research in game theory after taking a class from Michael Maschler, who was visiting Stanford from the Hebrew University of Jerusalem. Bob Wilson agreed to be my advisor and rescued me from having what looked to be a very short academic career after I failed one of my Ph.D. qualifying exams. He was on sabbatical that year, but met with me regularly once a week for an hour. In memory, our meetings followed a kind of script: I would spend a while explaining to him why I hadn't made progress that week, and then he would spend a while telling me not to be discouraged. Then I would describe some roadblock to further progress, and he would, as we finished our meeting, recommend a paper for me to read. Because his recommendations had always been very much on target, I would go straight from his office to the library and start to read the paper. As I did, I would think, this time Bob made a mistake, this paper has nothing to do with my problem. But then, somewhere in the middle of the paper would be a lemma or remark that helped me get around that roadblock …[56]

Figure 19. Lloyd Shapley[57]

Lloyd Shapley[58] pioneered the matching markets literature and the "Shapley value" concept in game theory is named after him. The Shapley value is a concept that measures the contribution

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[55] *Id.*

[56] Alvin E. Roth – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Fri. 30 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/2012/roth/biographical/.

[57] RAND Corporation, RAND's Lloyd Shapley Wins Nobel Prize in Economics, https://www.rand.org/blog/2012/10/rands-lloyd-shapley-wins-nobel-prize-in-economics.html.

[58] Lloyd S. Shapley – Biographical*. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 6 Oct 2022. https://www.nobelprize.org/prizes/economic-sciences/2012/shapley/biographical/; Lloyd Shapley, https://en.wikipedia.org/wiki/Lloyd_Shapley.

of each player when the gains and costs are distributed fairly between several actors in a coalition.[59] The market design literature arose out of game theory and matching concepts including cooperation as described in the two-sided marriage model of Gale and Shapley (1962).[60]

Professor Shapley was a leader in developing concepts of strategic analysis in game theory alongside von Neumann, Morgenstern, Schelling, Luce and Raiffa, and Nash.[61] His development as an economist started early but did not have a straightforward path.

In his Nobel Prize essays, Professor Shapley recounts his performance at Harvard as an undergraduate, after attending Phillips Exeter Academy and being raised as fourth of five children on Harvard campus with his father as the director of the Harvard Observatory,

> I didn't get my degree in '47. I finished all the requirements for the degree, but the last semester I also failed two courses … I took four courses over the load you take, and I failed two, and maybe got a couple of A's in the other courses. The math courses I was generally good at, and music courses sometimes. So they said, "No, you're on probation. We can't give a degree to someone on probation. If you survive for a year, you'll get the degree next year" … So I wasn't all that gung-ho about Harvard. My performance at Harvard hadn't been that much. Of course, a great deal of education takes place in a person hanging around – of course, I'd hung around Harvard beforehand.

But he found himself at RAND after applying for a job, and there he with a weekly seminar group met to study game theory and work through the new at the time, and now classic, *Theory of Games and Economic Behavior*,

> … this was reasonably soon after the publication of *Theory of Games and Economic Behavior*, John von Neumann and Oskar Morgenstern's opus, a big thing. I think it was published in '47, a so-called second edition, which simply has an appendix added, which they didn't have finished in time before. So it had appeared and had not made much of a splash, got big reviews and von Neumann, anyway, was well-known in mathematics already. But nothing had happened beyond that…. [Roger Snow and I] made some progress, and finally I guess I broke it, but Roger was also working on it. So it turned out to be Shapley-Snow … This was a work of mathematics where I had not really even read very many math papers as published and didn't have any clear concept that I was doing anything special except solving a problem…. So, von Neumann, partly, I guess, for his own ego, said, "I want to encourage this work," even though he was really not working on game theory anymore. He was working on computer ideas mostly. So he wants to encourage it. So it came back a big rave review or maybe a letter …. von Neumann was all excited about this, and he'll publish it, and he'll sponsor it in any journal you name, and so on. So at that point, my stock went up, and Roger's went up. At least these two kids – and there weren't all that many of us around – had something enough to get a real pro like von Neumann interested. So, of course, stop everything else while we write this paper and send it off. This is my first contribution, Shapley-Snow. I call it my piece, really, though I mean it's helpful to have Roger in the thing, but he kept saying, "You write it, and I'll read it."

[59] Shapley Value, Wikipedia, https://en.wikipedia.org/wiki/Shapley_value; Shapley Value, Investopedia, https://www.investopedia.com/terms/s/shapley-value.asp.
[60] Alvin E. Roth and Robert B. Wilson, "How Market Design Emerged from Game Theory: A Mutual Interview," Journal of Economic Perspectives, Vol. 33 No. 3, Summer 2019, pp. 118-143, https://pubs.aeaweb.org/doi/pdf/10.1257/jep.33.3.118.
[61] *Id.*

This work at RAND happened before he went to Princeton for graduate studies in mathematics, where he developed the "Shapley Value," a major concept in game theory. After grad school, Shapley returned to RAND and developed game theory and mathematical economics. His work on stable pairings and the deferred matching algorithm and "market games" has created the disciplines of game theory and market design. Then he moved to UCLA to teach and continue work in a joint appointment in math and economics. Peter Shapley, his son, notes that, "It was a joint appointment – in the math department to teach math to math students, and in the economics department to teach math to economics students. So despite being a professor of economics, he has never taught economics."[62]

2.2.3 *Elinor Ostrom (2009)*

Elinor Ostrom was awarded the Nobel Prize in Economics in October 2009 "for her analysis of economic governance, especially the commons."[63]

Figure 20. Elinor Ostrom[64]

Elinor Ostrom[65] established 8 principles for sustainable governance of common-pool resources (CPRs) in her book and academic articles, Governing the Commons: The Evolution of Institutions for Collective Action.[66]

[62] Lloyd S. Shapley – Biographical*. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 6 Oct 2022. https://www.nobelprize.org/prizes/economic-sciences/2012/shapley/biographical/.
[63] Press Release: The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, October 12, 2009, https://www.nobelprize.org/prizes/economic-sciences/2009/press-release/.
[64] Kenneth J. Arrow, Robert O. Keohane, and Simon A. Levin, Elinor Ostrom: An Uncommon Woman for the Commons, PNAS, Vol. 109 No. 33, https://www.pnas.org/doi/10.1073/pnas.1210827109
[65] Elinor Ostrom – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 29 Sep 2022, https://www.nobelprize.org/prizes/economic-sciences/2009/ostrom/biographical/; Elinor Ostrom, https://en.wikipedia.org/wiki/Elinor_Ostrom.
[66] Elinor Ostrom, Governing the Commons: The Evolution of Institutions for Collective Action. New York: Cambridge University Press (1990).

Professor Ostrom describes her path to a Ph.D. in economics in her biographical essay for her Nobel Prize acceptance,

> My initial discussions with the Economics Department at UCLA about obtaining a Ph.D. in Economics were, however, pretty discouraging. I had not taken mathematics as an undergraduate primarily because I had been advised as a girl against taking any courses beyond algebra and geometry in high school. While the Economics Department encouraged me to take an outside minor in economics for my Ph.D., they discouraged any further thinking about doing a Ph.D. in economics … I was, however, admitted in a class of 40 students with three other women. We were told after we began our program that the faculty had a very heated meeting in which they criticized the Departmental Committee for admitting any women and offering them assistantships. Fortunately, our fellow male graduate students were friendly and encouraged us all to continue in our program.[67]

Her work on commons, as opposed to private or government property, has been applied to spectrum auctions and arguments for more spectrum commons.[68] The design rules that she focuses on monitoring, sanctions, and enforcement and the role of community governance. Her work has also been cited in recent research on self-governance in spectrum regimes.[69]

2.2.4 Ronald Coase (1991)

Ronald Coase was awarded the Nobel Prize in Economics in October 1991 "for his discovery and clarification of the significance of transaction costs and property rights for the institutional structure and functioning of the economy."[70]

[67] Elinor Ostrom – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Thu. 29 Sep 2022, https://www.nobelprize.org/prizes/economic-sciences/2009/ostrom/biographical/.
[68] Elinor Ostrom, IDEAS, https://ideas.repec.org/e/c/pos55.html.
[69] Pedro Bustamante, Marcela Gomez, Ilia Murtazashvili, Martin Weiss, "Spectrum Anarchy: Why Self-Governance of the Radio Spectrum Works Better than We Think," *Journal of Institutional Economics*, Cambridge University Press, vol. 16(6), pages 863-882.
[70] Press Release: The Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel 1991, October 15, 1991,
https://www.nobelprize.org/prizes/economic-sciences/1991/press-release/.

Figure 21. Ronald Coase[71]

Ronald Coase[72]

Professor Coase recalls his humble beginnings as a child in London in his biographical essay for the Nobel Prize committee,

> My father, a methodical man, recorded in his diary that I was born at 3:25 p.m. on December 29th, 1910. The place was a house, containing two flats of which my parents occupied the lower, in a suburb of London, Willesden. My father was a telegraphist in the Post Office. My mother had been employed in the Post Office but ceased to work on being married. Both my parents had left school at the age of 12 but were completely literate. However, they had no interest in academic scholarship. Their interest was in sport. My mother played tennis until an advanced age. My father, who played football, cricket and tennis while young, played (lawn) bowls until his death. He was a good player, played for his county and won a number of competitions. He wrote articles on bowls for the local newspaper and for Bowls News.[73]

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[71] Patrick J. Lyons, Ronald H. Coase, 'Accidental' Economist Who Won a Nobel Prize, Dies at 102, N.Y. Times, Sept. 3, 2013, https://www.nytimes.com/2013/09/04/business/economy/ronald-h-coase-nobel-winning-economist-dies-at-102.html.

[72] Ronald H. Coase – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Wed. 28 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/1991/coase/biographical/; Ronald Coase, https://en.wikipedia.org/wiki/Ronald_Coase.

[73] Ronald H. Coase – Biographical. NobelPrize.org. Nobel Prize Outreach AB 2022. Wed. 28 Sep 2022. https://www.nobelprize.org/prizes/economic-sciences/1991/coase/biographical/.

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3 Spectrum Economics

3.1 History of Auctions

3.1.1 Telecommunications Act of 1996

Spectrum auctions started in the United States in 1994 and were codified in the Telecommunications Act of 1996. Soon after the passage of the 1996 Telecom Act, the FCC Wireless Bureau released a report to Congress on spectrum auctions.[74]

Figure 22. FCC Report to Congress in 1997 on Spectrum Auctions[75]

The report gives a history of comparative hearings, lotteries, and newly approved, auctions. In 1993, Congress authorized the FCC to use auctions, and in the first 4 years of the new rule, over 4,300 licenses were awarded for $23 billion.[76] In the words of two telecommunications attorneys and cited by the FCC Report, "[t]he new auction paradigm has drawn entry and new financing into telecommunications markets and has spurred the marketing of new technologies and the building of transmission capacity to meet growing demand."[77]

[74] *In the Matter of FCC Report to Congress on Spectrum Auctions*, FCC 97-353, WT Docket No. 97-150, Oct. 9, 1997, https://www.fcc.gov/sites/default/files/wireless/auctions/data/papersAndStudies/fc970353.pdf.
[75] *In the Matter of FCC Report to Congress on Spectrum Auctions*, FCC 97-353, WT Docket No. 97-150, Oct. 9, 1997, https://www.fcc.gov/sites/default/files/wireless/auctions/data/papersAndStudies/fc970353.pdf
[76] *Id.*
[77] Thomas J. Duesterberg & Peter K. Pitsch, "Wireless Services, Spectrum Auctions, and Competition in Modern Telecommunications," Outlook (May 1997), at 7, cited by FCC Report, *id.*

> *"The new auction paradigm has drawn entry and new financing into telecommunications markets and has spurred the marketing of new technologies and the building of transmission capacity to meet growing demand."*
>
> Source: Thomas J. Duesterberg & Peter K. Pitsch, *Wireless Services, Spectrum Auctions, and Competition in Modern Telecommunications*, Outlook (May 1997), p. 7 (*Duesterberg & Pitsch*).

Figure 23. Quote from FCC Report to Congress on the New Auction Paradigm[78]

Prior to this "new paradigm," the FCC used comparative hearings to applicants to distribute spectrum.[79] First-come, first-serve was the order of allocation unless a particular license had more than one applicant. In a manual, and time-consuming administrative process prior to automated auctions, regulators decided who to give spectrum licenses based on "public interest, convenience, or necessity" in a quasi-judicial forum.[80] Lotteries were also used for assigning a broad range of licenses starting in 1981.[81] The FCC was overwhelmed with pre-screening of spectrum applicants and by 1987, opened the lotteries up to all potential applicants, which led to the emergence of "application mills."[82]

Auctions were introduced in 1993 and rules governing auction structure by 1994.[83] The FCC released its report to Congress on spectrum auctions and continued to auction new spectrum in the late 1990s and early 2000s that form the basis of national cellular networks. Since then, the FCC has conducted over 100 auctions to meet demand for licenses to use the radio spectrum for wireless communications.

[78] Thomas J. Duesterberg & Peter K. Pitsch, "Wireless Services, Spectrum Auctions, and Competition in Modern Telecommunications," Outlook (May 1997), at 7, cited by FCC Report, *Id.*
[79] *In the Matter of FCC Report to Congress on Spectrum Auctions*, FCC 97-353, WT Docket No. 97-150, Oct. 9, 1997, https://www.fcc.gov/sites/default/files/wireless/auctions/data/papersAndStudies/fc970353.pdf [hereinafter "1997 FCC Report".
[80] *Id.* at 6.
[81] *Id.* at 7.
[82] *Id.*
[83] *Id.* at 9.

Figure 24. William E. Kennard (D), Chairman of the FCC from Nov. 3, 1997 to Jan. 19, 2001[84]

[84] FCC, Commissioners from 1934 to Present, https://www.fcc.gov/commissioners-1934-present; William Powell, Wikipedia, https://en.wikipedia.org/wiki/William_Kennard.

Figure 25. Michael K. Powell (R), Commissioner of the FCC from Nov. 3, 1997 to Mar. 17, 2005, and Chairman of the FCC from Jan. 22, 2001 to Mar. 15, 2005[85]

Spectrum prices and the interest from commercial bidders for auctioned frequency bands shows the trend toward more economic value from the radio spectrum over time. Through auctions, large sums of money have been bid, but more importantly, far more economic value has been unlocked for wireless services that use the radio spectrum in novel and efficient ways.

Table 1. Completed Spectrum Auctions above $100M Net Winning Bids

Auction	Name	Net Winning Bids	Licenses Auctioned	Licenses Won	Rounds	Dates
107	3.7 GHz Service	$81,114,481,921	5,684	5,684	97	12/8/2020 - 2/17/2021
97	AWS-3	$41,329,673,325	1,614	1,611	341	11/13/2014 - 1/29/2015
110	3.45 GHz Service	$22,418,284,236	4,060	4,041	151	10/5/2021 - 1/4/2022
1002	600 MHz Band	$19,318,157,706	2,912	2,776	58	8/16/2016 - 3/30/2017
73	700 MHz Band	$18,957,582,150	1,099	1,090	261	1/24/2008 - 3/18/2008
35	C and F Block PCS	$16,857,046,150	422	422	101	12/12/2000 - 1/26/2001
66	AWS-1	$13,700,267,150	1,122	1,087	161	8/9/2006 - 9/18/2006
5	Broadband PCS C Block	$10,071,708,842	493	493	184	12/18/1995 - 5/6/1996
103	Upper 37, 39, 47 GHz	$7,558,703,201	14,144	14,142	104	12/10/2019 - 3/5/2020
4	Br PCS A and B Block	$7,019,403,797	99	99	112	12/5/1994 - 3/13/1995
105	3.5 GHz Band	$4,543,232,339	22,631	20,625	76	7/23/2020 - 8/25/2020
11	Br PCS D, E, & F Block	$2,517,439,565	1,479	1,472	276	8/26/1996 - 1/14/1997
58	Broadband PCS	$2,043,230,450	242	217	91	1/26/2005 - 2/15/2005
102	Sp Frontiers – 24 GHz	$2,022,676,752	2,909	2,904	91	3/14/2019 - 5/28/2019

[85] FCC, Commissioners from 1934 to Present, https://www.fcc.gov/commissioners-1934-present; Michael Powell, Wikipedia, https://en.wikipedia.org/wiki/Michael_Powell_(lobbyist).

96	H Block	$1,564,000,000	176	176	167	1/22/2014 - 2/27/2014
10	Br PCS C Block	$904,607,467	18	18	25	7/3/1996 - 7/16/1996
101	Sp Frontiers – 28 GHz	$700,309,809	3,072	2,965	176	11/14/2018 - 1/24/2019
8	110 Degrees (DBS)	$682,500,000	1	1	19	1/24/1996 - 1/25/1996
1	Nw Narrowband (PCS)	$617,006,674	10	10	47	7/25/1994 - 7/29/1994
17	LMDS	$578,663,029	986	864	128	2/18/1998 - 3/25/1998
33	Upper 700 MHz GB	$519,892,575	104	96	66	9/6/2000 - 9/21/2000
108	2.5 GHz Band	$419,133,261	8,017	7,872	73	7/29/2022 - 8/29/2022
22	C, D, E, F Block Br PCS	$412,840,945	347	302	78	3/23/1999 - 4/15/1999
30	39GHz	$410,649,085	2,450	2,173	73	4/12/2000 - 5/8/2000
3	PCS	$392,706,797	30	30	105	10/26/1994 - 11/8/1994
34	800 MHz SMR	$319,451,810	1,053	1,030	76	8/16/2000 - 9/1/2000
6	Multipoint/Multich	$216,239,603	493	493	181	11/13/1995 - 3/28/1996
2	IVDS	$213,892,375	594	594	Oral	7/28/1994 - 7/29/1994
7	900 MHz Spec MRS	$204,267,144	1,020	1,020	168	12/5/1995 - 4/15/1996
15	DARS	$173,234,888	2	2	25	4/1/1997 - 4/2/1997
37	FM Broadcast	$147,876,075	288	258	62	11/3/2004 - 11/23/2004
69	1.4 GHz Bands	$123,599,000	64	64	267	2/7/2007 - 3/8/2007
53	MVDDS	$118,721,835	214	192	49	1/14/2004 - 1/27/2004

Source: FCC, Auctions Summary[86]

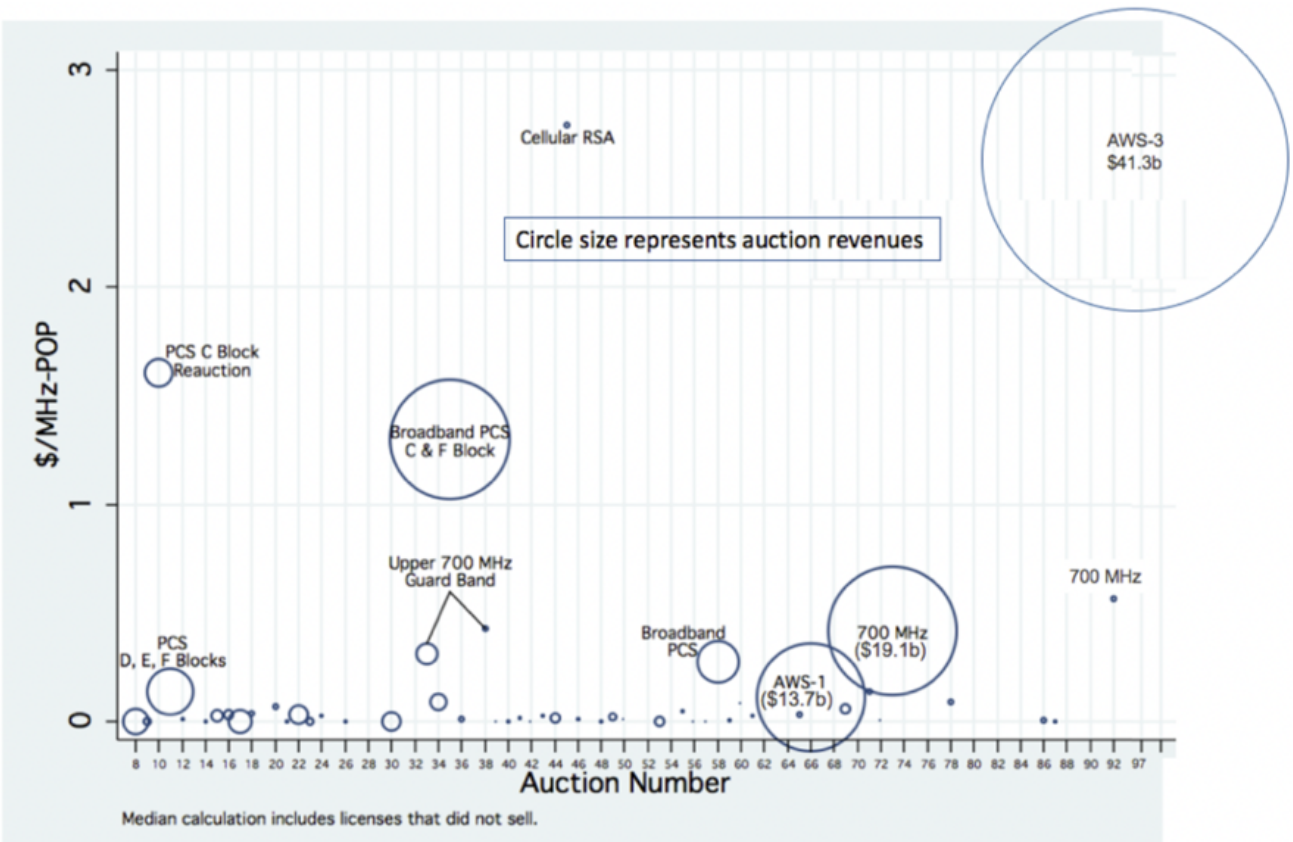

Figure 26. Early Auctions Compared to AWS-3 in Auction 97[87]

[86] FCC, Auctions Summary, https://www.fcc.gov/auctions-summary.
[87] Scott Wallsten, "Don't Be Disappointed by the FCC's Incentive Auction," Technology Policy Institute, Jan. 17, 2017, https://techpolicyinstitute.org/publications/miscellaneous/the-fccs-incentive-auction-is-not-a-disappointment/.

Auction results from the first few auctions through Auction 97: AWS-3 in 2015 are shown in the figure.[88] The predicted price for that spectrum was around $1.00 per MHz/pop, but ended up being $2.72 per MHz/pop for paired spectrum, which resulted in a $44 billion payout to the U.S. Treasury.[89]

Running spectrum auctions involves legal and compliance procedures, the competitive bidding process is rather straightforward. Bidders bid up to their true values to win spectrum licenses, competing with other bidders to win the license based on private information. The FCC sets a specific auction design and particular rules for bidders. Auction theory and technical details come into play in order to mitigate the bidder strategies toward collusion. Combinatorial bidding and the simultaneous multiple-round auctions have been implemented in order to prevent inefficient outcomes.

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[88] FCC, "Auction 97: Advanced Wireless Services (AWS-3)," https://www.fcc.gov/auction/97.
[89] Scott Wallsten, "Don't Be Disappointed by the FCC's Incentive Auction," Technology Policy Institute, Jan. 17, 2017, https://techpolicyinstitute.org/publications/miscellaneous/the-fccs-incentive-auction-is-not-a-disappointment/, citing Phil Goldstein, "AWS-3 Spectrum Auction Primer: What You Need to Know Before the Bidding Starts," Fierce Wireless, Nov. 12, 2014, https://www.fiercewireless.com/special-report/aws-3-spectrum-auction-primer-what-you-need-to-know-before-bidding-starts and Peter Cramton, "Bidding and Prices in the AWS-3 Auction," May 2015, http://www.cramton.umd.edu/papers2015-2019/cramton-aws-3-auction-prices.pdf.

Box 2: Behind the Scenes at an FCC Auction

Rules: For the auction of licenses in any particular service, the Commission establishes the requisite technical, service, and competitive bidding rules through notice and comment rulemaking in accordance with the Administrative Procedures Act. Once rules are promulgated, the Wireless Telecommunications Bureau initiates the following process.

Initial Public Notice: A Public Notice announces the date of the auction and the deadline for filing "short-form" applications to participate in the auction. The Public Notice specifies the licenses to be auctioned; the method of competitive bidding to be used in the event mutually exclusive applications are filed; the deadline for submitting the upfront payment and the amount of that payment for each license; and applicable bid requirements and other auction procedures.

Bidder Information Package: Soon after the release of the initial Public Notice, a Bidder Information Package is made available to prospective bidders. The Bidder Information Package generally contains detailed information about the auction and auction procedures, as well as information about incumbent licensees (if the spectrum has incumbents) based on the Commission's licensing records.

Status of Applications Public Notice: After reviewing the short-form applications, but prior to the upfront payment deadline, a Public Notice advises applicants of the status of their short-form applications. Applicants whose short-form applications are accepted or rejected are identified, and those applicants whose short-form applications are substantially complete, but contain minor errors or defects, are identified and provided a limited opportunity to correct their applications prior to the auction.

Qualified Bidders Public Notice: After the upfront payment deadline has passed, the Bureau issues a Public Notice identifying the applicants who are qualified to participate in the auction, *i.e.,* those applicants whose short-form applications were accepted for filing and who timely submitted upfront payments sufficient to make them eligible to bid on at least one of the licenses for which they applied.

Pre-Auction Assistance to Qualified Bidders: All qualified bidders are eligible to participate in a mock auction which enables them to become familiar with the software prior to the beginning of the auction. In some instances, the Commission also conducts a pre-auction seminar for qualified bidders. Registration materials are usually distributed by two overnight mailings, each containing part of a confidential identification code required for the bidder to place bids.

Auction: The auction is conducted and bids are accepted in each round of the auction. Round results and other related reports are provided during the course of the auction. Such reports compile results of all bids placed, current high bids, withdrawn bids, and the status of other auction procedures. During the auction, announcements are made directly to bidders via the automated bidding system. Round results and other important information are also posted to the Internet and the FCC electronic bulletin board.

Auction Closing Public Notice: After the close of the auction, a Public Notice announces the winning bidder for each license and establishes the deadline and procedures for winning bidders to make payment. The Public Notice will also include information about filing the "long-form" application necessary to obtain the license. Long-form applications are subject to review pursuant to the Communications Act. Under the statute, interested parties are given an opportunity to file petitions to deny against auction winners, and the Commission must determine whether such petitions have merit.

Figure 27. How to Run an FCC Spectrum Auction[90]

[90] 1997 FCC Report at 12.

Box 3: Preventing Collusion in Spectrum Auctions

In the *Competitive Bidding Second Report and Order*, the Commission adopted rules designed to prevent and facilitate the detection of collusive conduct in order to enhance and ensure the competitiveness of both the auction process and the post-auction market structure.

The Commission's anti-collusion rule requires that auction applicants identify any parties with whom they have entered into any consortium arrangements, joint ventures, partnerships or other agreements or understandings which relate in any way to the competitive bidding process. Applicants are also required to certify that they have not entered into any explicit or implicit agreements, arrangements or understandings of any kind with any parties, other than those identified, regarding the amount of their bids, bidding strategies, or the particular markets on which they will or will not bid.

With certain limited exceptions, from the time auction applications are filed prior to auction until the time that the winning bidder has made its required down payment, all bidders are prohibited from cooperating, collaborating, discussing or disclosing in any manner the substance of their bids or bidding strategies with other bidders that have applied to bid in the same geographic license area, unless such bidders are members of a bidding consortium or other joint bidding arrangement identified on the bidder's short-form application.

The Commission has indicated that it will conduct a detailed investigation of any specific allegations that an auction participant has violated the anti-collusion rule. In addition, where allegations may give rise to violations of the federal antitrust laws, the Commission will investigate and/or refer such cases to the United States Department of Justice for investigation. Bidders who are found to have violated the Commission's anti-collusion rules in connection with their participation in the auction process may, among other sanctions, be subject to the loss of their down payment or their full bid amount, face the cancellation of their licenses, and be prohibited from participating in future auctions.

The Commission first became aware of allegations of "bid signaling" (*e.g.*, the use of particular trailing digits on a bid to signal other bidders) in late 1996, during the PCS D, E and F block auction, when it received a complaint from a bidder who believed that a competing bidder was using unusual bid amounts to "signal" its market intentions. The Commission has begun an investigation into the allegations and is also examining bidding records from previous auctions to determine whether this practice occurred in the past. In addition, the Commission has referred the allegations to the Department of Justice, which is conducting its own investigation.

Figure 28. Collusion in Spectrum Auctions[91]

Box 1: Combinatorial Bidding

Combinatorial bidding, also known as "package bidding," allows bidders to place single bids for groups of licenses. For example, in one type of combinatorial auction, bidder A could place a bid of $100,000 for licenses 1, 2 and 4, while bidder B places a bid of $500,000 for licenses 2, 3 and 5. The computer system then calculates the revenue maximizing solution and awards the high bids for that round to the appropriate package(s).

Combinatorial bidding has advantages over other auction designs when there are strong synergies among items being auctioned and strong and divergent preferences among bidders. In the FCC auctions, strong synergies exist when licenses are worth more to some bidders as a package than individually. Strong and divergent preferences occur, for example, when a large company's business plan is not viable unless it is awarded a nationwide service area, whereas smaller users may desire the same spectrum for local service and need only a smaller service area.

[91] 1997 FCC Report at 16.

Figure 29. Combinatorial Bidding or "Package Bidding"[92]

Major Features of the Simultaneous Multiple-Round Auction

(1) Interdependent spectrum licenses with the potential for substantial aggregation or substitution are grouped and sold at the same time.

(2) All bidders submit bids over a sequence of rounds.

(3) At the end of each round, the high bid for each license determines who would be the winner of that license if no higher bids were later received, and also helps fix minimum acceptable bids for the next round.

(4) Bidders that fail to submit bids in a round and do not have sufficient standing high bids risk losing eligibility to submit bids in later rounds.

(5) All licenses remain open for bidding until bidding has ceased on all licenses.

Figure 30. Features of Simultaneous Multiple-Round Auction[93]

[92] 1997 FCC Report at 4.
[93] 1997 FCC Report at 18.

Box 5:
Some Procedural & Policy Rules for the Simultaneous Multiple-Round Auction

Upfront Payment: Upfront payments ensure that a bidder is sincere and financially prepared to win a license. It provides a bidder sufficient eligibility to bid upon licenses and entitles the bidder to a certain number of bidding units. These units determine a bidder's eligibility to bid on licenses in the auction, round by round. The upfront payment is not attributed to specific licenses, but instead, defines the maximum number of bidding units on which the bidder is permitted to bid in any single round. At the close of the auction, the Commission applies the upfront payment towards the winning bid amount, or other payments in the event of withdrawal or default. If a bidder does not win any licenses and has no withdrawal payments, then the upfront payment will be refunded.

Activity: To ensure that the auction closes within a reasonable period of time, an activity rule requires bidders to participate actively throughout the auction, rather than waiting until the end. A bidder's activity level in a given round is the sum of the bidding units associated with licenses (1) on which the bidder is the standing high bidder from the previous round; and (2) on which the bidder submits an acceptable bid in the current round. The minimum required activity level is expressed as a percentage of the bidder's maximum bidding eligibility (as determined by the upfront payment), and increases as the auction progresses through three bidding stages toward its conclusion. A bidder that does not satisfy the activity rule loses bidding eligibility. However, bidders generally are provided with five activity rule "waivers," which allow them a limited ability to maintain eligibility without violating the activity rules.

Withdrawals: In any given round, the firm which submits the highest bid on a license above the minimum acceptable bid becomes the standing high bidder for that license. If no higher bids are received for that license before the end of the auction, that firm acquires the right (as well as the commitment) to purchase the license at the price of the bid. However, firms also have the option of withdrawing high bids before the close of the auction. In such cases, the bidder generally will be subject to a withdrawal payment equal to the difference between the amount of the withdrawn bid and the license's final winning bid. No withdrawal payment is assessed if the subsequent winning bid exceeds the withdrawn bid.

Stopping Rule: Given the simultaneous bidding format, it is important to decide when the auction is over. In a sequential auction, where licenses are offered one at a time, bidding is over when no bidder raises the current high bid on the available license. In the simultaneous multiple-round auction, however, there are many different licenses for sale at the same time. The simultaneous multiple-round bid auctions conducted so far at the Commission have not closed until bidding activity stopped on all licenses.

Figure 31. Rules for Simultaneous Multiple-Round Auctions[94]

These auction design choices have been developed over the years through observing bidding behavior in early spectrum auctions. Surprising results in certain auctions, such as the AWS-1 auction in summer of 2006, showed that one bidder's strategic decisions to overcome limitations in the auction design may have allowed it to achieve a billion dollar discount to build a national network.[95] Budget and "exposure problems" in this auction led to the development of package bidding which was implemented in later auctions. The mechanism design in response to these complex scenarios has led to advances in economic theory that has led to acknowledgment in Nobel Prize awards.[96]

[94] 1997 FCC Report at 20.
[95] Jeremy Bulow, Jonathan Levin, Paul Milgrom, Winning Play in Spectrum Auctions, NBER Working Paper No. 14765, March 2009, http://www.nber.org/papers/w14765 [hereinafter Bulow et al., Winning Play] at 28 (describing SpectrumCo's bidding strategy to overcome the exposure problem).
[96] *See generally* Paul Milgrom, "Putting Auction Theory to Work: The Simultaneous Ascending Auction," Journal of Political Economy, 2000, 108(2), pp. 245-72; Paul Milgrom, "Package Auctions and Package Exchanges," Econometrica, 2007, 75(4), pp. 935-966.

To briefly summarize these concepts, the "exposure problem" in a simultaneous ascending auction means that new entrants that need many licenses across the country are unable to predict the final prices for all the licenses they need to win to build a national network, and thus, cannot allocate their budgets well. This means that bidders tend to settle on prices according to their budgets, and it has been observed that bidders "may wish to manipulate the price paths so larger licenses reach their final prices earlier in the auction than smaller ones."[97]

By round 10 or 11 in the PCS auction, Auction 35, and the AWS-1 auction, Auction 66, according to Bulow, Levin, and Milgrom (2009), the exposure problem is observed rather early in the auction rounds.[98] According to the authors, this gives a forecast of total prices in the final rounds.[99] This led to early bidders to realize that high bids on some licenses relative to total budgets would result in discounted bids on smaller licenses.[100] This understanding of exposure is explained as the cause of one bidder's successful auction strategy in the AWS-1 auction, Auction 66.[101]

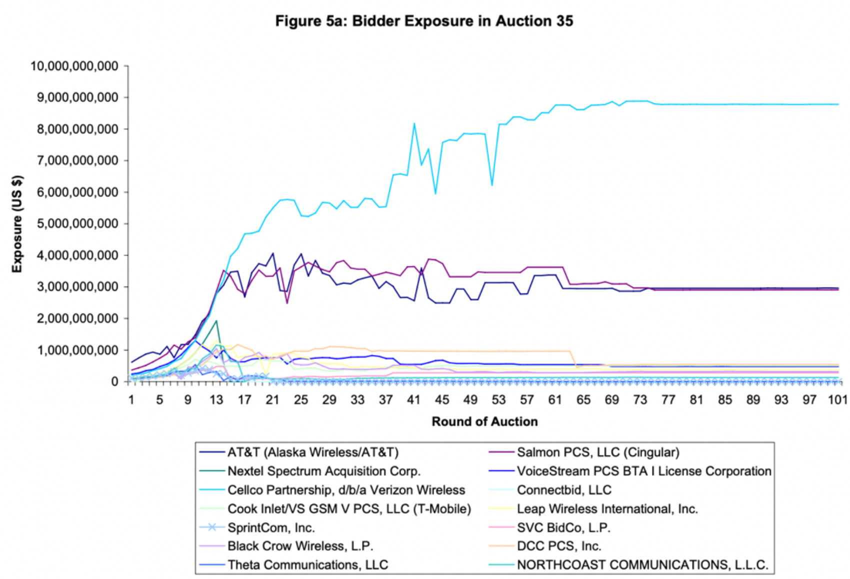


Figure 32. Bidder Exposure in Auction 35 (Bulow, et al., 2009)[102]

[97] Bulow et al., Winning Play, *supra* note 87, at 2.
[98] Bulow et al., Winning Play, *supra* note 87, at 2.
[99] Bulow et al., Winning Play, *supra* note 87, at 12.
[100] Bulow et al., Winning Play, *supra* note 87, at 10.
[101] Bulow et al., Winning Play, *supra* note 87, at 10.
[102] Bulow et al., Winning Play, *supra* note 87, at 34, fig. 5a.

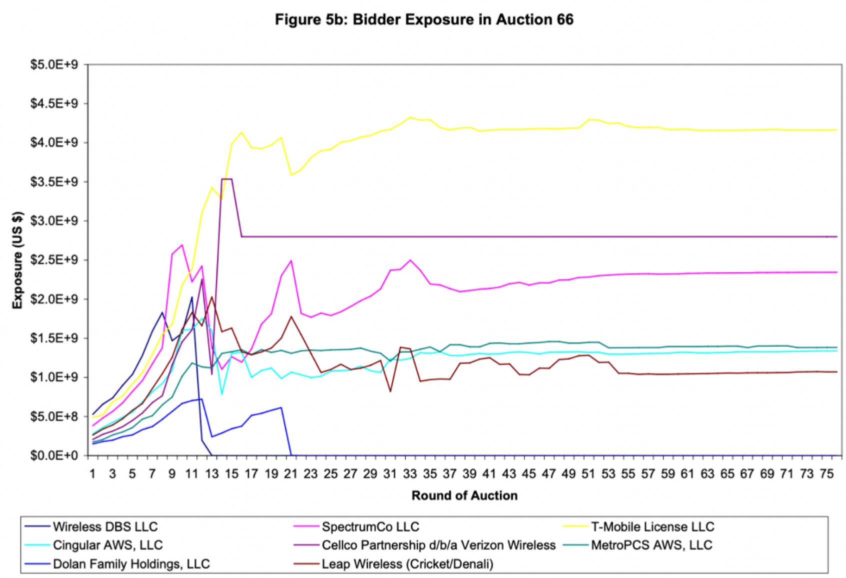


Figure 33. Bidder Exposure in Auction 66 (Bulow et al., 2009)[103]

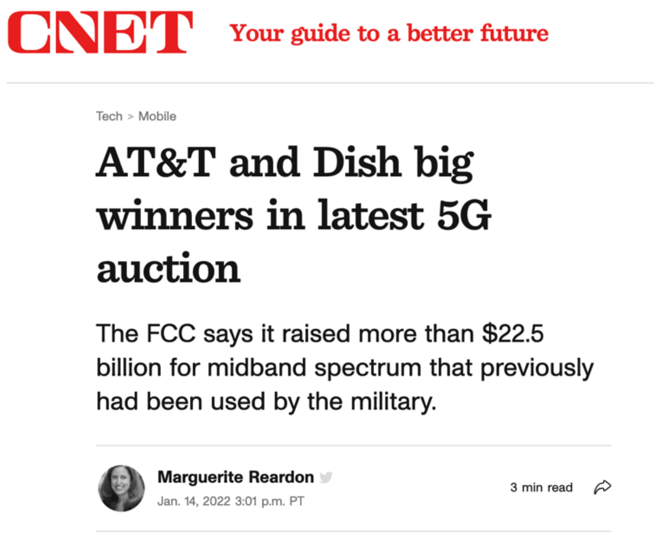
In the years since 2009, package bidding has been implemented in spectrum auctions to mitigate the exposure problem. Based on foundations discovered in these earlier auctions, the FCC has held larger and more complex auctions between 2010-2020 and 2020 to the present.

3.1.2 Recent Auctions

FCC Auction 107. Mid-band spectrum known as the "C-Band" was auctioned by the FCC in Auction 107 in early 2021.[104]

FCC Auction 110. Mid-band spectrum was also auctioned off by the FCC in Auction 110 in early 2022.[105] The spectrum band was 2.5 GHz to 3.5 GHz for mobile deployment of 5G.[106]

[103] Bulow et al., Winning Play, *supra* note 87, at 34, fig. 5b.
[104] FCC, Auction 107: 3.7 GHz Service, https://www.fcc.gov/auction/107.
[105] FCC, Auction 110: 3.45 GHz Service, https://www.fcc.gov/auction/110.
[106] Marguerite Reardon, "AT&T and Dish Big Winners in Latest 5G Auction," CNET, Jan. 14, 2022, https://www.cnet.com/tech/mobile/at-t-and-dish-big-winners-in-latest-5g-auction/



CNET Your guide to a better future

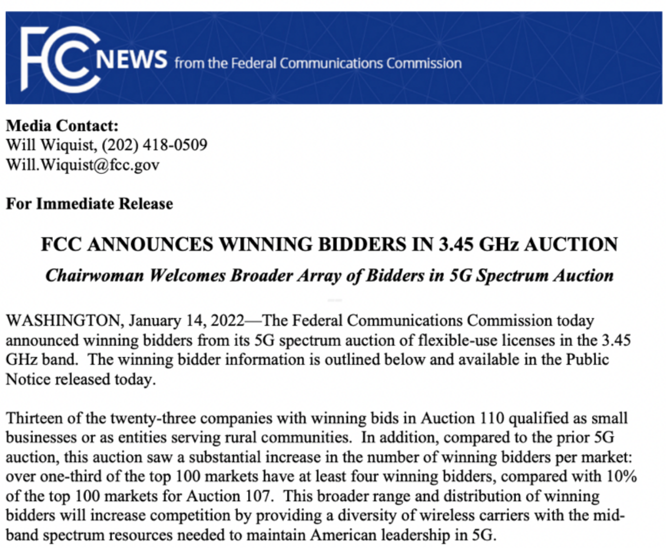
Tech > Mobile

AT&T and Dish big winners in latest 5G auction

The FCC says it raised more than $22.5 billion for midband spectrum that previously had been used by the military.

Marguerite Reardon
Jan. 14, 2022 3:01 p.m. PT
3 min read

Figure 34. Headline on Auction 110 Winners[107]



FCC NEWS from the Federal Communications Commission

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For Immediate Release

FCC ANNOUNCES WINNING BIDDERS IN 3.45 GHz AUCTION

Chairwoman Welcomes Broader Array of Bidders in 5G Spectrum Auction

WASHINGTON, January 14, 2022—The Federal Communications Commission today announced winning bidders from its 5G spectrum auction of flexible-use licenses in the 3.45 GHz band. The winning bidder information is outlined below and available in the Public Notice released today.

Thirteen of the twenty-three companies with winning bids in Auction 110 qualified as small businesses or as entities serving rural communities. In addition, compared to the prior 5G auction, this auction saw a substantial increase in the number of winning bidders per market: over one-third of the top 100 markets have at least four winning bidders, compared with 10% of the top 100 markets for Auction 107. This broader range and distribution of winning bidders will increase competition by providing a diversity of wireless carriers with the mid-band spectrum resources needed to maintain American leadership in 5G.

Figure 35. Winning Bidders in 3.45 GHz Auction 110[108]

[107] Marguerite Reardon, "AT&T and Dish Big Winners in Latest 5G Auction," CNET, Jan. 14, 2022, https://www.cnet.com/tech/mobile/at-t-and-dish-big-winners-in-latest-5g-auction/.
[108] FCC, "FCC Announces Winning Bidders in 3.45 GHz Auction," https://www.fcc.gov/document/fcc-announces-winning-bidders-345-ghz-auction.

The five bidders with the largest total gross winning bid amounts from both the clock and assignments phases were as follows:

Bidder	Total Gross Winning Bids
AT&T Auction Holdings, LLC	$9,079,177,491
Weminuche L.L.C.	$7,327,989,290
T-Mobile License LLC	$2,898,418,995
Three Forty-Five Spectrum, LLC	$1,379,489,483
United States Cellular Corp.	$579,646,526

The five bidders winning the largest number of licenses were as follows:

Bidder	Number of Licenses Won
AT&T Auction Holdings, LLC	1,624
Weminuche L.L.C.	1,232
United States Cellular Corp.	380
Cherry Wireless, LLC	319
T-Mobile License LLC	199

Figure 36. Winning Bidders in 3.45 GHz Auction 110[109]

These gross bids have increased into the tens of billions of dollars, which reveal the economic value and discounted cash flows expected from obtaining spectrum licenses on this valuable spectrum. The bidder's exercise in forecasting how much a particular spectrum license should be worth depends on spectrum valuation methods that rely on different accounting methods and various sources of transaction data and estimates of future activity on the spectrum.

3.2 Spectrum Valuation Methods

Capital markets and telecom firms need to assess the value of spectrum licenses on their balance sheets and for purposes of bidding in spectrum auctions. This exercise depends on inputs of data and methods of forecasting future profitability and use of the spectrum licenses.

3.2.1 Indefinitely Lived Intangible Assets

Spectrum licenses are considered for financial reporting purposes, indefinitely lived intangible assets, governed by the Financial Accounting Standards Board (FASB) Accounting Standards Codification (ASC) Topic 820 on Fair Value Measurements and Disclosures.[110] Companies that hold spectrum licenses are required to value the intangible assets on a regular basis because they are subject to impairment testing under FASB ASC 350-30-35 General Intangibles Other than Goodwill – Subsequent Measurement.[111] In fact, Sprint in 2004 took a $1.2 billion write-down, or impairment loss, on its spectrum holdings in Multichannel Distribution Service.[112]

But to do this valuation exercise, the valuation specialist needs to select a method to apply limited amounts of available data to determine a value for financial reports.[113] Two common methods are the market approach or income approach.

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[109] FCC, "FCC Announces Winning Bidders in 3.45 GHz Auction," https://www.fcc.gov/document/fcc-announces-winning-bidders-345-ghz-auction.
[110] Stout Advisory, Kimberly Randolph, ASA, "Tuning In to Spectrum Valuation," Stout Journal, Spring 2017, https://www.stout.com/-/media/pdf/sj17-tuning-in-to-spectrum-valuation-pdf.pdf.
[111] *Id.* at 2.
[112] Eli M. Noam, Media and Digital Management (Springer, 2019), at 407.
[113] *Id.* at 3.

The market approach, or "M&A" approach, uses transaction data from similar assets, and using that transaction data, multiples are derived to apply in the valuation estimate to the spectrum license at issue.[114] Factors of the spectrum license, such as the type of use, size of frequency band, band plan, geographic area, market area, encumbrances, and interference rights, are also included in the derived multiple from other transactions to be applied to the current asset.[115] These factors or features of the spectrum asset contribute to value in different measure and empirical studies have measured their impacts as drivers of spectrum value.[116] The empirical literature is discussed in more detail in the next section.

The income approach, or "greenfield" approach, is a projection exercise of discounted cash flow (DCF) model, based on the income stream from that particular asset, independent of other going concern value from the existing business.[117] Assumptions are made about the growth rate for revenue based on estimates from market participants. Expenses and costs are subtracted from the revenue projections.[118]

3.2.2 Spectrum Holdings of Publicly Traded Companies

Wireless companies include their wireless licenses on their balance sheets and conduct annual impairment testing. In AT&T's 2021 annual report, the firm describes how it uses the greenfield approach and market approach to determine the fair value of its licenses.[119] The wireless licenses held by the company are listed at $113.83 billion in net license value, an increase from $93.94 billion in the prior year, due to its participation in the C-Band auction in February 2021 as a winning bidder of 1,621 C-Band licenses for a total of $23.406 billion.[120] In January of 2022, AT&T also won 1,624 licenses in the 3.45 GHz Auction 110 for a total of $9.079 billion.[121] In June 2020, AT&T acquired $2.379 billion of 37/39 GHz spectrum at FCC auction as well.[122]

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[114] *Id.* at 3.
[115] *Id.* at 2-3.
[116] *Id.* at 2-3.
[117] *Id.*
[118] *Id.*
[119] AT&T 2021 Annual Report, https://investors.att.com/~/media/Files/A/ATT-IR-V2/financial-reports/annual-reports/2021/complete-2021-annual-report.pdf.
[120] AT&T 2021 Annual Report at 65.
[121] AT&T 2021 Annual Report at 65.
[122] AT&T 2021 Annual Report at 66.

U.S. Wireless Licenses

The fair value of U.S. wireless licenses is assessed using a discounted cash flow model (the Greenfield Approach) and a qualitative collaborative market approach based on auction prices, depending upon auction activity. The Greenfield Approach assumes a company initially owns only the wireless licenses and makes investments required to build an operation comparable to current use. These licenses are tested annually for impairment on an aggregated basis, consistent with their use on a national scope for the United States. For impairment testing, we assume subscriber and revenue growth will trend up to projected levels, with a long-term growth rate reflecting expected long-term inflation trends. We assume churn rates will initially exceed our current experience but decline to rates that are in line with industry-leading churn. We used a discount rate of 9.25%, based on the optimal long-term capital structure of a market participant and its associated cost of debt and equity for the licenses, to calculate the present value of the projected cash flows. If either the projected rate of long-term growth of cash flows or revenues declined by 0.5%, or if the discount rate increased by 0.5%, the fair values of these wireless licenses would still be higher than the book value of the licenses. The fair value of these wireless licenses exceeded their book values by more than 10%.

Figure 37. Description of Impairment Testing of AT&T Wireless Licenses[123]

Consolidated Balance Sheets
Dollars in millions except per share amounts

	December 31, 2021	2020
Assets		
Current Assets		
Cash and cash equivalents	**$ 21,169**	$ 9,740
Accounts receivable – net of related allowance for credit loss of $771 and $1,221	**17,571**	20,215
Inventories	**3,464**	3,695
Prepaid and other current assets	**17,793**	18,358
Total current assets	**59,997**	52,008
Noncurrent Inventories and Theatrical Film and Television Production Costs	**18,983**	14,752
Property, Plant and Equipment – Net	**125,904**	127,315
Goodwill	**133,223**	135,259
Licenses – Net	**113,830**	93,840
Trademarks and Trade Names – Net	**21,938**	23,297
Distribution Networks – Net	**11,942**	13,793
Other Intangible Assets – Net	**11,783**	15,386
Investments in and Advances to Equity Affiliates	**7,274**	1,780
Operating Lease Right-Of-Use Assets	**24,180**	24,714
Other Assets	**22,568**	23,617
Total Assets	**$ 551,622**	$ 525,761

Figure 38. Balance Sheet of AT&T Showing "Licenses – Net" in Spectrum Assets[124]

[123] AT&T 2021 Annual Report, at 27.
[124] AT&T 2021 Annual Report, at 48.

Our other intangible assets at December 31 are summarized as follows:

		2021			2020		
Other Intangible Assets	Weighted-Average Life	**Gross Carrying Amount**	**Accumulated Amortization**	**Currency Translation Adjustment**	Gross Carrying Amount	Accumulated Amortization	Currency Translation Adjustment
Amortized intangible assets:							
Wireless licenses	21.6 years	**$ 3,083**	**$ 307**	**$ (440)**	$ 2,979	$ 271	$ (421)
Orbital slots	N/A	**—**	**—**	**—**	5,825	—	—
Trademarks and trade names	38.3 years	**18,781**	**2,077**	**(7)**	20,016	1,518	(442)
Distribution network	10.0 years	**18,399**	**6,457**	**—**	18,414	4,621	—
Released television and film content	17.8 years	**10,939**	**6,978**	**—**	10,940	6,240	—
Customer lists and relationships	11.2 years	**637**	**483**	**(98)**	4,100	1,645	(460)
Other	22.3 years	**10,987**	**3,221**	**—**	11,311	2,615	(5)
Total	24.6 years	**$ 62,826**	**$ 19,523**	**$ (545)**	$ 73,585	$ 16,910	$ (1,328)

Indefinite-lived intangible assets not subject to amortization:

	2021	2020
Wireless licenses	**$ 111,494**	$ 85,728
Trade names	**5,241**	5,241
Total	**$ 116,735**	$ 90,969

Figure 39. AT&T's Wireless Licenses Amortized and Not Subject to Amortization[125]

Among other intangible assets, AT&T's balance sheet from its 2021 annual report shows that it considers the weighted average life span of its wireless licenses to be 21.6 years subject to amortization for a gross carrying amount of $3.083 billion, along with indefinite-lived intangible assets not subject to amortization for a gross carrying amount of $111.494 billion as of 2021. This accounting treatment shows the total portfolio of multiple types of licenses across the radio spectrum held by a publicly traded company under accounting rules for intangible assets.

3.2.3 Price per Mhz-Pop

Outside of corporate balance sheets, when regulators and commercial entities discuss the value of spectrum licenses, they use a unit measurement of price per MHz-pop. This is a simple multiple that combines the size of the frequency band in megahertz with the population size of the coverage area. This unit price is used to describe auction results in a single point estimate with normalization for the population that underlies the geographic area of the license. For instance, if a PCS license that covers 1 million people with 15 MHz of spectrum was sold for $17,600,000, then the price per mhz-pop would be $1.17.[126]

The price per mhz-pop metric is generally used to describe the outcomes of auctions, but is not without some criticism. Some experts have suggested alternative metrics that take into account other features of the spectrum license, such as the frequency of the band, whether the band plan is for paired bands or unpaired bands, with guard bands or not, or whether there are encumbrances and other rules that restrict usage of the spectrum. Bandwidth and population alone do not predict whether commercial bidders will pay a premium for certain licenses. The table shows FCC auctions, prior to 2015, ordered by descending gross bids, and the bandwidth size of the band. As seen in the data, the size of the auction depends on far more factors than bandwidth alone for these nationwide licenses.

[125] AT&T 2021 Annual Report, at 70.
[126] Stout, *Id.* at 3.

Table 2. Bandwidths Auctioned (pre-2015)

Auction	Year	Name	Gross Bids	Start MHz	End MHz	Bandwidth
97	2015	AWS-3	$44,899,451,600	1695 MHz	2180 MHz	65 MHz
73	2008	700 MHz Band	$19,120,378,000	698 MHz	806 MHz	62 MHz
35	2001	PCS (A, B, C, D, E, & F Block)	$17,597,015,000	15 MHz	10 MHz	70 MHz
66	2006	AWS-1	$13,879,110,200	1710 MHz	2155 MHz	90 MHz
5	1996	PCS (A, B, C, D, E, & F Block)	$13,428,945,122	1895 MHz	1990 MHz	30 MHz
4	1995	PCS (A, B, C, D, E, & F Block)	$7,019,403,797	1850 MHz	1965 MHz	30 MHz
11	1997	PCS (A, B, C, D, E, & F Block)	$2,715,885,604	1865 MHz	1975 MHz	30 MHz
58	2005	PCS (A, B, C, D, E, & F Block)	$2,253,802,000	1850 MHz	1975 MHz	30 MHz
96	2014	H Block	$1,564,000,000	1915 MHz	2000 MHz	10 MHz
10	1996	PCS (A, B, C, D, E, & F Block)	$904,607,467	1895 MHz	1990 MHz	30 MHz
17	1998	LMDS	$834,177,095	27,500 MHz	31,300 MHz	1300 MHz
1	1994	Narrowband PCS	$650,306,674	901 MHz	941 MHz	0.7875 MHz
33	2000	Upper 700 MHz & Guard Bands	$545,885,000	746 MHz	794 MHz	6 MHz
22	1999	PCS (A, B, C, D, E, & F Block)	$532,970,215	1895 MHz	1975 MHz	55 MHz
3	1994	Narrowband PCS	$488,772,800	901 MHz	941 MHz	450 kHz
30	2000	39 GHz	$467,214,200	38.6 GHz	40.0 GHz	1400 MHz
34	2000	SMR 800 MHz	$337,494,900	806.0125 MHz	854.7375 MHz	10 MHz
2	1994	218-219 MHz (Formerly IVDS)	$248,743,000	218 MHz	219 MHz	1 MHz
6	1996	MDS	$239,729,992	2150 MHz	2680 MHz	78 MHz

Source: FCC, Available Band Plans[127]

3.2.4 Valuation Estimates: Federal Inventory

The other challenge in valuing spectrum is the federal use and inventory of dozens of government agencies. The market approach could be used to estimate the value of the spectrum with comparisons of nearby or similar spectrum assets that have been sold in the private market. Yet, this value may be difficult to ascertain due to thin markets for spectrum such as radar or long-range defense communications. The income approach also has drawbacks because there are few sources of comparison for cash flows generated by government spectrum uses, the bulk of which are for national security, defense, law enforcement, weather, aviation, transportation, and global positioning purposes.

Several bills have been introduced in Congress to ask the federal government to account for its spectrum holdings in order to better allocate these resources between commercial users who are looking for spectrum and government agencies which may have unused spectrum in its inventory. Legislation is also required for federal agencies to find unused spectrum for auction to commercial users. Other mechanisms such as the Spectrum Relocation Fund and Spectrum Pipeline make funds available to support federal agencies to clear spectrum and make available more frequencies for commercial users.

[127] FCC, Available Band Plans, https://www.fcc.gov/economics-analytics/auctions-division/auctions/band-plans.

Table 3. Proposed Legislation Related to Federal Spectrum Valuation

Bill	Title	Congress	Introduced	Co-Sponsors
S.4117	Spectrum Innovation Act of 2022[128]	117th Congress (2021-2022)	April 28, 2022	Sen. Ben Lujan, Sen. John Thune, Sen. Marsha Blackburn
S.553	Government Spectrum Valuation Act[129]	117th Congress (2021-2022)	March 3, 2021	Sen. Mike Lee
S.3717, S.1605, P.L. 117-81	Spectrum IT Modernization Act of 2020,[130] included in National Defense Authorization Act for Fiscal Year 2022[131]	116th Congress (2019-2020)	May 13, 2020	Sen. Roger Wicker, Sen. Maria Cantwell, Sen. James Inholfe, Sen. Jack Reed
S.1626	Government Spectrum Valuation Act[132]	116th Congress (2019-2020)	May 22, 2019	Sen. Mike Lee, Sen. Ted Cruz
P.L. 1625	Mobile Now Act,[133] included in the Consolidated Appropriations Act of 2018	115th Congress (2017-2018)	Jan. 3, 2017	Sen. John Thune, Sen. Bill Nelson
S.2211	Spectrum Relocation Fund Act of 2015[134]	114th Congress (2015-2016)	Oct. 27, 2015	Sen. Jerry Moran, Sen. Tom Udall
P.L. 114-74	Spectrum Pipeline Act of 2015, included in the Bipartisan Budget Act of 2015[135]	114th Congress (2015-2016)	March 4, 2015	Rep. Patrick Meehan, Rep. Peter Roskam, Rep. Tom Reed
S.3433	Radio Spectrum Inventory Act of 2012[136]	112th Congress (2011-2012)	July 25, 2012	Sen. Olympia Snowe, Sen. Mark Warner
P.L. 112-96	Middle Class Tax Relief and Job Creation Act of 2012[137]	112th Congress (2011-2012)	Dec. 9, 2011	Rep. Dave Camp, Rep. Spencer Bachus, Rep.

[128] Spectrum Innovation Act of 2022, S.4117, 117th Congress (2021-2022), introduced in the Senate on April 28, 2022, Sen. Ben Ray Lujan, Sen. John Thune, Sen. Marsha Blackburn, https://www.congress.gov/bill/117th-congress/senate-bill/4117 (to make 3.1-3.45 GHz band frequencies available for non-Federal use, shared Federal and non-Federal use, or a combination thereof).

[129] Government Spectrum Valuation Act, S.553, 117th Congress (2021-2022), introduced in the Senate on March 3, 2021, Sen. Mike Lee, https://www.congress.gov/bill/117th-congress/senate-bill/553.

[130] Spectrum IT Modernization Act of 2020, S.3717, 116th Congress (2019-2020), introduced on May 13, 2020, Sen. Roger Wicker, Sen. Maria Cantwell, Sen. James Inholfe, Sen. Jack Reed, https://www.congress.gov/bill/116th-congress/senate-bill/3717.

[131] P.L. 117-81, National Defense Authorization Act for Fiscal Year 2022, S.1605, 117th Congress (2021-2022), introduced May 13, 2021, Sen. Rick Scott, Sen. Marco Rubio, Sen. Alex Padilla, https://www.congress.gov/bill/117th-congress/senate-bill/1605.

[132] Government Spectrum Valuation Act, S.1626, 116th Congress (2019-2020), introduced in the Senate on May 22, 2019, Sen. Mike Lee and Sen. Ted Cruz, https://www.congress.gov/bill/116th-congress/senate-bill/1626.

[133] Mobile Now Act, S.19, 115th Congress (2017-2018), introduced Jan. 3, 2017, Sen. John Thune, Sen. Bill Nelson, https://www.congress.gov/bill/115th-congress/senate-bill/19 (making 500 MHz of spectrum available from federal and non-federal sources).

[134] Spectrum Relocation Fund Act of 2015, S.2211, 114 Congress (2015-2016), introduced Oct. 27, 2015, https://www.congress.gov/bill/114th-congress/senate-bill/2211 (to authorize additional uses of the Spectrum Relocation Fund).

[135] P.L. 114-74, Bipartisan Budget Act of 2015, H.R.1314, 114th Congress (2015-2016), introduced March 4, 2015, Rep. Patrick Meehan, Rep. Peter Roskam, Rep. Tom Reed, https://www.congress.gov/bill/114th-congress/house-bill/1314 (appropriating $500 million in existing balances in the Spectrum Relocation Fund, and up to 10% of future balances, for research and development and planning activities).

[136] Radio Spectrum Inventory Act of 2012, S.3433, 112th Congress (2011-2012), introduced on July 25, 2012, Sen. Olympia Snowe and Sen. Mark Warner, https://www.congress.gov/bill/112th-congress/senate-bill/3433.

[137] P.L. 112-96, Middle Class Tax Relief and Job Creation Act, 112 Congress (2011-2012), introduced Dec. 9, 2011, Rep. Dave Camp, Rep. Spencer Bachus, Rep. Daniel Lungren, Rep. Frank Lucas, Rep. Fred Upton, Rep. Ileana Ros-Lehtinen, https://www.congress.gov/bill/112th-congress/house-bill/3630 (amended the CSEA to "allow eligible Federal entities to receive payments for sharing costs in addition to relocation costs and to expand the types of costs for which agencies could receive payments from the SRF. In addition, the Tax Relief Act required eligible

				Daniel Lungren, Rep. Frank Lucas, Rep. Fred Upton, Rep. Ileana Ros-Lehtinen
P.L. 108-494	Commercial Spectrum Enhancement Act[138]	108th Congress (2003-2004)	Nov. 20, 2004	Rep. Fred Upton

3.3 Spectrum Valuation Factors

What drives the value of a spectrum license, as observed in auction transactions and secondary market sales? Is it the size of the band, the use of the band, the market location, the band plan, or the frequency of the band? Economists have studied data from transactions in the United States and globally. Some of the hypotheses lack counterfactual data, but policymakers generally agree on certain observations from the market.

3.3.1 Frequency

Mobile devices that generate the most economic value and commercial revenue are deployed on certain frequencies that have favorable propagation characteristics. The particular frequency of a spectrum license thus drives the value of the spectrum because of the valuable uses that are deployed on those airwaves.

3.3.2 Paired vs. Unpaired

Aside from the frequency of the band, the structure of the band plan also can facilitate certain technologies and uses. Mobile devices with two-way communications have been designed to transmit signals on paired bands "by diminishing interference from incompatible adjacent operations."[139]

In the AWS-3 auction, the FCC asked the public for comment on how to design the band plan for 1675 MHz-1710 MHz band with a focus on the 15 or 20 MHz in the upper portion of the band, from 1690 MHz-1710 MHz and 1695 MHz-1710 MHz.[140]

Federal entities to follow new procedures to receive payments from the SRF, including submission of a transition plan and approval of that plan by a Technical Panel comprised of three members, one appointed by each of OMB, NTIA, and the FCC," explained in Executive Office of the President, "Memorandum for the Heads of Executive Departments and Agencies," M-16-13, June 2, 2016, https://www.whitehouse.gov/wp-content/uploads/legacy_drupal_files/omb/memoranda/2016/m-16-13.pdf.)

[138] P.L. 108-494, Commercial Spectrum Enhancement Act, 108th Congress (2003-2004), introduced Nov. 20, 2004, https://www.congress.gov/bill/108th-congress/house-bill/5419 (creating the Spectrum Relocation Fund for research and development and planning activities).

[139] Coleman Bazelon, The Economic Basis of Spectrum Value: Pairing AWS-3 with the 1755 MHz Band is More Valuable than Pairing it with Frequencies from the 1690 MHz Band, The Brattle Group, Apr. 11, 2011, https://www.brattle.com/wp-content/uploads/2017/10/8222_the_economic_basis_of_spectrum_value_-_pairing_aws-3_bazelon_apr_11_2011.pdf [hereinafter Bazelon, Spectrum Value], citing Notice of Proposed Rulemaking in the Matter of Service Rules for Advanced Wireless Services in the 2155-2175 MHz Band." FCC Docket 07-164 adopted September 7, 2007, released September 19, 2007.

[140] Bazelon, Spectrum Value, *supra* note 103.

3.3.3 Encumbered vs. Unencumbered

Uncertainty in whether to expect interference or not through encumbrances can lower the desirability of spectrum licenses for commercial operations.[141]

3.3.4 International Harmonization

Spectrum bands are more valuable if global standards are aligned with certain technologies on those bands. Hardware devices are manufactured at scale to serve a larger user base with network effects.[142]

3.3.5 Licensed vs. Unlicensed

Exclusive use or unlicensed shared use are two types of spectrum license rules. The FCC decides whether to deem a particular band eligible for licensed or unlicensed use. What was written in 2009 is still true today, "[a]t present, no existing market mechanism allows for the trading of radio spectrum between licensed and unlicensed uses. Whenever spectrum is made available for reallocation, the FCC faces a dilemma in determining which access regime to use."[143] There are tradeoffs, however, in using a particular band for licensed or unlicensed use.

Regulators are currently "attempting to guess how much bandwidth should be allocated to various types of licensed and unlicensed services – and imposing different rules within and across these allocations,"[144] but some scholars have been calling for a more systematic, market-based way of deciding these allocation tradeoffs.

It's undisputed that unlicensed spectrum, particularly the bands under Part 15 rules, generates enormous economic value through Wi-Fi technologies.[145] However, the lesson from Wi-Fi often does not translate to other unlicensed bands.[146] Moreover, the relevant comparison for policymakers is how much more or less value could be achieved from market-driven demand for flexible exclusive use licenses, which, used by nationwide networks, generates consumer and producer surplus in the trillions of dollars.[147]

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[141] Bazelon, Spectrum Value, *supra* note 103.
[142] Bazelon, Spectrum Value, *supra* note 103.
[143] Coleman Bazelon, Licensed or Unlicensed: The Economic Considerations in Incremental Spectrum Allocations, IEEE Communications Magazine, Vol. 47, Issue 3, March 2009, pp. 110-116, https://ieeexplore.ieee.org/document/4804395.
[144] Thomas W. Hazlett and Michael Honig, Valuing Spectrum Allocations, 23 Mich. Telecom. & Tech. L. Rev. 45 (2016), https://repository.law.umich.edu/cgi/viewcontent.cgi?article=1222&context=mttlr.
[145] Hazlett and Honig, Valuing Spectrum Allocations, *supra* note 136, at 75 tbl.4 (literature review of studies estimating the economic value of unlicensed spectrum); see generally Kenneth R. Carter, Ahmed Lahjouji & Neal McNeil, A Joint OSP-OET White Paper on Unlicensed Devices and Their Regulatory Issues, FCC, OSP Working Paper No. 39 (May 2003), 5, http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-234741A1.pdf.
[146] Hazlett and Honig, Valuing Spectrum Allocations, *supra* note 136, at 86 (describing the 20 years of unused unlicensed band in the U-PCS allocation at 1915-1920 MHz which did not generate economic value, and was eventually considered for flexible use licenses in an auction in 2014 which sold for $1.56 billion in gross bids).
[147] Hazlett and Honig, Valuing Spectrum Allocations, *supra* note 136, at 81, tbl.6 (literature review of studies estimating the economic benefits of U.S. mobile network services, citing Hazlett, Munoz, & Avanzini (2012)

The market-based mechanisms for discovering what the demand for a particular band is the reason that licensed spectrum is more economically efficient than unlicensed spectrum. Hazlett and Honig describe this policy decision the best,

> Most fundamentally, that is not because the apps provided in licensed spectrum are more valuable than the apps provided in unlicensed. It is because market-based mechanisms that reveal superior information about relative values, and that allow for adjustments to be made by well-incentivized actors not constrained by administrative spectrum allocation rules, can accommodate efficient activities with special force. Were the parties to be arguing for more unlicensed allocations, or for different types of unlicensed rules, to bid against parties with different arguments, demands for the conflicting approaches could be made visible. New bandwidth could be made available, without the debilitating burdens of deadening regulatory delay or tragedy of the anti-commons, to support the most valuable.[148]

The goal of spectrum policy is to reallocate spectrum into more productive uses, but with limited information, the regulators may find that market-based mechanisms for determining band plans could be an alternative way to the current lobbying and jockeying among industry, government, and Congress for determining new allocations on the spectrum.

3.3.6 Non-Market Values

National security and other values influence the way that spectrum allocations are weighted against each other. The Department of Defense has the most influence in radio spectrum policy due to its large wireless operations and national security mandate. These non-market values predominate in politics and may be at odds with economic efficiency in some cases. The DoD Electromagnetic Spectrum Superiority Strategy is one of several defense initiatives that contribute to a national spectrum strategy that affects other federal agencies.[149]

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[148] Hazlett and Honig, Valuing Spectrum Allocations, *supra* note 136, at 110.

[149] Briana Reilly, "DOD 'Engaged' in Work to Develop National Spectrum Strategy," Inside Defense, Sept. 19, 2022, https://insidedefense.com/daily-news/dod-engaged-work-develop-national-spectrum-strategy; Jason Miller, "For DoD, Solving Spectrum Sharing is a Matter of National, Economic Security," Federal News Network, Jan. 4, 2022, https://federalnewsnetwork.com/defense-main/2022/01/for-dod-solving-spectrum-sharing-is-a-matter-of-national-economic-security/ ("The Defense Department is slowly chipping away at 117 different tasks to implement the October 2020 Electromagnetic Spectrum Superiority Strategy").

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4 Market Tools

Wireless technology is continually improving with new transmitters and receivers in development and deployment across the radio spectrum from low to high frequencies. Market tools have been adopted by regulators to help facilitate the transfer of spectrum licenses from one use to another. While governments can use command-and-control methods to decide how to reallocate spectrum from one type of use to another, market-oriented approaches have proven to be more economically efficient. Price discovery and competitive bidding by spectrum licensees can occur with private information, rather than a central office that may be asked to pick winners and losers on imperfect information.[150] The number of different spectrum bands,

[150] *See generally* Friedrich A. Hayak, "The Use of Knowledge in Society," American Economic Review (Sept. 1945).

different spectrum users, and new proposals necessitates market tools that can help speed up changes in the spectrum allocation table.

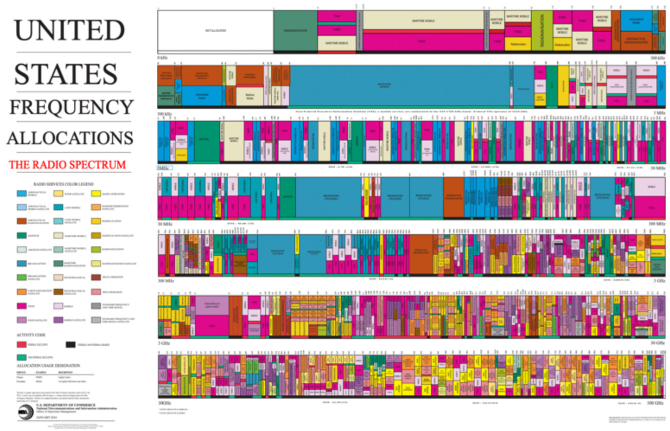

Figure 40. U.S. Frequency Allocation Table[151]

4.1 Reallocation Challenges

Market tools to determine how to reallocate spectrum to its highest valued uses have been implemented in federal radio policy, notably with the introduction of spectrum auctions in the 1990s. There are, however, several challenges that arise in how regulators choose to use market tools, particularly in the pre-auction policy decisions and the design choices in the auctions themselves.

4.1.1 Before the Auction

Before the auction, there's a pre-auction of sorts to determine what kind of auction and what rules should apply to the reallocation of spectrum. Some have called it the beauty pageant that precedes the auction, where interested parties such as incumbents and new entrants go to the FCC to lobby the agency to design the rules of the auction in a way that benefits their own interests and property rights.

There are many decisions that need to be made before an auction is announced and conducted. The FCC opens a public docket to ask for input on which frequency bands should be up for auction, what services to allow on the newly available spectrum, who to allow to be eligible to bid on the spectrum, how the neighboring licensees should be compensated or not for changes to their spectrum emission environment, and many more questions. Whether to implement a new type of auction, such as the incentive auction, starts with a proposal at the FCC and requires support by industry and the regulator to try a new method of distribution.

[151] U.S. Department of Commerce, National Telecommunications and Information Administration, U.S. Frequency Allocation Chart, https://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf.

This pre-game or pre-auction jockeying has predictable lines of argumentation and policymaking. The notable features of the negotiation include the specter of windfall and the power of holdup or the "interference veto."

4.1.2 Windfalls

If the FCC allowed broadcasters, for instance, to convert their beachfront property to flexible-use licenses, a windfall of billions of dollars would be granted to those incumbent broadcast station owners. Such a decision by the FCC would have saved time and effort in running a complex incentive auction, but it also would have been an unfair allocation of value to already entrenched broadcast station owners.

Economists, however, are less concerned with the specter of windfalls to incumbent parties than fairness may dictate. The total surplus, which is consumer surplus plus producer surplus, and reductions in deadweight loss, is the concern of economists. Increasing total welfare and reducing deadweight loss may be the outcome in a situation that awards large windfalls to station owners. If the total welfare gains are greater than the windfall payments in full, then the benefits to social welfare outweigh the costs. On the other hand, if the windfall payments are so large that incumbents have little incentive to innovate or compete, then windfalls are net-negative propositions for the FCC.

4.1.3 Holdup

Michael Heller's The Gridlock Economy describes the recurring phenomenon of "holdup" in property rights regimes.[152] He refers to gridlock as the result of individual property holders' use of holdup techniques in situations that may lead to greater gains for those who can holdout the longest.

The incentive for incumbent licensees to holdout for higher prices is seen in real property cases too, where eminent domain may need to be resorted to, with constitutional consequences, in order to achieve commercial development.[153]

In spectrum auctions, the holdout problem has been dealt with through the incentive auction format with a reverse auction that precedes the forward auction. In the first phase, the auction design elicits bids from incumbents to reflect their true value that they would be willing to accept for compensation to clear the band. Without such a reverse auction, many incumbents may find that in game theoretic strategy, the better decision is to holdout perpetually and not clear the bands. But the socially beneficial outcome would be for these incumbents to allow new uses to better use the spectrum, thus, the challenge of overcoming holdup.

In the second phase, auction mechanisms such as package bidding and descending clock auctions and combinatorial bids also mitigate the risk of collusion by bidders to block or holdup other bidders from gathering a meaningful spectrum footprint.

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[152] Michael Heller, The Gridlock Economy (Boston: Press, 2006).
[153] *See generally* Kelo v. New London, 545 U.S. 469, 125 S. Ct. 2655 (2005).

The tragedy of the commons dynamics are explored in the governance literature by Elinor Ostrom.[154] Local or polycentric governance can mitigate the risks of deadweight loss from underuse or holdup of common goods. When more local forms of governance are implemented on smaller parcels, the risk of holdup is smaller, compared to centralized and large-scale rules that encourage incumbents to act strategically.

Because spectrum is a non-rivalrous, non-excludable good, there are important considerations to craft a reallocation market tool that enables participants to voluntarily transact in order to reach higher social welfare values. Even though both parties could transact and gain from the trade, there are transaction costs that may prevent the parties from reaching the trade. Ronald Coase is best known for this area of economic theory with his classic scholarship on "The Problem of Social Cost,"[155] and "The Federal Communications Commission."[156] In these articles, he unpacks the transaction costs that may block parties from reaching beneficial trades.

Whether radio spectrum would be better organized under a governance or property rights regime involves an understanding of the nature of holdup by spectrum licensees. There are tradeoffs in whether a tort or property rights regime would better fit the type of boundary disputes that happen between spectrum neighbors and new entrants. Some argue that because of the non-rivalrous and non-excludable nature of the spectrum, a nuisance regime is more efficient than a property regime. Others oppose such a view, claiming that a property rights regime is more functional than a nuisance regime.[157] Still others have a hybrid approach to zoning regimes that would combine elements of the two.[158] In the classic "View of the Cathedral," tort scholars Douglas Melamed and Guido Calabresi discuss the considerations for each type of rule.[159]

This discussion of governance or property rights directly applies to how the FCC decides whether, how much, and where to allocate bands to unlicensed or licensed users. In the pre-auction phase, the decision on what the use of the band will be still remains a beauty contest of sorts. Some have suggested that even this decision on type of use should be decided through a market mechanism. In a stage 0 auction, perhaps the FCC should allow participants to bid on their choice of spectrum band rules. In some cases, however, there will be few participants that are willing to bid on an unlicensed designation, a public good, if you will. Where everyone has access and no one pays for access, few private parties would want to carry the cost for all the other free riders, at least goes the argument. Presumably, however, today, some market

[154] Ostrom, E. 1990. Governing the Commons: The Evolution of Institutions for Collective Action. New York: Cambridge University Press.

[155] Ronald Coase, "The Problem of Social Cost," Journal of Law and Economics, Vol. 3 (1960), pp. 1-44.

[156] Ronald Coase, "The Federal Communications Commission", Journal of Law and Economics: Vol. 2: No. 1 (1959).

[157] Thomas W. Hazlett, A Law & Economics Approach to Spectrum Property Rights: A Response to Weiser and Hatfield, 15 Geo. Mason L. Rev. 975 (2008).

[158] Phil Weiser and Dale Hatfield, Spectrum Policy Reform and the Next Frontier of Property Rights, George Mason Law Review, 15 Geo. Mason L. Rev. 549 (2008); Phil Weiser and Dale Hatfield, Property Rights in Spectrum: Taking the Next Step, George Mason Law Review, Vol. 15, No. 3 (2008).

[159] Guido Calabresi & A. Douglas Melamed, "Property Rules, Liability Rules, and Inalienability: One View of the Cathedral," 85 Harv. L. Rev. 1089 (1972)).

participants may be willing to bid for Wi-Fi designations, such as Wi-Fi equipment manufacturers, and coalitions of technology firms that rely on unlicensed airwaves.

4.1.4 The "Interference Veto"

Another complication of reallocating spectrum is the specter of an "interference veto" where somewhere years in advance, a neighboring or incumbent spectrum licensee claims the threat of harmful interference with a new use. In this situation, the new use has gone through years of vetting, analysis, and engineering studies, and concerns raised were addressed and commented on publicly. After the new use is approved and deployed, a harmful interference claim arises anew. Such is the case with the FAA and 5G conflict, as an example. Another example is the Ligado Networks and Department of Defense's concern for the GPS network.

In this "interference veto" scenario, the threat of harmful interference can hang over any new entrant, even after regulatory dockets have been completed and approvals have been gained, and monetary transfers have been made. The FCC may have even run a multi-billion-dollar auction, as is the case in the FAA and 5G conflict in the C-Band, and still face an unexpected crisis that rises to the White House for dispute resolution.

4.2 Secondary Markets

4.2.1 History of Secondary Markets

In 2003 and 2004, the FCC facilitated the development of secondary markets in radio spectrum through two regulatory proceedings that established new procedures for registering license sales and transfers of control that occurred outside of FCC auctions in private transactions.[160] In 2005, the Universal Licensing System needed some adjustments in order to accommodate the filing of these new assignments and transfers of control, and in 2006, a new FCC Form 608 was established to notify the FCC of private commons arrangements.[161]

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[160] FCC, Secondary Markets Initiative and Spectrum Leasing, https://www.fcc.gov/secondary-markets-initiative-and-spectrum-leasing; citing In the Matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, Report & Order and Further Notice of Proposed Rulemaking, FCC 03-113, Oct. 6, 2003, https://docs.fcc.gov/public/attachments/FCC-03-113A1.pdf; Memorandum Opinion and Order, DA 04-239, Jan. 30, 2004, https://docs.fcc.gov/public/attachments/DA-04-239A1.pdf; Second Report & Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking, FCC 04-167, Sept. 2, 2004, https://docs.fcc.gov/public/attachments/FCC-04-167A1.pdf.

[161] FCC, Public Notice, WTB Announces Changes to the Universal Licensing System to Implement the Commission's Immediate Approval Procedures for Wireless License Assignments and Transfers, July 29, 2005, DA 05-2226, https://docs.fcc.gov/public/attachments/DA-05-493A1.pdf; WTB Announces FCC Form 608 is Available for Filing Spectrum Leasing Notifications and Applications and Private Commons Arrangements, DA 06-1723, Aug. 28, 2006, https://docs.fcc.gov/public/attachments/DA-06-1723A1.pdf. .

Federal Communications Commission **FCC 03-113**

JOINT STATEMENT OF
CHAIRMAN MICHAEL K. POWELL and COMMISSIONER KEVIN J. MARTIN

Re: *Promoting Efficient Use of the Spectrum Through Elimination of Barriers to the Development of Secondary Markets; Report and Order and Further Notice of Proposed Rulemaking; WT Docket No. 00-230*

Today's action is one of the most important spectrum reform decisions by this Commission in the last decade. For years, the Commission has rhetorically praised the concept and possibilities created by secondary markets in spectrum. Today that rhetoric turns into reality. Our decision unlocks value trapped for too many years in a regulatory box. That box was most clearly epitomized by the anachronistic 40-year old *Intermountain Microwave* standard, which required Commission prior approval for a license transfer any time a licensee ceded any of a panoply of responsibilities associated with equipment, salaries, personnel and sundry other activities. We are pleased to announce the passing of *Intermountain*, as we explicitly abandon that standard for spectrum leases. Built on the 2000 *Spectrum Policy Statement* as refined and developed by this Commission, today we adopt a new standard more narrowly tailored to the statutory requirements and more suited to today's marketplace. Our decision signals a new day of increased spectrum access and improved services for consumers.

Figure 41. Joint Statement of Chairman Michael K. Powell and Commissioner Kevin J. Martin on Secondary Markets[162]

Upon the passage of the 2003 order, Chairman Michael Powell remarked on the importance of the secondary markets order in a joint statement with Commissioner Kevin Martin, "Today's action is one of the most important spectrum reform decisions by this Commission in the last decade…"[163] He goes on to note that the FCC order serves as a reform to the "anachronistic 40-year old *Intermountain Microwave* standard, which required Commission prior approval for a license transfer any time a licensee ceded any of a panoply of responsibilities…"[164] Based on the 2000 *Spectrum Policy Statement*, the FCC's new standard "signals a new day of increased spectrum access and improved services for consumers."[165]

In order to get to these regulatory changes, the FCC started the process in 2000 with a policy statement on principles for promoting efficient use of spectrum through secondary markets,[166]

[162] FCC, Joint Statement of Chairman Michael K. Powell and Commissioner Kevin J. Martin on WT Docket No. 00-230, FCC 03-113, Oct. 6, 2003, FCC, Public Forum on Secondary Markets in Radio Spectrum, DA 00-1139, Transcript, May 23, 2000, https://www.fcc.gov/realaudio/tr053100.pdf.
[163] FCC, Joint Statement of Chairman Michael K. Powell and Commissioner Kevin J. Martin on WT Docket No. 00-230, FCC 03-113, Oct. 6, 2003, FCC, Public Forum on Secondary Markets in Radio Spectrum, DA 00-1139, Transcript, May 23, 2000, https://www.fcc.gov/realaudio/tr053100.pdf.
[164] *Id.*
[165] *Id.*
[166] FCC, Policy Statement, Principles for Promoting the Efficient Use of Spectrum by Encouraging the Development of Secondary Markets, FCC 00-401, Dec. 1, 2000, https://docs.fcc.gov/public/attachments/FCC-00-401A1.pdf.

opened a docket with a notice of proposed rulemaking,[167] and held a public forum on secondary markets.[168]

In fact, the work towards secondary markets began in March 5, 1996[169] and April 6, 1999[170] with *En Banc* Hearings on Spectrum Management.[171] Based on extensive public hearings and panelist testimony, the FCC released their 2000 Spectrum Policy Statement and Secondary Markets Initiative.

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[167] FCC, Notice of Proposed Rulemaking, Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, FCC 00-402, Nov. 27, 2000, https://docs.fcc.gov/public/attachments/FCC-00-402A1.pdf.

[168] FCC, Public Forum on Secondary Markets in Radio Spectrum, DA 00-1139, Transcript, May 23, 2000, https://www.fcc.gov/realaudio/tr053100.pdf (for the May 31, 2000 forum).

[169] FCC, En Banc Hearing on Spectrum Policy, Panelists and Transcript, Mar. 5, 1996, https://transition.fcc.gov/Reports/enbanc_spectrum.rpt.txt.

[170] FCC, En Banc Hearing on Spectrum Management, Panelists, Apr. 6, 1999, https://www.fcc.gov/news-events/events/1999/04/en-banc-hearing-on-spectrum-management; Transcript, https://transition.fcc.gov/enbanc/040699/tr040699.pdf. .

[171] FCC, Policy Statement, Principles for Promoting the Efficient Use of Spectrum by Encouraging the Development of Secondary Markets, FCC 00-401, Dec. 1, 2000, https://docs.fcc.gov/public/attachments/FCC-00-401A1.pdf, at ¶ 8.

1

IN THE UNITED STATES FEDERAL COMMUNICATIONS COMMISSION

In the Matter of:)
)
SECONDARY MARKET FORUM)
)

Main Commission Meeting Room
Federal Communications Commission
445 12th Street, S.W.
Washington, D.C.

Wednesday,
May 31, 2000

APPEARANCES:

DALE HATFIELD, Chief, Office of Engineering and Technology, FCC
WILLIAM KENNARD, Chairman, FCC
SUSAN NESS, Commissioner, FCC
HAROLD FURCHTGOTT-ROTH, Commissioner, FCC
PETER CRAMTON, Chairman, Spectrum Exchange and Professor of Economics, University of Maryland
MORGAN O'BRIEN, Vice Chairman, Nextel Communications
CARESSA BENNET, Counsel for the Rural Telecommunications Group
MARK CROSBY, President and CEO, Industrial Telecommunications Associations
ROBERT PEPPER, Chief, Office of Plans and Policy, FCC
SHARON CROWE, Vice President, Bandwidth Markets, Williams Communications
LAURENCE GREEN, Director, Strategy Unit, UK Radiocommunications Agency
MIKE ANTONOVICH, Senior Vice President, Broadcast Services, PanAmSat Corporation
RICHARD REECE, Chairman, Red Bat Communications
TOM HAZLETT, Resident Scholar, American Enterprise Institute
RICH BARTH, Vice President and Director of Telecommunications Strategy and Regulation, Motorola Corporation
JOE MITOLA, Consulting Scientist, Mitre Corporation
MICHELLE FARHQUAR, Attorney, Hogan and Hartson
ROBERT SHIVER, Chief Executive Officer and President, Securicor Wireless Holdings, Inc.

Figure 42. Transcript from Public Forum on Secondary Markets, May 2000[172]

[172] FCC, Public Forum on Secondary Markets in Radio Spectrum, DA 00-1139, Transcript, May 23, 2000, https://www.fcc.gov/realaudio/tr053100.pdf.

17. We believe that a secondary market for spectrum resources can develop as it has for wireline bandwidth, which is now being actively traded like traditional commodities such as oil, gas, and grains.[24] We believe that the limited secondary market activity in spectrum usage rights is the result of a combination of factors that include: 1) regulatory constraints, 2) the availability of equipment for operation, and 3) the lack of adequate systems and information for the conduct of effective trading and market operations. We believe that it is possible to achieve improvements in each of these areas, and thereby to move towards a more freely functioning system of secondary markets for spectrum usage rights. In developing specific initiatives for improving secondary markets, we believe it is appropriate to rely on the general economic theory of markets. Certain essential elements that need to be present for a market system to operate most effectively include: 1) clearly defined economic rights; 2) full information on prices and products available to all participants; 3) mechanisms for bringing buyers and sellers together to make transactions with a minimum of administrative cost and delay; 4) easy entry and exit to the market by both buyers and sellers; and 5) effective competition, with many buyers and sellers.[25]

Figure 43. Essential Elements for Market System in Spectrum Assets[173]

In the 2000 Spectrum Policy Statement, the FCC outlined its findings on the essential elements for secondary market activity to operate effectively. The FCC based their secondary market initiative on "the general economic theory of markets," and noted that elements that are needed for market functioning are: "1) clearly defined economic rights; 2) full information on prices and products available to all participants; 3) mechanisms for bringing buyers and sellers together to make transactions with a minimum of administrative cost and delay; 4) easy entry and exit to the market by both buyers and sellers; and 5) effective competition, with many buyers and sellers."[174]

Whether these conditions are too strict is up for debate by economists and legal scholars. Regulators need not wait for exact definitions of rights or full information on prices before markets can be implemented and iterative learning obtained.[175] Nevertheless, secondary markets in "traditional commodities such as oil, gas, and grains" have exhibited these characteristics, and the FCC determined that, so too, can intangible assets such as spectrum licenses.[176]

4.2.2 Secondary Market Transactions

[173] FCC, Policy Statement, Principles for Promoting the Efficient Use of Spectrum by Encouraging the Development of Secondary Markets, FCC 00-401, Dec. 1, 2000, https://docs.fcc.gov/public/attachments/FCC-00-401A1.pdf, at ¶ 17.

[174] *Id.* n.25 ("Of course, real world markets rarely satisfy fully all the conditions of perfect competition. They nonetheless often perform effectively. In particular, less-than-perfectly competitive markets can constitute mechanisms for generating public benefits superior to non-price mechanisms such as reliance on regulatory or administrative processes.").

[175] *See* Thomas Hazlett & Sarah Oh, "Exactitude in Defining Rights: Radio Spectrum and the 'Harmful Interference' Conundrum," 28 Berkeley Tech. L.J. 227-340 (2013), https://btlj.org/data/articles2015/vol28/28_1/28-berkeley-tech-l-j-0227-0340.pdf.

[176] FCC, Policy Statement, Principles for Promoting the Efficient Use of Spectrum by Encouraging the Development of Secondary Markets, FCC 00-401, Dec. 1, 2000, https://docs.fcc.gov/public/attachments/FCC-00-401A1.pdf, at ¶ 17.

After approving new procedures for secondary market transactions, licensees submitted their applications to the FCC for these private transfers. Mayo and Wallsten (2009) tabulated completed assignments of authorization and transfers of control from pre-1994 to 2009.[177]

Completed Assignments of Authorization and Transfers of Control by ULS Procedure[a]

Receipt Year	Notification-Track[b]			Approval-Track[c]		
	Total	Assignment	Transfer	Total	Assignment	Transfer
Pre-1994 [d]	28	12	16	2,754	1,115	1,639
1994	130	51	79	371	116	255
1995	2	1	1	14	11	3
1996	115	49	66	62	42	20
1997	457	219	238	395	214	181
1998	365	88	277	558	236	322
1999	346	209	137	906	416	490
2000	514	311	203	2,136	1,557	579
2001	559	308	251	3,285	2,888	397
2002	287	217	70	3,181	2,646	535
2003	166	100	66	2,322	1,946	376
2004	308	158	150	2,151	1,677	474
2005	358	269	89	2,558	2,102	456
2006	327	243	84	2,671	2,020	651
2007	211	139	72	2,301	1,579	722
2008	325	130	195	1,994	1,515	479
2009	96	26	70	215	178	37
Unkown	474	447	27	31	19	12
Total	5,068	2,977	2,091	27,905	20,277	7,628

Figure 44. Completed Assignments of Authorization (Mayo and Wallsten, 2009, tbl.2)

Over 2,000 transactions on average occurred each year between 2000 and 2008 (Mayo and Wallsten, 2009, tbl.2) in the approval track, most of which were assignments with some transfers.[178] Of these transactions, most of the approved assignments were in the industrial/business service code category, with other categories of transactions seen in commercial land mobile, microwave, public safety, and cellular bands.[179]

[177] John Mayo and Scott Wallsten, "Enabling Efficient Wireless Communications: The Role of Secondary Spectrum Markets," Technology Policy Institute Working Paper, June 2009, https://techpolicyinstitute.org/wp-content/uploads/2010/01/enabling-efficient-wireless-co-2007662.pdf.
[178] *Id.*
[179] *Id.* at tbl.3.

Completed Approval-Track Assignments of Authorization and Transfers of Control[a]
by Service Code Category,[b] 1994-2009[c]

Receipt year	Cellular	PCS	Industrial/ Business	Land Mobile		Broadband radio	Educational broadband	Public safety	Microwave	Paging	Coast & Ground	Other[d]	Unknown[e]	Total[f]
				Commercial	Private									
1994	0	1	0	0	0	0	0	0	0	0	0	0	370	371
1995	0	13	0	0	0	0	0	0	0	0	0	0	1	14
1996	0	54	0	1	0	0	0	0	0	0	0	0	7	62
1997	0	392	0	1	0	0	0	0	0	2	0	0	0	395
1998	136	177	0	14	0	0	0	0	81	135	0	8	16	558
1999	238	267	2	39	0	3	0	0	340	87	0	3	5	906
2000	234	295	534	489	12	0	0	5	584	95	0	94	1	2,136
2001	23	278	1,600	1,082	71	1	0	67	303	56	37	44	2	3,285
2002	38	188	2,017	589	47	0	0	217	325	68	93	10	7	3,181
2003	33	294	1,419	272	80	0	0	166	252	63	50	20	4	2,322
2004	98	235	1,431	173	50	0	0	94	260	57	58	10	0	2,151
2005	31	237	1,560	455	47	90	23	109	220	78	67	15	8	2,558
2006	100	220	1,500	373	75	70	27	302	264	76	43	9	5	2,671
2007	120	191	1,370	166	62	81	24	204	361	47	52	4	2	2,301
2008	103	182	1,075	93	57	189	43	163	308	31	50	5	2	1,994
2009	0	10	133	9	6	0	0	45	21	6	5	0	0	215
Totals	1,154	3,034	12,641	3,756	507	434	117	1,372	3,319	801	455	222	3,215 [g]	27,905 [g]

Figure 45. Completed Approval-Track Assignments by Service Code Category (Mayo and Wallsten 2009, tbl.3)

Aside from assignments or transfers, spectrum licensees started to lease their spectrum holdings under the new rules and Form 603-T. Between 2004 and 2006, approximately 300 completed spectrum leases were filed at the FCC, most of which were de facto transfers and the rest of which were spectrum manager applications.[180]

Completed Spectrum Leases
2004 - August 27, 2006

Receipt year	Leases and Subleases			Lease Assignments & Transfers
	Spectrum Manager	*De facto* Transfer	Total	
2004	50	70	120	2
2005	96	229	325	13
2006	54	301	355	38

Figure 46. Completed Spectrum Leases 2004-2006 (Mayo and Wallsten, 2009, tbl.4)

Of these completed spectrum leases, most were in service code categories for PCS and educational broadband.[181]

[180] *Id.* at tbl.4.
[181] *Id.* at tbl.5.

Completed Spectrum Leases, Application Form 608 New Leases and Subleases[a] by Service Code Category,[b] and Term Length,[c] 2006-2009[d]													
Receipt Year	Lease Term	Cellular	PCS	Industrial/Business	Land Mobile Commercial	Broadband Radio	Educational Broadband	Microwave	Paging	Coast & Ground	Other[e]	Unknown[f]	Total[g]
2006	Short	1	4	-	1	-	-	5	1	-	-	1	10
	Long	-	10	5	3	9	128	6	-	-	-	-	161
2007	Short	8	44	1	6	6	6	7	3	-	-	-	79
	Long	-	61	20	18	14	403	24	2	-	1	-	541
2008	Short	29	106	-	11	14	6	46	5	-	1	1	202
	Long	2	51	4	16	13	219	55	1	13	-	-	372
2009	Short	1	3	-	3	5	-	2	1	-	-	-	15
	Long	-	7	-	1	2	14	6	-	1	-	-	31
Total		41	286	30	59	63	776	151	13	14	2	2	1411

Figure 47. Completed Spectrum Leases by Service Category (Mayo and Wallsten, 2009, tbl.5)

The more important question for these secondary market transactions is the magnitude of the spectrum traded, not necessarily the number of transactions or categories. Mayo and Wallsten (2009) tracked the MHz-Pops of these transfers and leases to normalize the transactions by the amount of bandwidth and the population sizes of the geographic areas of the license areas. In billions of MHz-Pop, the largest amounts of spectrum trades happened in 2002 with 582.770 billion MHz-Pop traded, then in 1999 with 185.610 billion MHz-Pop traded, and 2006 with 144.192 billion MHz-Pop traded.[182] The bulk of spectrum rights traded were in the microwave bands in 2002, 1999, and 2006.

Spectrum Traded in Voluntary, Non-Pro Forma Transfers and Full Assignments of Market-Based Licenses by Service Code Category in billions of MHz-Pops							
Year	PCS	Land Mobile Commercial	Broadband Radio	Microwave	Paging	Coast & Ground	Total
1997	0.307	0.004					0.311
1998	3.051	0.013		10.576			13.640
1999	12.106	2.530		170.974			185.610
2000	13.436	0.716		9.035	0.004		23.191
2001	9.175	0.468		87.200	0.005		96.848
2002	5.390	0.354		577.000	0.012	0.014	582.770
2003	12.613	0.121		49.100	0.016	0.001	61.851
2004	14.575	0.188		14.674	0.056	0.015	29.509
2005	7.659	7.510	12.600	56.200	0.030	0.035	84.034
2006	8.918	1.100	1.030	133.000	0.052	0.093	144.192
2007	9.143	2.200	2.400	37.899	0.027	0.043	51.712
2008	12.581	0.326	18.699	10.052	0.009	0.087	41.754
2009	0.613	0.034	0.014	1.130	0.006		1.797

Figure 48. Spectrum Traded by Service Code Category (Mayo and Wallsten, 2009, tbl.6)

An updated set of statistics for the last decade, between 2009 and 2022, would be well-worth studying. Nevertheless, observing the activity in secondary market transactions in the first

[182] *Id.* at tbl.6.

decade of the FCC's program shows that there are markets for spectrum licenses outside of auctions.

Market tools can include auctions, but they also include secondary market procedures such as assignments, transfers, and leases. The FCC is still involved in registering and being a source of truth and provenance for the holders of spectrum rights, but private entities are able to negotiate and contract on their own before filing updates to the FCC's Universal License System and obtaining approvals for the transfers.

4.2.3 Perspectives on Spectrum Markets

Peter Huber, a name partner of a national law firm, and prominent writer of a well-read legal treatise, has argued to eliminate the FCC's role in spectrum transactions,[183] but until Congress changes the authorizing statute of the FCC, the agency with the Department of Commerce, have authority over allocations and license registrations on the U.S. radio spectrum.

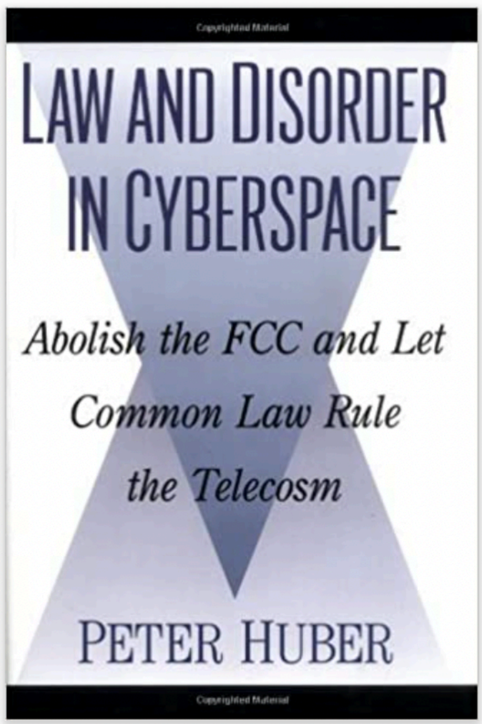


Figure 49. Law and Disorder in Cyberspace (Peter Huber, Oxford University Press, 1997)

[183] Peter Huber, Law and Disorder in Cyberspace: Abolish the FCC and Let Common Law Rule the Telecosm (Oxford University Press, 1997), https://www.amazon.com/Law-Disorder-Cyberspace-Abolish-Telecosm/dp/0195116143.

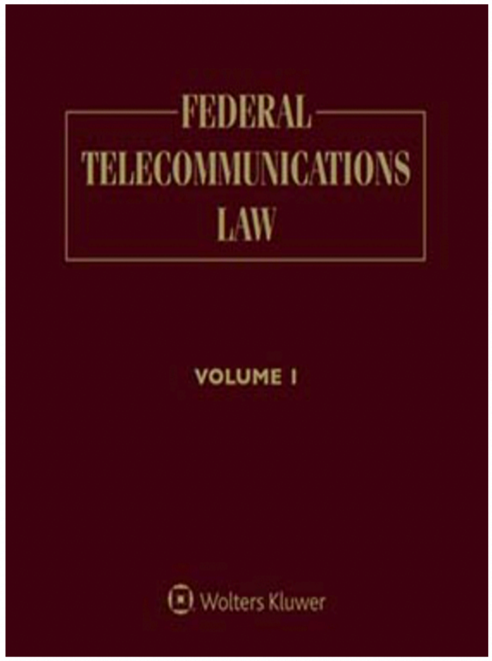


Figure 50. Federal Telecommunications Law by Peter Huber, Michael Kellogg, John Thorne

The political economy that governs the radio spectrum ecosystem explains why some market tools are implemented and others are not currently feasible. The regulators, industry, constituents, and international governance bodies all have incentives and strategic behavior that leads to slow change and often inefficient outcomes. Thomas Hazlett has chronicled political episodes that have shaped spectrum policy since the Radio Act of 1934.[184]

[184] Thomas Hazlett, The Political Spectrum: The Tumultuous Liberation of Wireless Technology, from Herbert Hoover to the Smartphone (Yale University Press, 2017), https://www.amazon.com/Political-Spectrum-Tumultuous-Liberation-Technology/dp/0300210507.

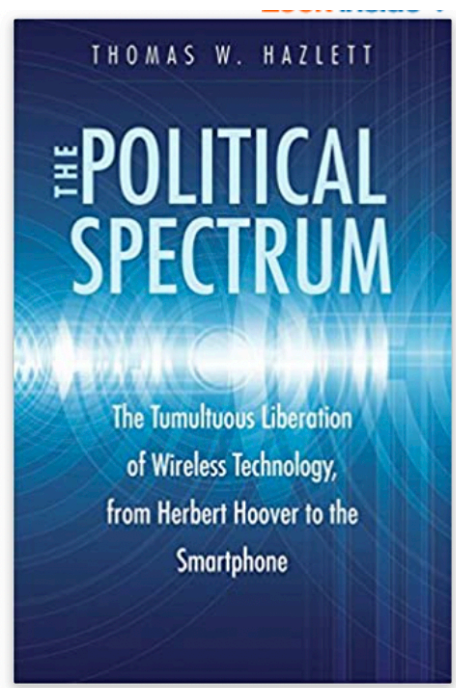


Figure 51. The Political Spectrum: The Tumultuous Liberation of Wireless Technology, from Herbert Hoover to the Smartphone (Thomas Hazlett, Yale University Press, 2017)

Despite the politics and regulations governing radio spectrum, entrepreneurs have found ways to purchase spectrum licenses to build nationwide networks. Craig McCaw is one business leader who patched together a cellular phone empire during the transition from beauty pageants to lotteries (before auctions) which he then sold to AT&T in 1994 for $12.6 billion.[185]

[185] O. Casey Corr, Money From Thin Air (Crown Business, 2000), https://www.amazon.com/gp/product/0812926978/.

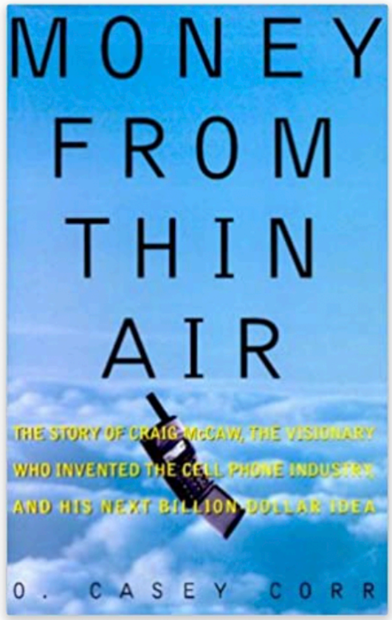
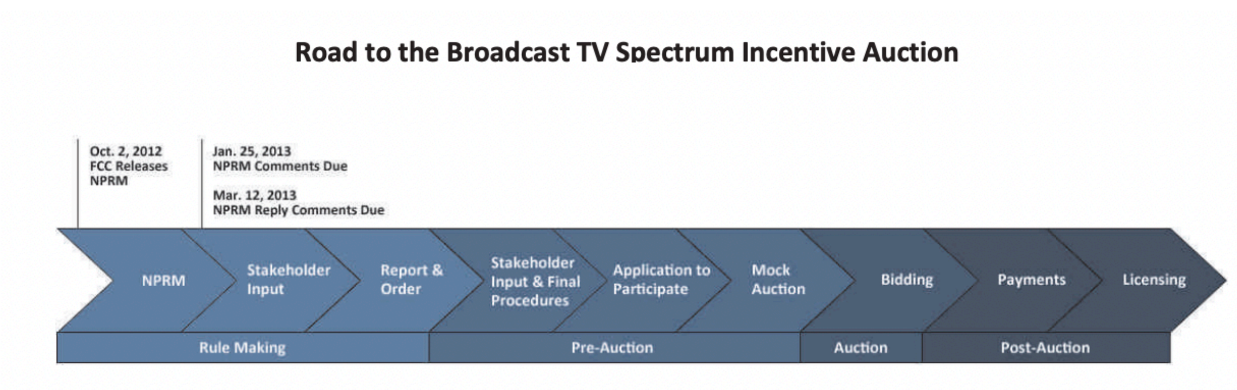


Figure 52. Money from Thin Air: The Story of Craig McCaw (O. Corey Corr, 2000)

4.3 Incentive Auctions

In 2012, the FCC started planning for the first-ever "incentive auction" that would clear the spectrum band of broadcast TV stations and auction that newly cleared spectrum to new licensees.[186] FCC Auctions 1001 and 1002 were started in March 2016 and ended April 2017, with 39 months of additional time for TV stations to transition to new channel assignments.[187]



[186] FCC, The Broadcast Television Spectrum Incentive Auction: A Staff Summary, Jan. 16, 2013, https://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-staff-summary.
[187] FCC, Broadcast Incentive Auction and Post-Auction Transition, May 9, 2017, https://www.fcc.gov/about-fcc/fcc-initiatives/incentive-auctions.

Figure 53. Roadmap to Broadcast TV Auction[188]

The broadcast TV incentive auction is an example of a market tool that enabled spectrum users to reorder the radio spectrum. The auction successfully cleared a valuable spectrum band by compensating broadcast TV stations to move their operations to other bands or to turn off altogether. But the auction also showed that less than the full amount of spectrum was cleared than could have been available.

Yet, $19.8 billion was raised for 84 MHz of "beachfront property" spectrum, 70 MHz for licensed and 14 MHz for unlicensed, with highly favorable characteristics for mobile communications.[189] The price of the spectrum amounted to $0.50 per MHz/pop on average, which was less than the projected $0.85-$0.95 per MHz/pop estimated by wireless providers.[190]

In the next sections, we go into the details of the broadcast TV incentive auction with a discussion of reasons why the auction was designed the way it was.[191] Alternative ways of clearing and auctioning the broadcast TV band were proposed and considered, but this format was ultimately selected after a lengthy notice and proposed rulemaking proceeding. The alternatives, such as overlay licenses[192] could have had other thorny issues and challenges, such as the possibility of windfall profits to incumbent licensees. Recall the discussion above about the pros and cons of windfalls in reallocation decisions on particular spectrum bands.

4.3.1 Digital Television Transition

Around the world, analog television stations were upgrading to digital television signals in the digital television transition, also known as the "digital switchover" or "analogue shutdown."[193] The transition started in 2003 in Berlin as the first city and 2006 in Luxembourg as the first country to complete the transition.[194]

[188] FCC, The Broadcast Television Spectrum Incentive Auction: A Staff Summary, Jan. 16, 2013, https://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-staff-summary.
[189] FCC, Broadcast Incentive Auction and Post-Auction Transition, May 9, 2017, https://www.fcc.gov/about-fcc/fcc-initiatives/incentive-auctions.
[190] Scott Wallsten, "Don't Be Disappointed by the FCC's Incentive Auction," Technology Policy Institute, Jan. 17, 2017, https://techpolicyinstitute.org/publications/miscellaneous/the-fccs-incentive-auction-is-not-a-disappointment/, citing Craig Moffett (2017).
[191] *Id.*, citing Evan Kwerel and John Williams, "A Proposal for A Rapid Transition to Market Allocation of Spectrum," FCC OPP Working Paper Series, 2002, http://wireless.fcc.gov/auctions/conferences/combin2003/papers/masterevanjohn.pdf.
[192] *Id.*, citing Thomas Hazlett, "Optimal Abolition of FCC Allocation of Radio Spectrum," Journal of Economic Perspectives Vol. 22 (Winter 2008).
[193] Digital Television Transition, https://en.wikipedia.org/wiki/Digital_television_transition.
[194] *Id.*

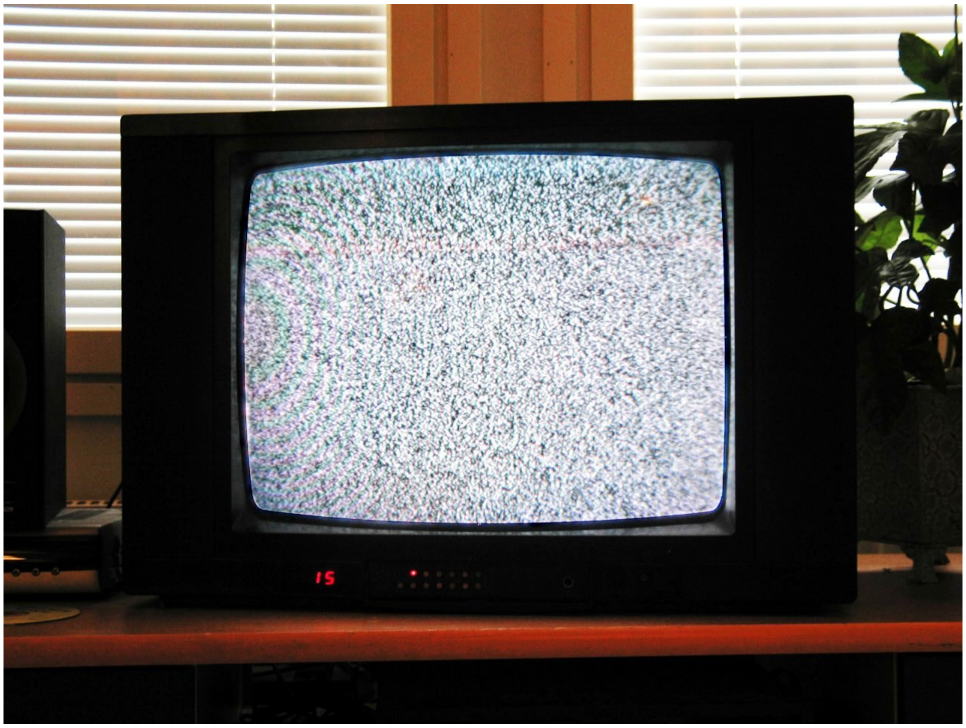


Figure 54. "An Analog TV Showing Noise"[195]

[195] Noise (video), Wikipedia, https://en.wikipedia.org/wiki/Noise_%28video%29.

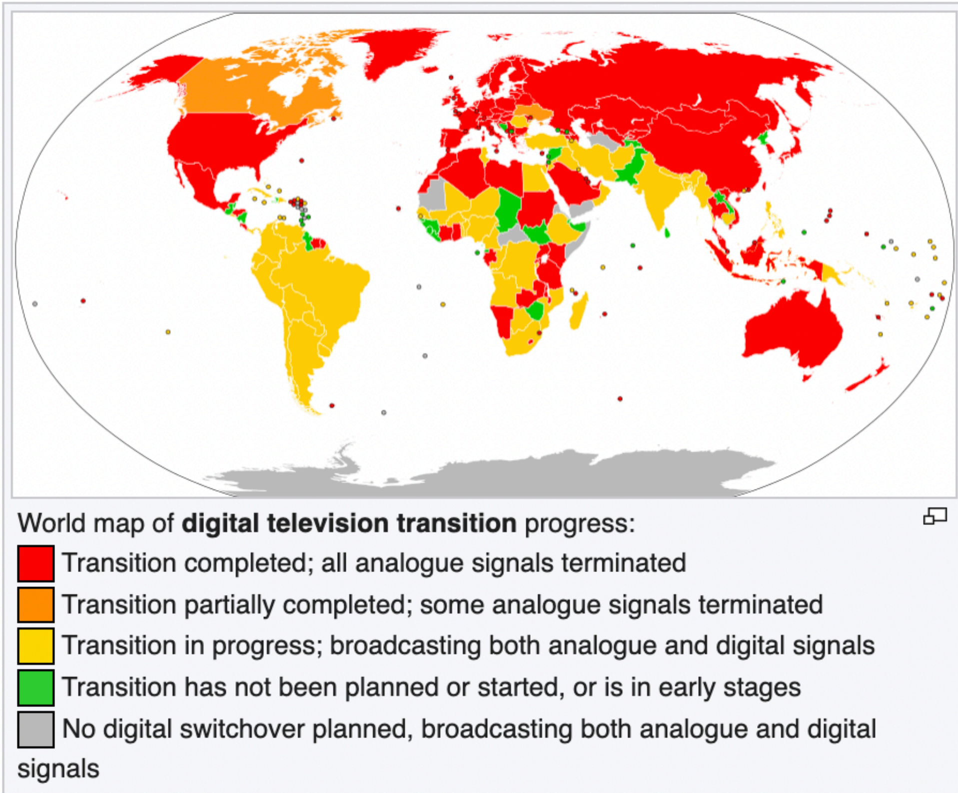


Figure 55. Global Digital Television Transition Status[196]

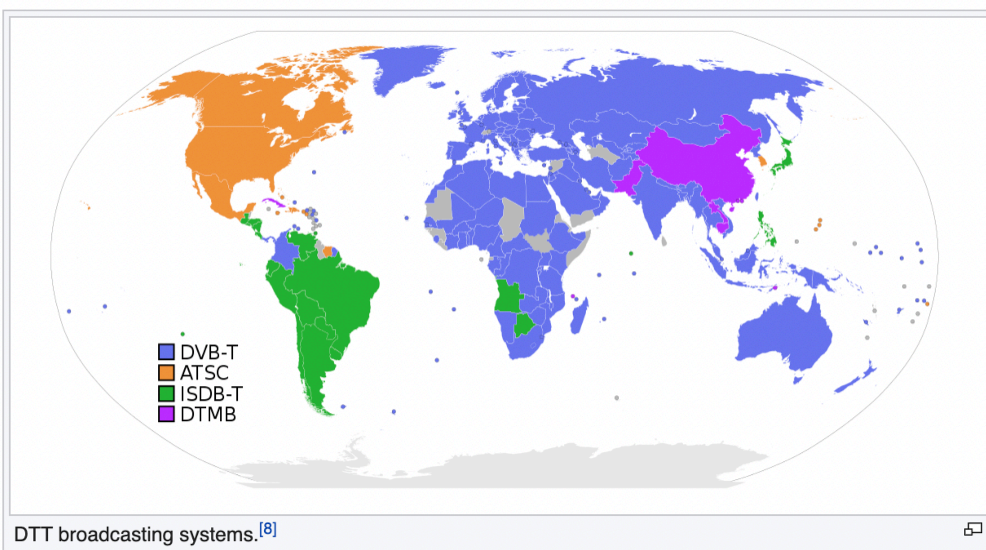


Figure 56. New Digital TV Standards[197]

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[196] Digital Television Transition, https://en.wikipedia.org/wiki/Digital_television_transition.
[197] Broadcast Television Systems, https://en.wikipedia.org/wiki/Broadcast_television_systems.

Since many households still used analog or "bunny ear" television sets, governments around the world subsidized digital-to-analog converter boxes so that analog televisions could still receive new digital signals.[198] To distribute the subsidies, the United States government used TV box vouchers and coordinated with electronics stores to distribute the digital converter boxes around the country.

Figure 57. A Digital TV Converter Box[199]

Figure 58. TV Converter Box Coupon Program Voucher[200]

4.3.2 FCC Broadcast TV Spectrum Incentive Auction

In 2012, the FCC released a notice of proposed rulemaking in Docket No. 12-268 to implement the Spectrum Act that included instructions for an incentive auction earlier outlined in the National Broadband Plan.[201]

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198 Digital Television Adaptor, https://en.wikipedia.org/wiki/Digital_television_adapter.

199 Source: Jeffrey Beall, Digital Television Adaptor, https://en.wikipedia.org/wiki/Digital_television_adapter.

200 Digital Television Transition in the United States, https://en.wikipedia.org/wiki/Digital_television_transition_in_the_United_States.

201 FCC, The Broadcast Television Spectrum Incentive Auction: A Staff Summary, Jan. 16, 2013, https://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-staff-summary, citing In the Matter of Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, Notice of Proposed Rulemaking, Docket No. 12-268, FCC 12-118, October 2, 2012, https://transition.fcc.gov/Daily_Releases/Daily_Business/2012/db1002/FCC-12-118A1.pdf.

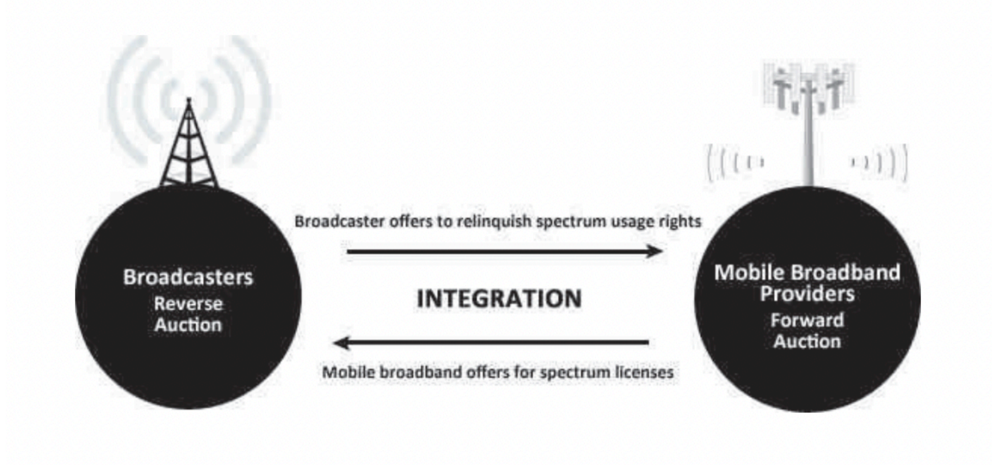

Figure 59. “A Novel Design for a Novel Process”[202]

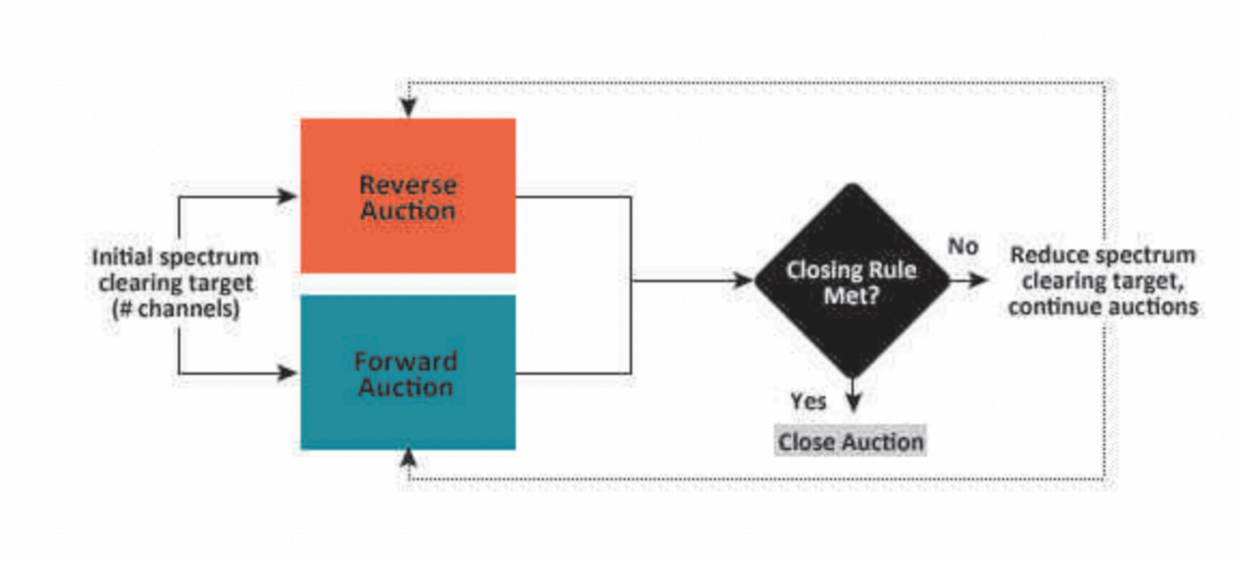

Figure 60. Simplified Version of Decision Chart for Auction Model[203]

[202] FCC, The Broadcast Television Spectrum Incentive Auction: A Staff Summary, Jan. 16, 2013, https://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-staff-summary.
[203] *Id.*

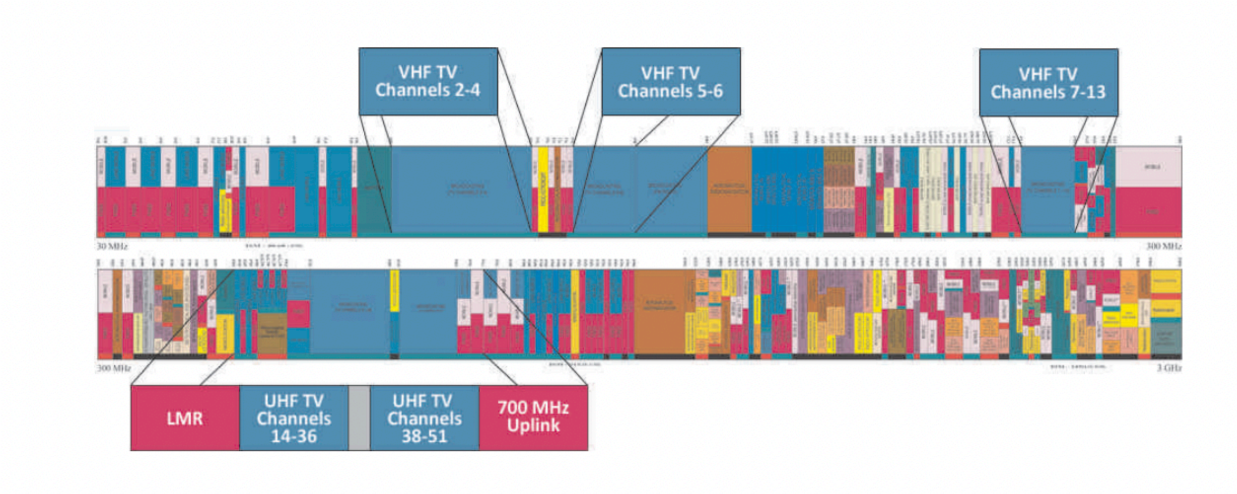

Figure 61. U.S. Broadcast Television Band with 8,402 TV Stations Prior to Auction[204]

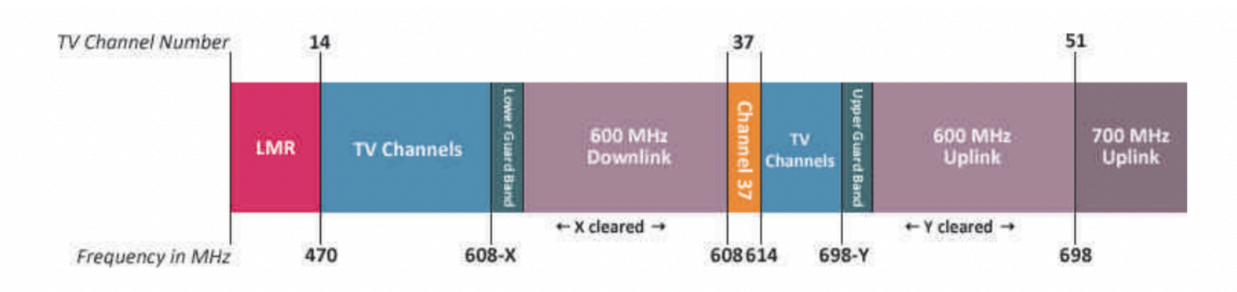

Figure 62. 600 MHz Band Pre Incentive Auction[205]

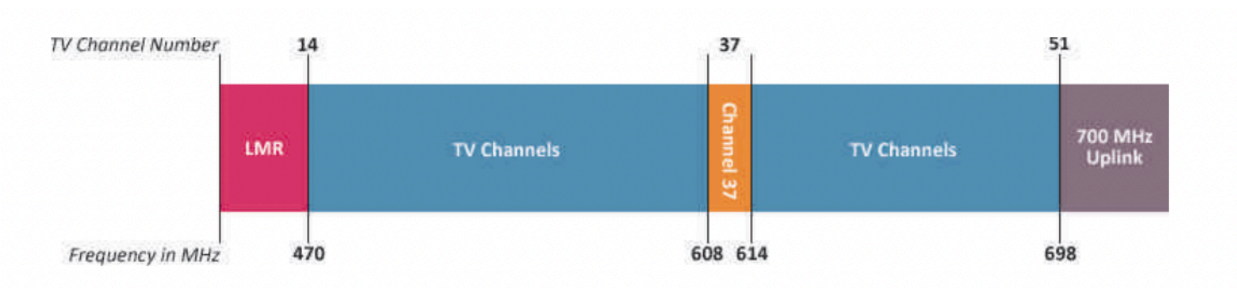

Figure 63. Proposed 600 MHz Band Post Incentive Auction[206]

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[204] FCC, The Broadcast Television Spectrum Incentive Auction: A Staff Summary, Jan. 16, 2013, https://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-staff-summary.
[205] *Id.*
[206] *Id.*

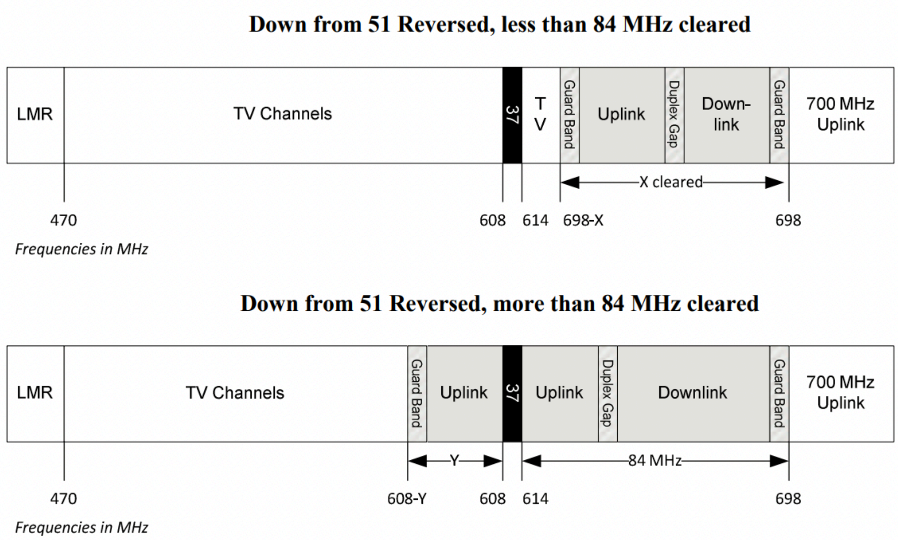

Figure 64. "Down from 51 Reversed" Band Plan Variations[207]

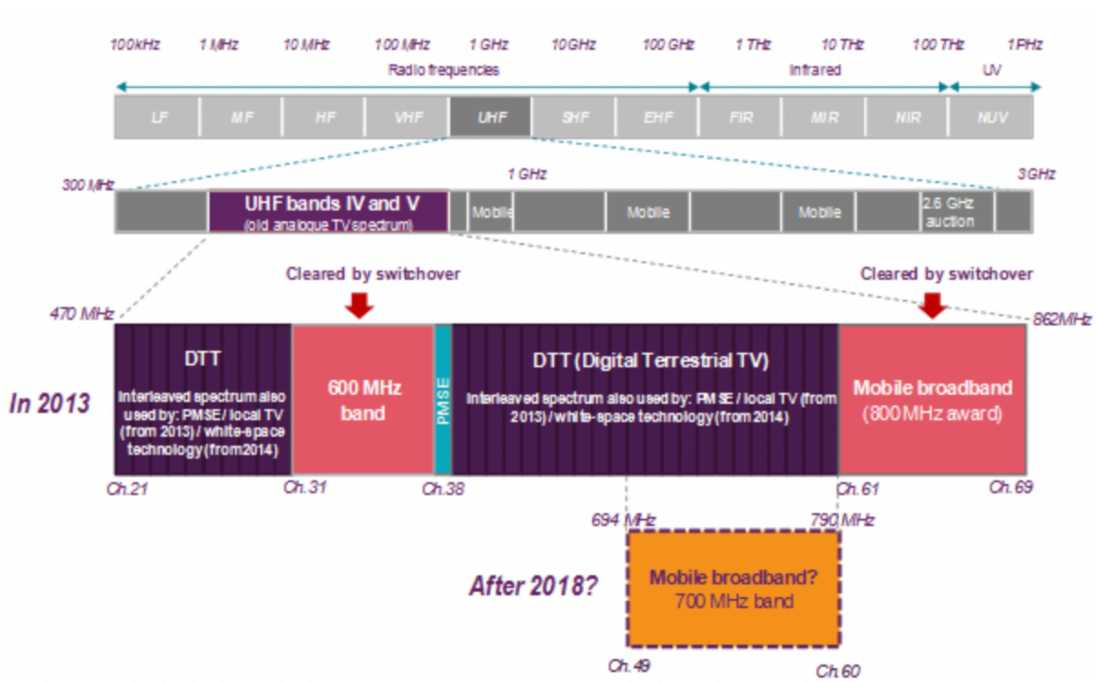

Figure 65. Digital TV in the UK in the 700 MHz Band[208]

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[207] FCC, WTB Seeks to Supplement the Record on the 600 MHz Band Plan, May 17, 2013, https://www.fcc.gov/document/wtb-seeks-supplement-record-600-mhz-band-plan.

[208] OFCOM, Future Use of the 700 MHz Band, Apr. 24, 2013, https://www.ofcom.org.uk/consultations-and-statements/category-1/700mhz-cfi, at fig.1.

In the regulatory docket, various band plans were considered to clear less than 84 MHz and more than 84 MHz of television band spectrum from the analog to digital transition. The FCC finally landed on the 84 MHz band plan in the Incentive Auction Report and Order.[209]

4.3.3 FCC Auction 1001: Reverse Auction – Clearing

FCC Auction 1001[210] was a descending auction or a reverse auction that was designed to elucidate how much value would need to be compensated to the broadcast stations in order for them to give up their spectrum and clear it for new users.[211]

Reverse auction winning bids totaled $10,054,676,822.[212] Of those auction revenues, eligible broadcasters and MVPDs received $1.75 billion in reimbursement payments.[213]

FCC Broadcast Television Spectrum Incentive Auction
Auction 1001
Winning Bids
(Sorted by DMA and Call Sign)
Date of Report: 04/04/2017 03:56 PM ET

Appendix A

Call Sign	Facility ID	DMA	Bidder as of Closing PN	FRN as of Closing PN	Pre-Auction Band	Winning Bid Option	Compensation	Pre-Auction CSA	Post-Auction CSA
WCDC-TV	74419	Albany-Schenectady-Troy, NY	NEXSTAR BROADCASTING, INC.	0009961889	UHF	Go off-air	$ 34,558,086	No	Yes
WAGT	70699	Augusta, GA	Gray Television Licensee, LLC	0003748241	UHF	Go off-air	$ 40,763,036	No	No
WUTB	60552	Baltimore, MD	Deerfield Media (Baltimore) Licensee, LLC	0022739833	UHF	Go off-air	$ 122,912,964	Yes	Yes
WBIN-TV	14682	Boston, MA	WBIN, Inc.	0020871042	UHF	Go off-air	$ 68,081,337	Yes	Yes
WDPX-TV	6476	Boston, MA	ION Media Boston License, Inc.	0003720208	UHF	Go off-air	$ 43,467,644	No	Yes
WFXZ-CD	64833	Boston, MA	WFXZ-CD Station, LLC	0021355565	UHF	Go off-air	$ 63,949,770	No	Yes
WGBH-TV	72099	Boston, MA	WGBH Educational Foundation	0003764560	UHF	Move to Low-VHF	$ 161,723,929	No	Yes
WLVI	73238	Boston, MA	WHDH-TV	0003613825	UHF	Go off-air	$ 162,108,481	Yes	Yes
WMFP	41436	Boston, MA	NRJ TV Boston License Co, LLC	0020523098	UHF	Go off-air	$ 93,647,708	No	Yes
WYCN-CD	9766	Boston, MA	OTA Broadcasting (BOS), LLC	0022430631	UHF	Go off-air	$ 80,401,978	No	Yes
WYDN	18783	Boston, MA	Educational Public TV Corporation	0008778565	UHF	Go off-air	$ 134,987,151	No	Yes
WIVB-TV	7780	Buffalo, NY	NEXSTAR BROADCASTING, INC.	0009961889	UHF	Go off-air	$ 46,015,135	Yes	Yes
WNYB	30303	Buffalo, NY	Faith Broadcasting Network, Inc.	0007202963	UHF	Move to Low-VHF	$ 31,960,949	No	Yes
WVTT-CD	10869	Buffalo, NY	Woodland Communications, LLC	0024819252	UHF	Move to High-VHF	$ 9,119,631	No	Yes
WNNE	73344	Burlington, VT-Plattsburgh, NY	Hearst Stations Inc.	0001587583	UHF	Go off-air	$ 50,464,592	No	Yes
WVTA	69943	Burlington, VT-Plattsburgh, NY	Vermont ETV, Inc.	0005067830	UHF	Go off-air	$ 56,648,952	Yes	No
WPBO	66190	Charleston-Huntington, WV	THE OHIO STATE UNIVERSITY	0006031983	UHF	Go off-air	$ 8,822,670	No	No

Figure 66. Excerpt from FCC Auction 1001 Winning Bids[214]

[209] In the Matter of Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, Report and Order, 29 FCC Rcd 6567, https://www.fcc.gov/document/fcc-adopts-rules-first-ever-incentive-auction, https://docs.fcc.gov/public/attachments/FCC-14-50A1.pdf.
[210] FCC, Auction 1001, https://www.fcc.gov/auction/1001.
[211] Janette Stewart and Mark Colville, "The US Incentive Auction and What it Means for Spectrum Auctions in Other Countries," Analysys Mason, July 19, 2017, https://www.analysysmason.com/about-us/news/newsletter/the-us-incentive-auction-jul17/.
[212] FCC Announces Results of World's First Broadcast Incentive Auction, https://www.fcc.gov/document/fcc-announces-results-worlds-first-broadcast-incentive-auction-0; *id*., FCC, Public Notice, Incentive Auction Closing and Channel Reassignment Public Notice, DA 17-314, Apr. 13, 2017, https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf.
[213] *Id.* at para. 2.
[214] FCC Announces Results of World's First Broadcast Incentive Auction, Apr. 13, 2017, https://www.fcc.gov/document/fcc-announces-results-worlds-first-broadcast-incentive-auction-0; *id*., Appendix A, https://docs.fcc.gov/public/attachments/DA-17-314A2.pdf. .

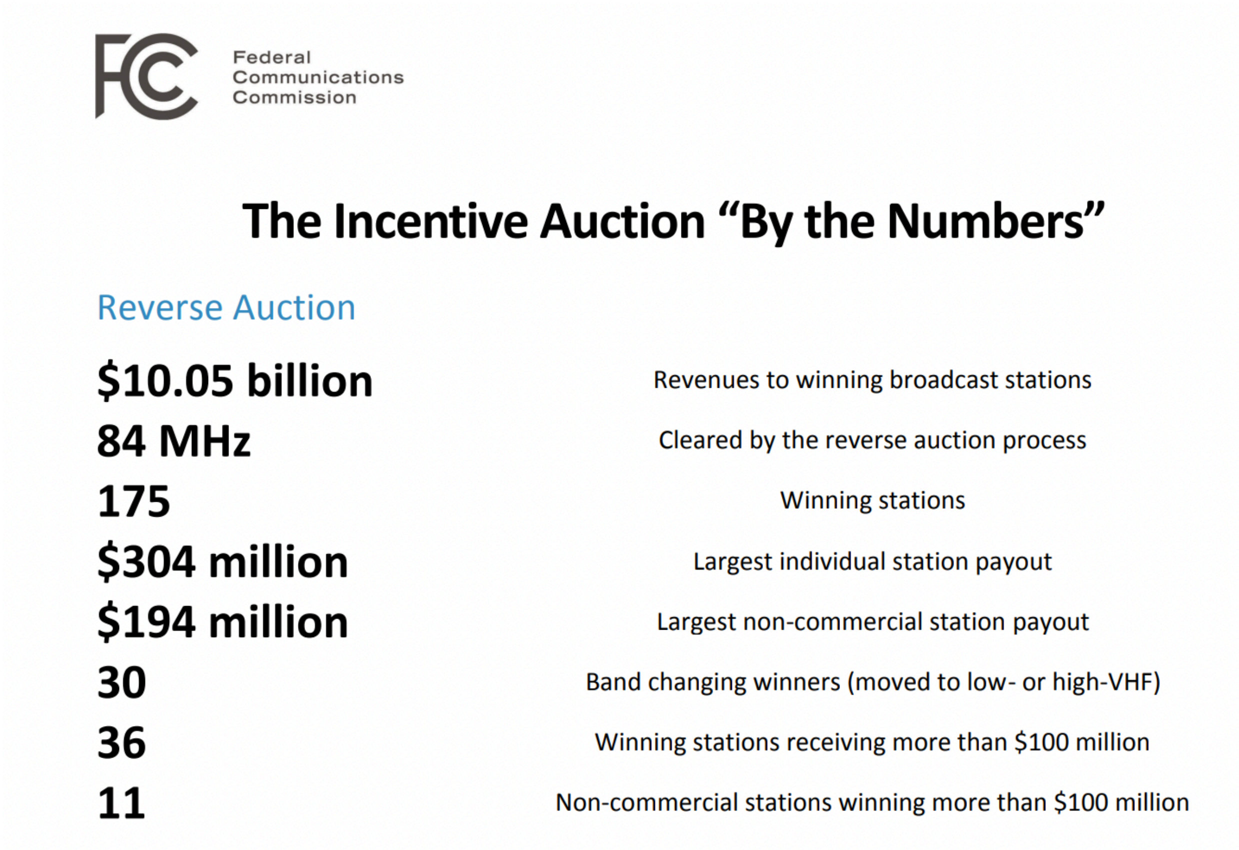
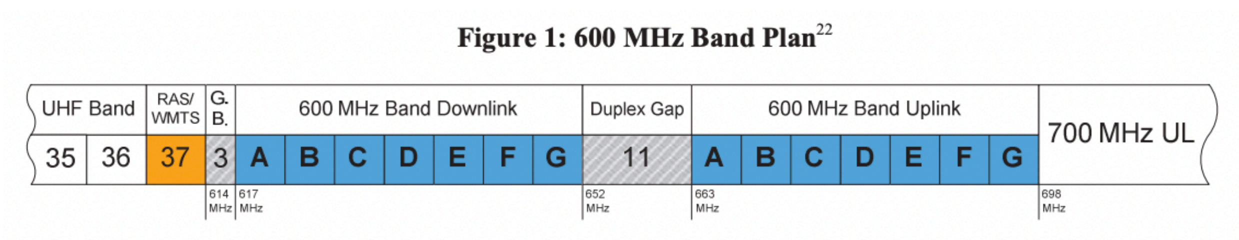


Figure 67. Reverse Auction - Results “By the Numbers”[215]

4.3.4 FCC Auction 1002: Forward Auction – New Licenses

FCC Auction 1002[216] was an ascending auction where mobile operators bid on the newly cleared spectrum.



[215] FCC Announces Results of World’s First Broadcast Incentive Auction, https://www.fcc.gov/document/fcc-announces-results-worlds-first-broadcast-incentive-auction-0; *id*., Fact Sheet, https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf.

[216] FCC, Auction 1002, https://www.fcc.gov/auction/1002.

Figure 68. 600 MHz Band Plan[217]

Table 1: 600 MHz Band License Summary

Block	Downlink Frequencies (in MHz)	Uplink Frequencies (in MHz)	Total Bandwidth	Geographic Area Type	No. of Licenses
A	617-622	663-668	10 MHz	PEA	416
B	622-627	668-673	10 MHz	PEA	416
C	627-632	673-678	10 MHz	PEA	416
D	632-637	678-683	10 MHz	PEA	416
E	637-642	683-688	10 MHz	PEA	416
F	642-647	688-693	10 MHz	PEA	416
G	647-652	693-698	10 MHz	PEA	416

Figure 69. 600 MHz Band License Summary[218]

[217] In the Matter of Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, Report and Order, 29 FCC Rcd 6567, https://www.fcc.gov/document/fcc-adopts-rules-first-ever-incentive-auction, https://docs.fcc.gov/public/attachments/FCC-14-50A1.pdf.

[218] In the Matter of Expanding the Economic and Innovation Opportunities of Spectrum Through Incentive Auctions, Report and Order, 29 FCC Rcd 6567, https://www.fcc.gov/document/fcc-adopts-rules-first-ever-incentive-auction, https://docs.fcc.gov/public/attachments/FCC-14-50A1.pdf.

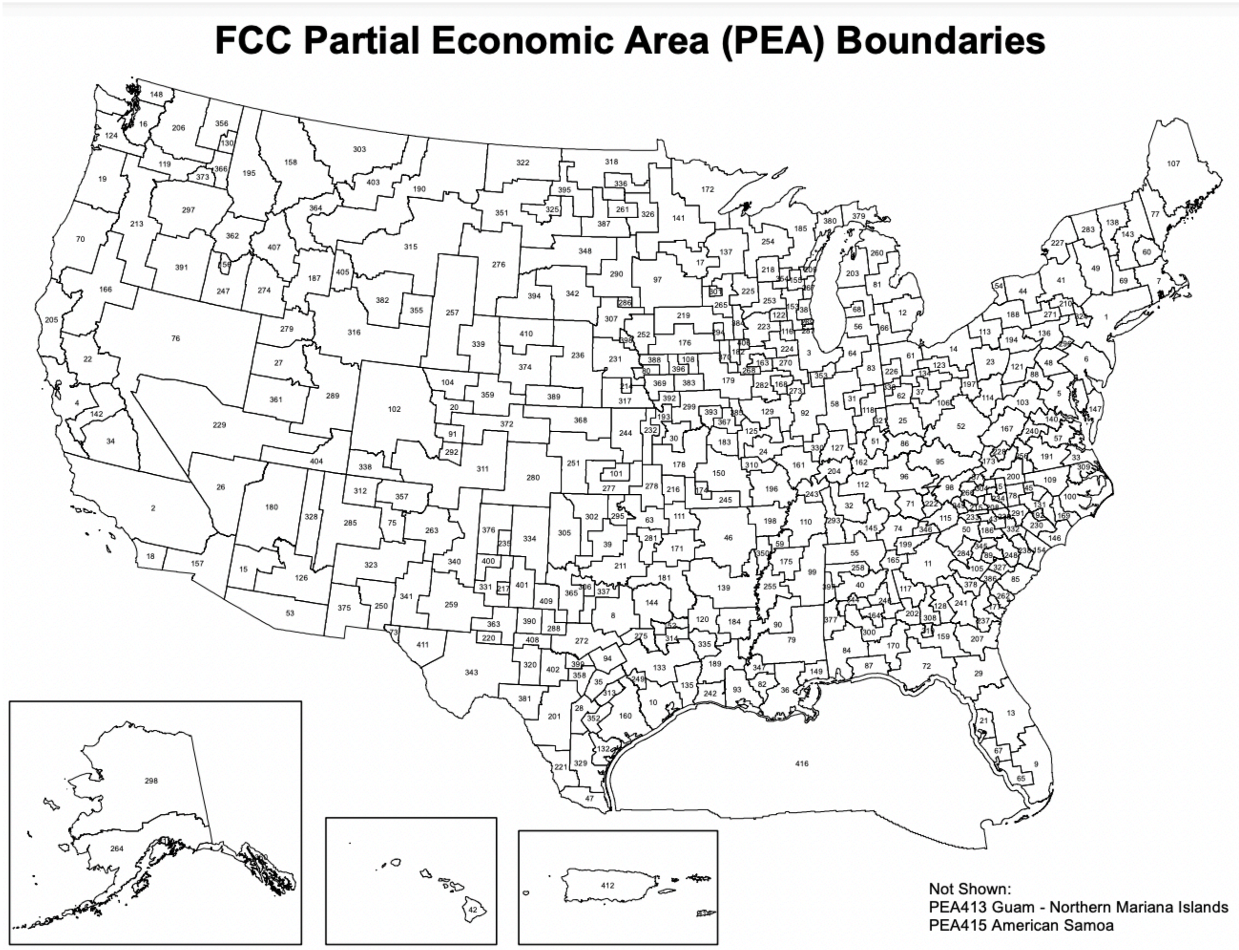


Figure 70. Forward Auction Partial Economic Area (PEA) Boundaries[219]

Forward auction winning bids totaled $19,768,437,378.[220] There were 50 bidders for 2,776 licenses. The licensed spectrum in the 600 MHz Band Plan included 70 MHz of spectrum in 7 pairs of 5 MHz blocks.[221] There were 2,912 new licenses available, but 2,776 licenses were released. An uplink band and downlink band were separated by a duplex gap and a guard band.

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[219] FCC, WTB Provides Details about Partial Economic Areas, https://www.fcc.gov/document/wtb-provides-details-about-partial-economic-areas; *Id*., Attachment, https://docs.fcc.gov/public/attachments/DA-14-759A4.pdf.

[220] FCC Announces Results of World's First Broadcast Incentive Auction, https://www.fcc.gov/document/fcc-announces-results-worlds-first-broadcast-incentive-auction-0; *id*., FCC, Public Notice, Incentive Auction Closing and Channel Reassignment Public Notice, DA 17-314, Apr. 13, 2017, https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf.

[221] FCC, Public Notice, Incentive Auction Closing and Channel Reassignment Public Notice, DA 17-314, Apr. 13, 2017, https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf.

FCC Public Reporting System

Dashboard
Reverse Auction
Auction Summary
Announcements
Initial Commitments
Winning Bids
Bids
Results
Statistics
Stations
Ownership Changes
Forward Auction
Auction Summary
Announcements
Bids
Results
Product Status
Bidder Status
Bidder Market
Stage Transition
Split Transition
Max Reserved Blocks
License Impairment
Markets
Band Plans

Incentive Auction: Forward Auction Results

Search Off Download CSV (146864 rows)

Your request exceeds the limit of 9000 records. Please add filters (e.g. a specific round number) to reduce the number of records to download

To customize your report, you can click on [x] to hide columns in the table below.

Showing first 1000 of 146864 rows

Auction ID	Stage	Round	Market Number	Market Name	Category	Bidder	FRN	Processed Demand
1002	1	1	PEA001	New York, NY	C1	AT&T Spectrum Holdings LLC	0025241142	10
1002	1	1	PEA001	New York, NY	C1	Bluewater Wireless II, L.P.	0025247107	2
1002	1	1	PEA001	New York, NY	C1	CC Wireless Investment, LLC	0025232257	10
1002	1	1	PEA001	New York, NY	C1	Channel 51 License Co LLC	0025259565	3
1002	1	1	PEA001	New York, NY	C1	ParkerB.com Wireless L.L.C.	0025268459	4
1002	1	1	PEA001	New York, NY	C1	T-Mobile License LLC	0001565449	2
1002	1	1	PEA001	New York, NY	C1	UNITED STATES CELLULAR CORPORATION	0004372322	2
1002	1	1	PEA002	Los Angeles, CA	C1	AT&T Spectrum Holdings LLC	0025241142	5
1002	1	1	PEA002	Los Angeles, CA	C1	Bluewater Wireless II, L.P.	0025247107	1
1002	1	1	PEA002	Los Angeles, CA	C1	CC Wireless Investment, LLC	0025232257	5

Figure 71. FCC Auction 1002 Results[222]

FCC Incentive Auction - Forward Auction
Auction 1002
Bidder Summary

Appendix B

FEDERAL COMMUNICATIONS COMMISSION · USA ·

Date of Report: 04/06/2017 08:50 AM ET

Bidder	FRN	Bidding Credit Type	Number of Licenses Won	Number of PEAs	Gross Adjusted Payment	Net Adjusted Payment
Agri-Valley Communications, Inc.	0003778362	rural - 15%	5	3	$ 5,285,000	$ 4,492,250
AT&T Spectrum Holdings LLC	0025241142		23	18	$ 910,202,302	$ 910,202,302
Bluegrass Consortium	0025234709	rural - 15%	4	4	$ 3,928,000	$ 3,338,800
Bluewater Wireless II, L.P.	0025247107	small - 25%	66	64	$ 718,323,225	$ 568,323,225
CC Wireless Investment, LLC	0025232257		73	72	$ 1,724,877,376	$ 1,724,877,376
Cellco Partnership d/b/a Verizon Wireless	0003290673		0	0	$ 0	$ 0
Cellular South Licenses, LLC	0020434767		11	6	$ 19,453,000	$ 19,453,000
Channel 51 License Co LLC	0025259565	small - 25%	8	5	$ 1,008,704,549	$ 858,704,549

Figure 72. Excerpt from FCC Incentive Auction Results – Auction 1002[223]

[222] FCC Public Reporting System, https://auctiondata.fcc.gov/public/projects/1000/reports/forward-results.
[223] FCC, Forward Auction Auction 1002 Bidder Summary, https://docs.fcc.gov/public/attachments/DA-17-314A3.pdf.

Forward Auction

$19.8 billion	Gross revenues (2nd largest in FCC auction history)
$19.3 billion	Revenues net of requested bidding credits
$7.3 billion	Auction proceeds for federal deficit reduction
70 MHz	Largest amount of licensed low-band spectrum ever made available at auction
14 MHz	Spectrum available for wireless mics and unlicensed use
2,776	License blocks sold (out of total of 2,912 offered)
$1.31	Average price/MHz-pop *sold* in Top 40 PEAs
$.93	Average price/MHz-pop *sold* nationwide
50	Winning bidders
23	Winning bidders seeking rural bidding credits
15	Winning bidders seeking small business bidding credits

Figure 73. Forward Auction - Results "By the Numbers"[224]

4.4 CBRS and SAS/PAL Regime

Another way to allocate scarce spectrum resources is through a tiered sharing regime such as the Spectrum Access System (SAS) configuration on the Citizen's Band Radio (CBRS) bands. This design and infrastructure is localized to 150 MHz of 3.5 GHz spectrum which is also shared with incumbent military radar users. In order to accommodate incumbent users and allow for new wireless users, the FCC approved a plan for several spectrum manager companies to manage databases and priority access (PAL) licenses in addition to equipment certified for use on these bands. Different tiers of users have different access rights, as managed by databases.

[224] FCC, FCC Announces Results of World's First Broadcast Incentive Auction, https://www.fcc.gov/document/fcc-announces-results-worlds-first-broadcast-incentive-auction-0; *id*., Fact Sheet, https://docs.fcc.gov/public/attachments/DOC-344398A1.pdf.

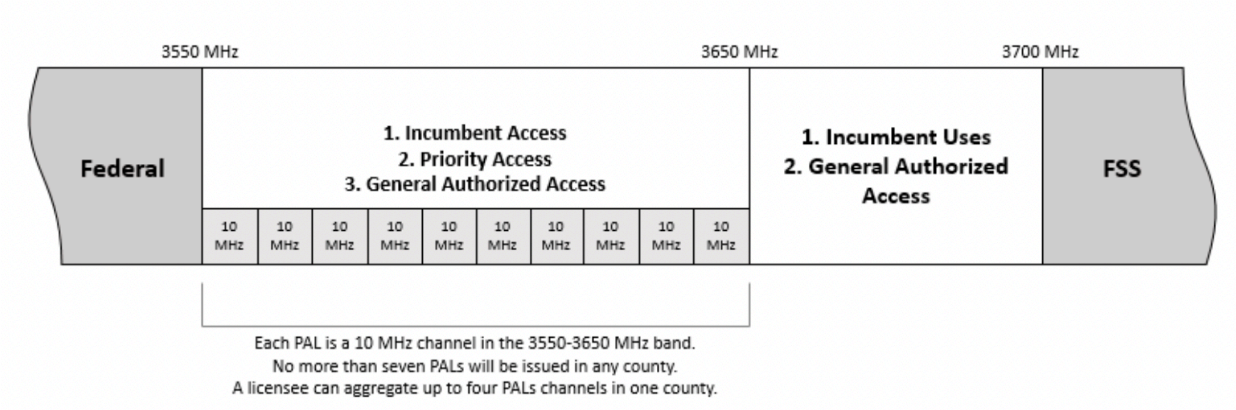


Figure 74. Band Plan for 3.5 GHz Band[225]

4.4.1 Priority Access

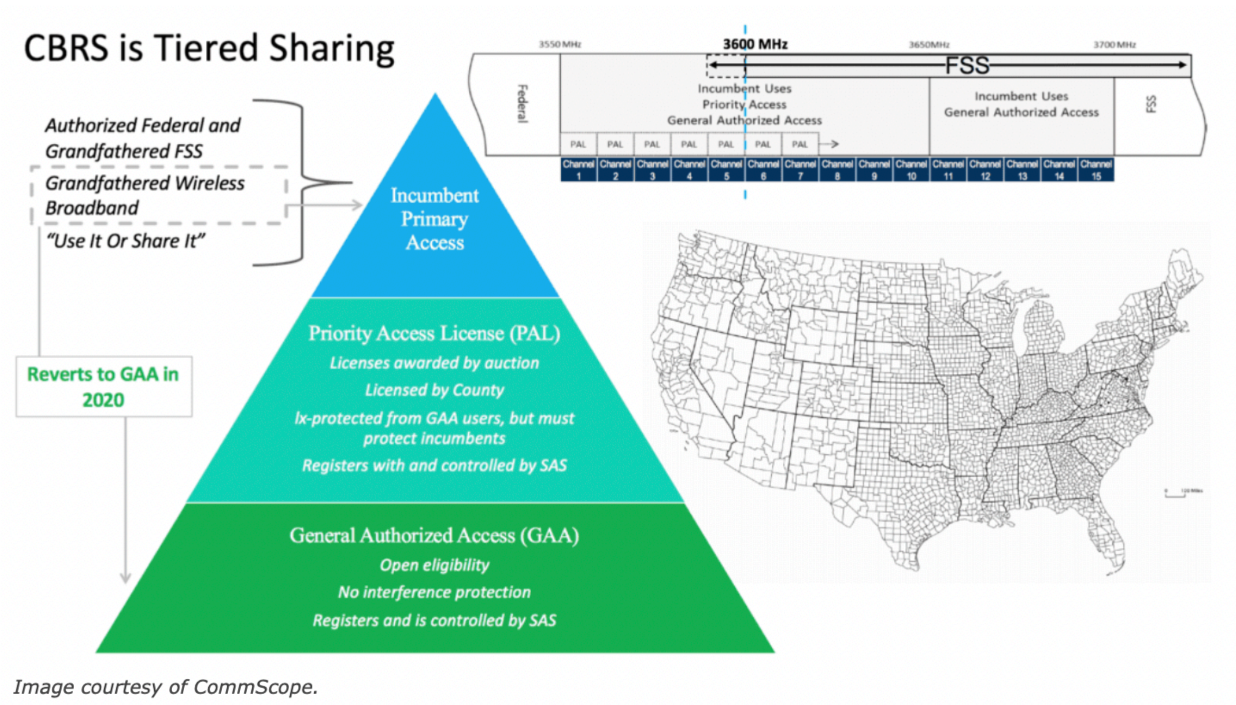
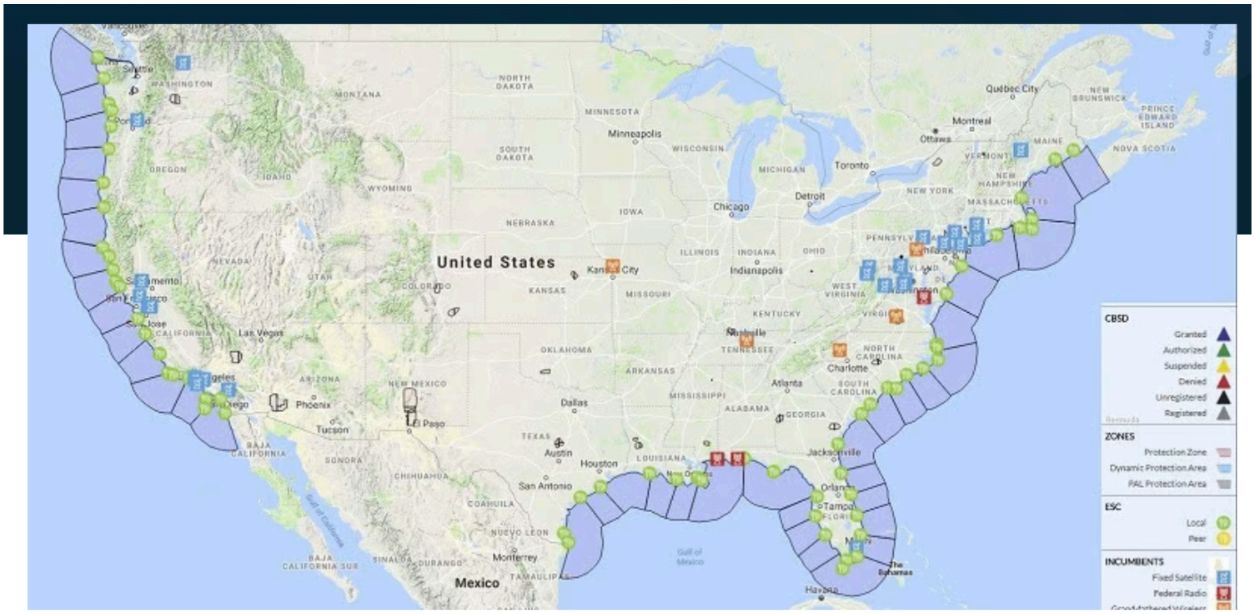


Figure 75. Citizens Broadband Radio Service (CBRS)[226]

[225] FCC, 3.5 GHz Band Overview, https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview.
[226] Sean Kinney, "Where Are We Today with CBRS and What's Next?" RCR Wireless, Dec. 16, 2019, https://www.rcrwireless.com/20191216/policy/cbrs-whats-next, citing image source, CommScope.



The CommScope SAS, in coordination with the environmental sensing capability, identifies wireless signals of incumbent users to avoid interference from CBRS operations. (CommScope/Business Wire)

Figure 76. CommScope Interoperability Testing of Incumbent Military Radar on CBRS Bands[227]

The FCC considered the CBRS tiered sharing regime for many years through public comment and a final rulemaking.[228] The Wireless Bureau and OET at the FCC, along with the NTIA and DoD, has certified several companies including Amdocs, CommScope, Federated Wireless, Google, Sony, and Key Bridge.[229] The SAS regime is administered by automated frequency coordinators who use databases to track and manage users of the spectrum at all times and places. The spectrum bands are also monitored with Environmental Sensing Capability (ESC) sensors.[230]

[227] Monica Alleven, "Ericsson, CommScope Complete CBRS Interoperability Tests," Fierce Wireless, Apr. 12, 2018, https://www.fiercewireless.com/wireless/ericsson-commscope-complete-cbrs-interoperability-tests.
[228] FCC, 3.5 GHz Band Overview, https://www.fcc.gov/wireless/bureau-divisions/mobility-division/35-ghz-band/35-ghz-band-overview.
[229] *Id.*
[230] *Id.*

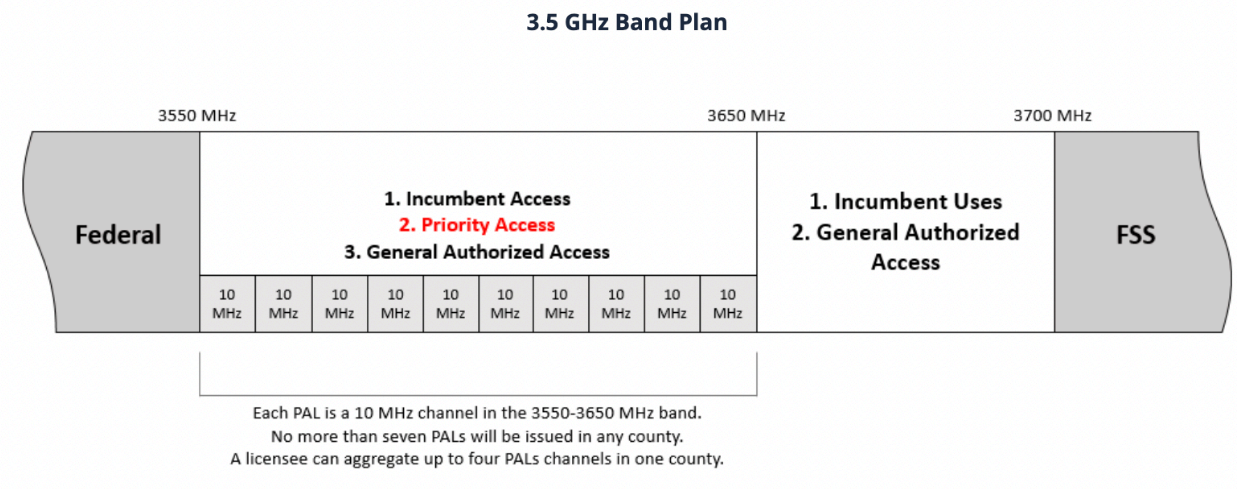


Figure 77. 3.5 GHz Band Plan in FCC Auction 105 for Tier 2 Priority Access Licenses (PALs)[231]

FCC Auction 105 in July and August of 2020 distributed the Tier 2 priority access licenses (PAL) on a county-by-county basis for 10 MHz channels in 3550-3650 MHz band for 10-year renewable terms.[232] In this auction, 23,631 PAL licenses were auctioned for 7 PALs in each of the 3,233 county-based license areas.[233]

4.4.2 Secondary Markets for Priority Access Licenses

The FCC allows for secondary markets in the priority access licenses (PAL), allowing for partitioning, disaggregation, partial assignment, transfer, and de facto transfer leasing arrangements.[234] This light-touch leasing and flexibility in leasing rights was incorporated to allow for more flexible transfer of these PAL rights to help users find spectrum they need where they need it.

4.5 Experimental Licenses

The FCC has granted more than 2,000 experimental licenses per year in its experimental licensing program, with upgrades to its rules to allow for "program licenses" in 2017.[235] The FCC describes this program, "The program licenses are designed to streamline the process for institutions that regularly file for experimental applications such as universities, R&D development companies, and medical institutions and also conduct a large portion of their experiments within geographic areas under their control. This new program licenses also

[231] FCC, Auction 15: 3.5 GHz Band, https://www.fcc.gov/auction/105.
[232] *Id.*; FCC, Auction 15: 3.5 GHz Band, https://www.fcc.gov/auction/105.
[233] FCC, Auction 15: 3.5 GHz Band, https://www.fcc.gov/auction/105.
[234] *Id.*
[235] FCC, Open for Business: FCC's New Experimental Licensing System Accepting New Applications, Julius Knapp, Apr. 14, 2017, https://www.fcc.gov/news-events/blog/2017/04/14/open-business-fccs-new-experimental-licensing-system-accepting-new.

provide for 'Innovation Zones', geographic areas that the Commission can define and make available for experiments."[236]

In 2013, the FCC sought to expand opportunities for radio experimentation and market trials under Part 5 of the FCC's rules.[237] The FCC responded to a recommendation set forth in 2009 and in the 2010 National Broadband Plan to "establish more flexible experimental licensing rules for spectrum and to facilitate the use of spectrum by innovators."[238]

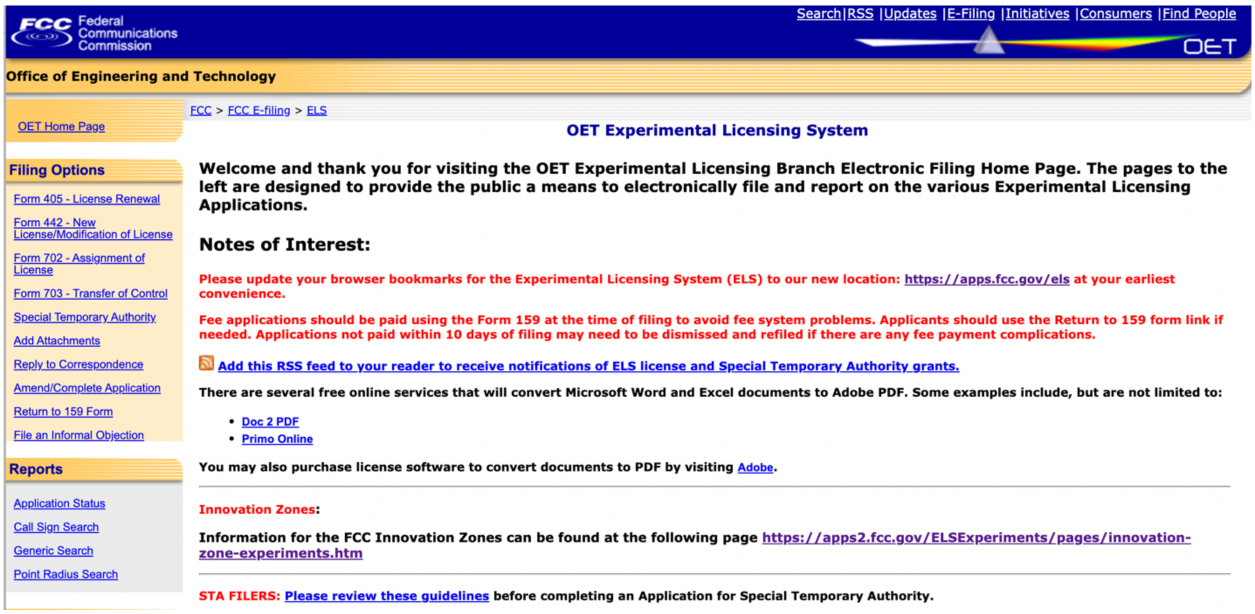


Figure 78. FCC's OET Experimental Licensing System[239]

[236] *Id.*
[237] FCC, Report and Order on Significant Changes to Experimental Rules, Jan. 31, 2013, https://www.fcc.gov/document/report-and-order-significant-changes-experimental-rules; In the Matter of Promoting Expanded Opportunities for Radio Experimentation and Market Trials under Part 5 of the Commission's Rules and Streamlining Other Related Rules, and 2006 Biennial Review of Telecommunications Regulations – Part 2 Administered by the Office of Engineering and Technology (OET), ET Docket No. 10-236, ET Docket Not. 06-155, Jan. 31, 2013, https://docs.fcc.gov/public/attachments/FCC-13-15A1.pdf, citing Fostering Innovation in the Wireless Communications Market, GN Docket No. 90-157; A National Broadband Plan for Our Future; GN Docket No. 09-51; Notice of Inquiry, 24 FCC Rcd 11322, at 11343-44, para. 65 (2009).
[238] Statement of Chairman Julius Genachowski, Jan. 31, 2013, https://docs.fcc.gov/public/attachments/FCC-13-15A2.pdf; Connecting America: The National Broadband Plan, March 2010 (available at http://www.broadband.gov/plan), at Recommendation 5.14, p.96.
[239] FCC, OET Experimental Licensing System, https://apps.fcc.gov/oetcf/els/index.cfm.

Figure 79. FCC's Form 442 for Experimental Station Authorization[240]

In FCC Form 442, there are four types of experimental licenses available, Conventional Experimental License, Program Experimental License, Medical Testing License, and Compliance Testing License.[241]

In the Spectrum Horizons proceeding in 2018 for spectrum above 95 GHz, the FCC noted the 13 experimental radio licenses active as of 2018.[242] This listing shows interest by the research community and technology companies in conducting equipment experiments at higher frequencies.

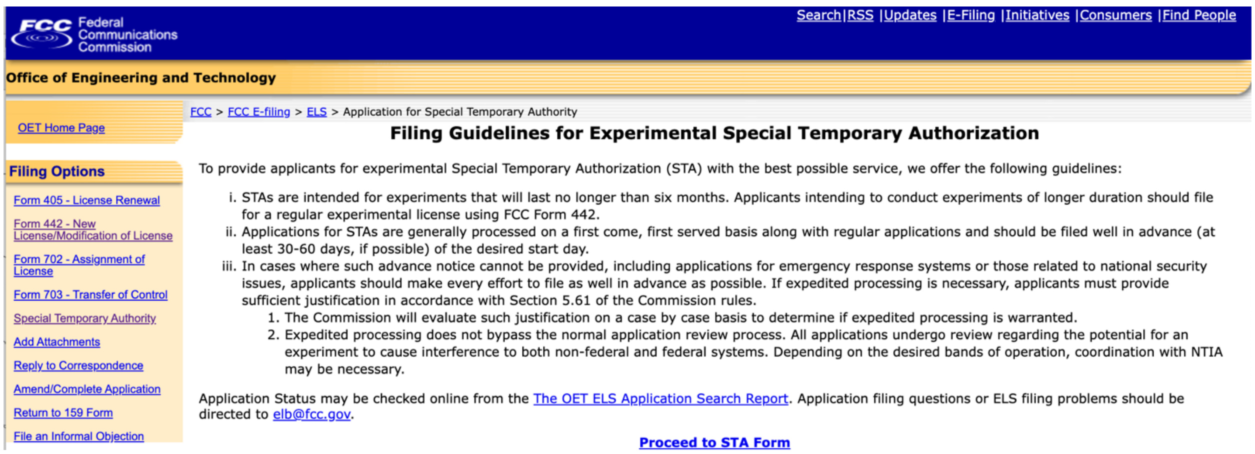
[162] Those 13 experiments are being conducted by the following licensees under the listed call signs. (1) Brown University (WI2XVS) – Propagation measurements, including passive bands at approximately 100, 200, 300, and 400 GHz. (2) Lockheed Martin Corporation (WG2XJE) – Radar cross-section measurements in various bands, including 95-100 GHz. (3) Northrop Grumman Systems Corporation (WJ2XEM) – Testing of frequency hopping systems in two bands, including the 92-96 GHz band. (4) NYU Tandon School of Engineering (WI2XSY) – Propagation testing, including 5G, in various bands, including 140-160 GHz. (5) Raytheon IDS (KI2XGC) – Development of antenna test ranges in various bands, including 92-100 GHz. (6) Raytheon Missile Systems (WB2XGB) – Testing, development, and demonstration of radars in three bands, including 92-100 and 102-105 GHz. (7) Raytheon Missile Systems (WI2XWW) – Testing of carbon-loaded Teflon equipment for US Army in the 92-96 GHz band. (8) Raytheon Missile Systems (WG2XHU) –Testing of RF deterrent system in the 94-96 GHz band. (9) Raytheon Missile Systems (WM9XAM) –Testing antenna patterns in the 90-102 GHz frequency range. (10) S2 Corporation (WH2XUK) – Development of a broadband spatial/spectrum receiver in support of developing a broadband staring receiver in various bands, including 26.5-100 GHz. (11) Sierra Nevada Corporation (WE2XCP) – Testing helicopter autonomous landing system in the 92.5-95.5 GHz band. (12) The Boeing Company (KB2XEU) – Testing of company's antennas in various bands, including 148.5-151.5 and 185-190 GHz. (13) University of Buffalo (WM9XGE) – Propagation measurements in the 1 THz region. Database query of January 30, 2018.

[240] FCC, Dashboard for Experimental Radio Station Authorization (Form 442), https://apps.fcc.gov/oetcf/els/forms/442Dashboard.cfm.
[241] FCC, Dashboard for Experimental Radio Station Authorization (Form 442), https://apps.fcc.gov/oetcf/els/forms/442Dashboard.cfm.
[242] In the Matter of Spectrum Horizons, ET Docket No. 18-21, RM-11795, Notice of Proposed Rulemaking and Order, Feb. 28, 2018, https://docs.fcc.gov/public/attachments/FCC-18-17A1_Rcd.pdf.

Figure 80. The 13 Experimental Radio Licenses above 95 GHz as of 2018[243]

4.5.1 *Special Temporary Authority (STA)*

In addition to these types of experimental licenses, there is another type of experimental license called Special Temporary Authority (STA) that are intended for experiments that last for no longer than six months, processed on a first come, first serve basis, filed 30-60 days in advance of use.[244]


Federal Communications Commission

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Office of Engineering and Technology

OET Home Page

Filing Options

- Form 405 - License Renewal
- Form 442 - New License/Modification of License
- Form 702 - Assignment of License
- Form 703 - Transfer of Control
- Special Temporary Authority
- Add Attachments
- Reply to Correspondence
- Amend/Complete Application
- Return to 159 Form
- File an Informal Objection

FCC > FCC E-filing > ELS > Application for Special Temporary Authority

Filing Guidelines for Experimental Special Temporary Authorization

To provide applicants for experimental Special Temporary Authorization (STA) with the best possible service, we offer the following guidelines:

i. STAs are intended for experiments that will last no longer than six months. Applicants intending to conduct experiments of longer duration should file for a regular experimental license using FCC Form 442.
ii. Applications for STAs are generally processed on a first come, first served basis along with regular applications and should be filed well in advance (at least 30-60 days, if possible) of the desired start day.
iii. In cases where such advance notice cannot be provided, including applications for emergency response systems or those related to national security issues, applicants should make every effort to file as well in advance as possible. If expedited processing is necessary, applicants must provide sufficient justification in accordance with Section 5.61 of the Commission rules.
   1. The Commission will evaluate such justification on a case by case basis to determine if expedited processing is warranted.
   2. Expedited processing does not bypass the normal application review process. All applications undergo review regarding the potential for an experiment to cause interference to both non-federal and federal systems. Depending on the desired bands of operation, coordination with NTIA may be necessary.

Application Status may be checked online from the The OET ELS Application Search Report. Application filing questions or ELS filing problems should be directed to elb@fcc.gov.

Proceed to STA Form

Figure 81. Filing Guidelines for Experimental Special Temporary Authorization[245]

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243 In the Matter of Spectrum Horizons, ET Docket No. 18-21, RM-11795, Notice of Proposed Rulemaking and Order, Feb. 28, 2018, https://docs.fcc.gov/public/attachments/FCC-18-17A1_Rcd.pdf, at ¶ 67 n.162.
244 FCC, Filing Guidelines for Experimental Special Temporary Authorization, https://apps.fcc.gov/oetcf/els/forms/STANotificationPage.cfm.
245 FCC, Filing Guidelines for Experimental Special Temporary Authorization, https://apps.fcc.gov/oetcf/els/forms/STANotificationPage.cfm.

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FCC, The Broadcast Television Spectrum Incentive Auction: A Staff Summary, Jan. 16, 2013, https://www.fcc.gov/document/broadcast-television-spectrum-incentive-auction-staff-summary.

FCC, Broadcast Incentive Auction and Post-Auction Transition, May 9, 2017, https://www.fcc.gov/about-fcc/fcc-initiatives/incentive-auctions.

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5 New Developments

New technologies such as low earth orbit satellite constellations, private 5G networks, and dynamic sharing zones use the radio spectrum in ways that raise policy questions and economic considerations. Economic tradeoffs for how to best allocate spectrum licenses are weighed against each other, especially when spectrum needs to be shared or when incumbents are wary of adjacent band interference.

5.1 Satellite Constellations

Companies such as SpaceX and Amazon are launching low earth orbit satellite constellations in order to increase broadband connectivity around the globe. Currently at the FCC and the ITU, the rules for non-geostationary satellite orbit (NGSO) interference and sharing have not been finalized yet, but because these technologies are coming to market, the regulators are considering how to manage congestion on the airwaves.

Operators of geostationary orbit (GSO) satellites are also seeking more spectrum for operations as well, and also raise concerns about interference with adjacent band uses, particularly in terrestrial rollouts of 5G wireless services.

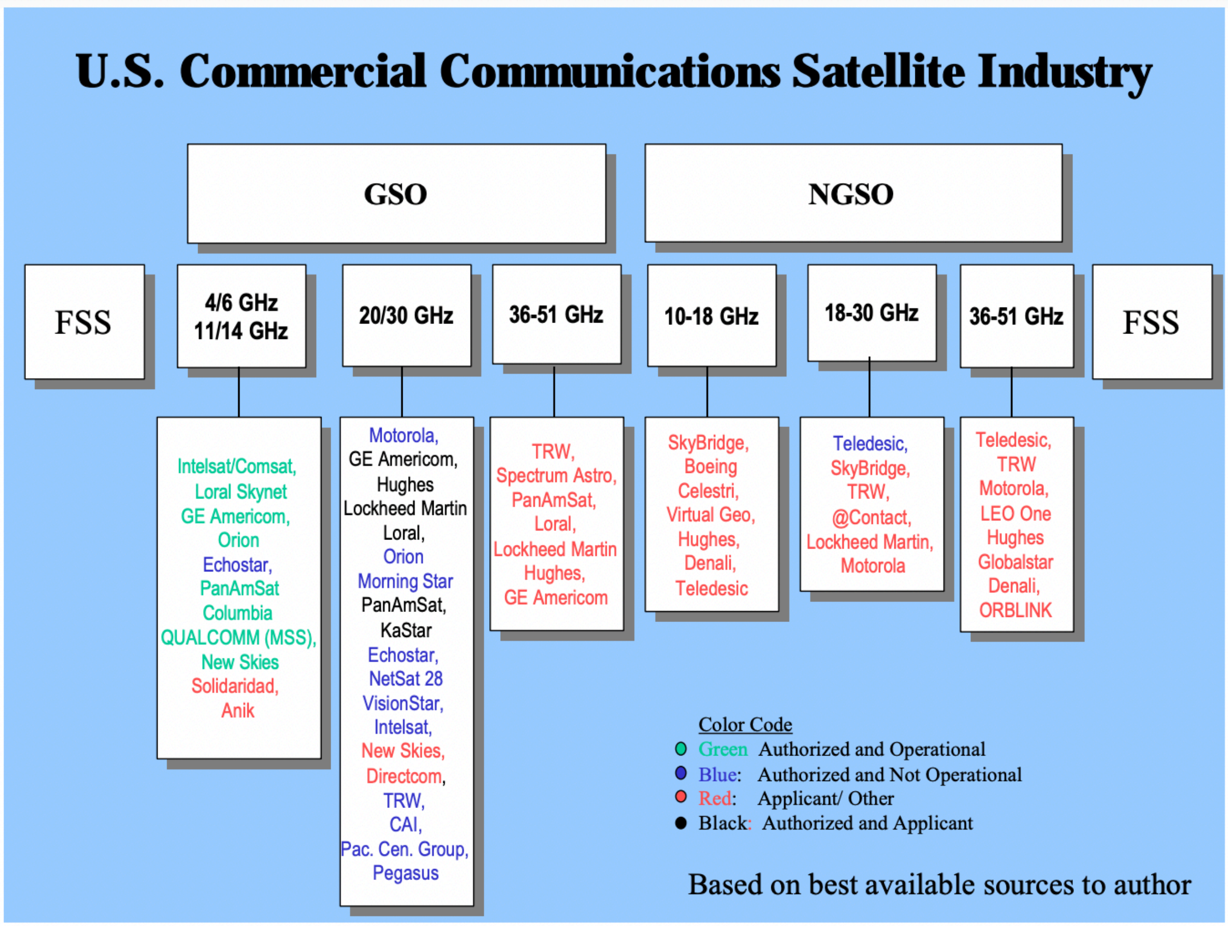


Figure 82. Satellite Operators in GSO and NGSO Bands[246]

5.1.1 NGSO Low-Earth Orbit Satellites

[246] Edward M. Davison, Program Manager, Satellite Coordination and Policy, Office of Spectrum Management, ITS/NTIA, "Spectrum Issues Related to Satellite Communications," p. 5, https://its.ntia.gov/media/30236/dav_s.pdf.

The FCC recently opened a notice of proposed rulemaking in order to solicit comments on how to update the rules governing NGSO FSS systems (non-geostationary satellite orbit, fixed-satellite service).[247] In particular, spectrum sharing requirements and mechanisms are at issue for these new low earth orbit satellites, and how to protect earlier-round systems and how to require sharing among satellites in the same processing round.[248]

Federal Communications Commission **FCC 21-123**

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems	)))	IB Docket No. 21-456
	)	
Revision of Section 25.261 of the Commission's Rules to Increase Certainty in Spectrum Sharing Obligations Among Non-Geostationary Orbit Fixed-Satellite Service Systems	))))	RM-11855

ORDER AND NOTICE OF PROPOSED RULEMAKING

Adopted: December 14, 2021 **Released: December 15, 2021**

Figure 83. NGSO NPRM IB Docket No. 21-456[249]

These satellites operate in a number of satellite spectrum bands, such as the Ka-band, and 10.7-12.7 GHz, 12.75-13.25 GHz, 13.8-14.5 GHz, 17.7-18.6 GHz, 18.8-20.2 GHz, and 27.5-30 GHz Bands, 37.5-40.0 GHz, 40.0-42.0 GHz, 47.2-50.2 GHz, and 50.4-51.4 GHz Bands.[250]

[247] In the Matter of Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems and Revision of Section 25.261 of the Commission's Rules to Increase Certainty in Spectrum Sharing Obligations Among Non-Geostationary Orbit Fixed-Satellite Service Systems, FCC IB Docket No. 21-456, RM-11855, Order and Notice of Proposed Rulemaking, Dec. 15, 2021, https://www.fcc.gov/document/fcc-moves-facilitate-satellite-broadband-competition-0.

[248] *Id.* at ¶ 1.

[249] In the Matter of Revising Spectrum Sharing Rules for Non-Geostationary Orbit, Fixed-Satellite Service Systems and Revision of Section 25.261 of the Commission's Rules to Increase Certainty in Spectrum Sharing Obligations Among Non-Geostationary Orbit Fixed-Satellite Service Systems, FCC IB Docket No. 21-456, RM-11855, Order and Notice of Proposed Rulemaking, Dec. 15, 2021, https://www.fcc.gov/document/fcc-moves-facilitate-satellite-broadband-competition-0

[250] I*d*. at ¶ 9, citing In the Matter of Cut-off Established for Additional NGSO FSS Applications or Petitions for Operations in the 10.7-12.7 GHz, 12.75-13.25 GHz, 13.8-14.5 GHz, 17.7-18.6 GHz, 18.8-20.2 GHz, and 27.5-30 GHz Bands, Public Notice, DA 20- 325 (IB Sat. Div. 2020); Cut-off Established for Additional NGSO-like Satellite Systems in the 37.5-40.0 GHz, 40.0-42.0 GHz, 47.2-50.2 GHz, and 50.4-51.4 GHz Bands, Public Notice, DA 21-941 (IB Sat. Div. 2021); Kuiper Systems, LLC, Application for Authority to Deploy and Operate a Ka-band Non-Geostationary Satellite Orbit System, Order and Authorization, 35 FCC Rcd 8324 (2020).

The FCC recently issued a separate notice of proposed rulemaking to solicit comments about the use of the Ku-band in the 17.3-17.7 GHz and 17.7-17.8 GHz band for NGSO operators.[251]

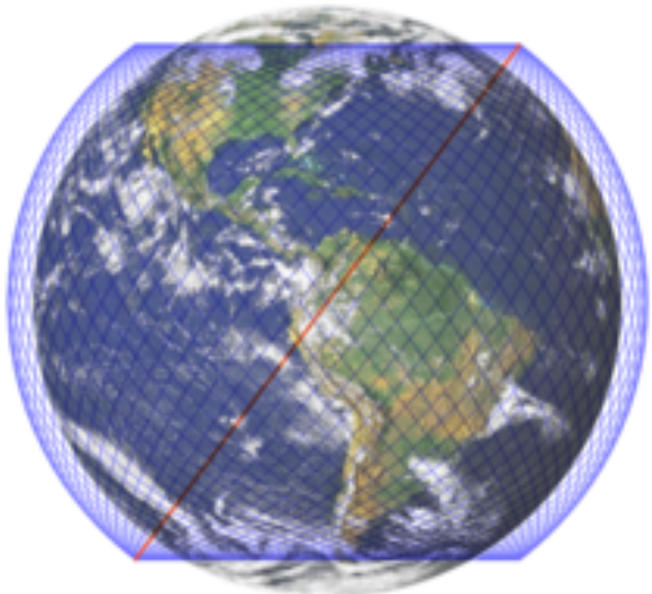


Figure 84. Starlink's Constellation Phase 1 Plan with 1584 Satellites at 550 km Altitude[252]

[251] In the Matter of Amendment of Parts 2 and 25 of the Commission's Rules to Enable GSO Fixed-Satellite Service (Space-to-Earth) Operations in the 17.3-17.8 GHz Band, to Modernize Certain Rules Applicable to 17/24 GHz BSS Space Stations, and to Establish Off-Axis Uplink Power Limits for Extended KaBand FSS Operations, and Amendment of Parts 2 and 25 of the Commission's Rules to Enable NGSO Fixed-Satellite Service (Space-to-Earth) Operations in the 17.3-17.8 GHz Band, Report and Order and Notice of Proposed Rulemaking, Aug. 3, 2022, FCC IB Docket No. 20-330, IB Docket No. 22-273, https://www.fcc.gov/document/fcc-updates-17-ghz-rules-support-spectrum-satellite-broadband.
[252] Starlink, Constellation Design and Status, https://en.wikipedia.org/wiki/Starlink.

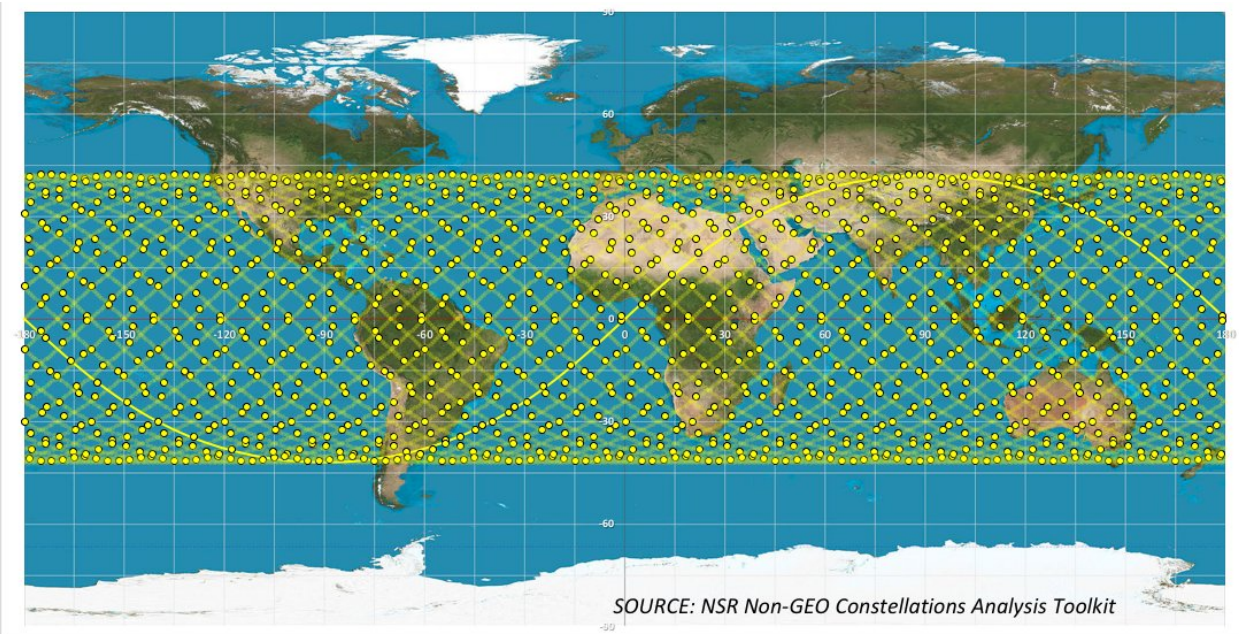
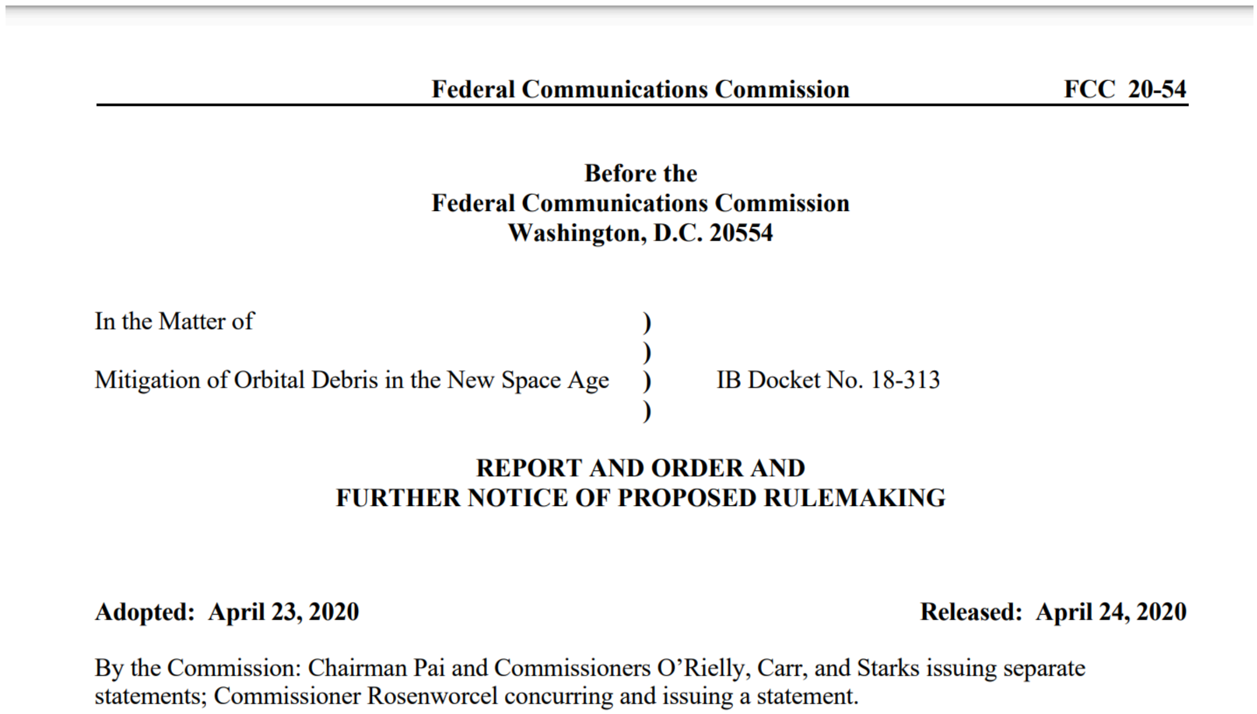


Figure 85. Amazon's Project Kuiper's 3,236 Satellite Plan at 590-630 km Altitude[253]

The FCC has also issued a notice of proposed rulemaking to update its older *2004 Orbital Debris Order* on how to mitigate increasing amounts of orbital debris from LEO and NGSO space station licenses.[254] Prior to 2004, the FCC reviewed orbital debris mitigation plans on a case-by-case basis.[255] As part of its licensing applications, satellite companies submitted debris mitigation plans to the FCC.[256] In coordination with the Department of Commerce, NOAA, and Federal Aviation Administration, and international bodies, the federal regulators have to coordinate and be careful about legal authority and jurisdiction. The issue of orbital debris involves NASA and the Department of Defense in particular. NASA Debris Assessment Software and "large object" measurement standards are applied to NGSO satellite licensees[257] and some petitioners asked the FCC to apply the same measurements to the GSO satellites as well.[258] The FCC declined to apply these new standards to GSO satellites, which are currently under a disclosure standard, particular orbital locations, and well-established disposal procedures.[259]

[253] Northern Sky Research, Analysys Mason, https://twitter.com/NSR_SatCom; https://twitter.com/thesheetztweetz/status/1299032138440994818.
[254] In the Matter of Mitigation of Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd 4156, 4158, para. 3 (2020), https://www.fcc.gov/document/fcc-updates-orbital-debris-mitigation-rules-new-space-age-0.
[255] *Id*. at *para*. 16.
[256] *Id*.
[257] *Id*. at para. 33-35.
[258] *Id*. at para. 37.
[259] *Id*.



Federal Communications Commission **FCC 20-54**

Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of	)	
	)	
Mitigation of Orbital Debris in the New Space Age	)	IB Docket No. 18-313
	)	

REPORT AND ORDER AND
FURTHER NOTICE OF PROPOSED RULEMAKING

Adopted: April 23, 2020 **Released: April 24, 2020**

By the Commission: Chairman Pai and Commissioners O'Rielly, Carr, and Starks issuing separate statements; Commissioner Rosenworcel concurring and issuing a statement.

Figure 86. Orbital Debris NPRM[260]

[260] In the Matter of Mitigation of Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking, 35 FCC Rcd 4156, 4158, para. 3 (2020), https://www.fcc.gov/document/fcc-updates-orbital-debris-mitigation-rules-new-space-age-0; https://docs.fcc.gov/public/attachments/FCC-20-54A1.pdf.

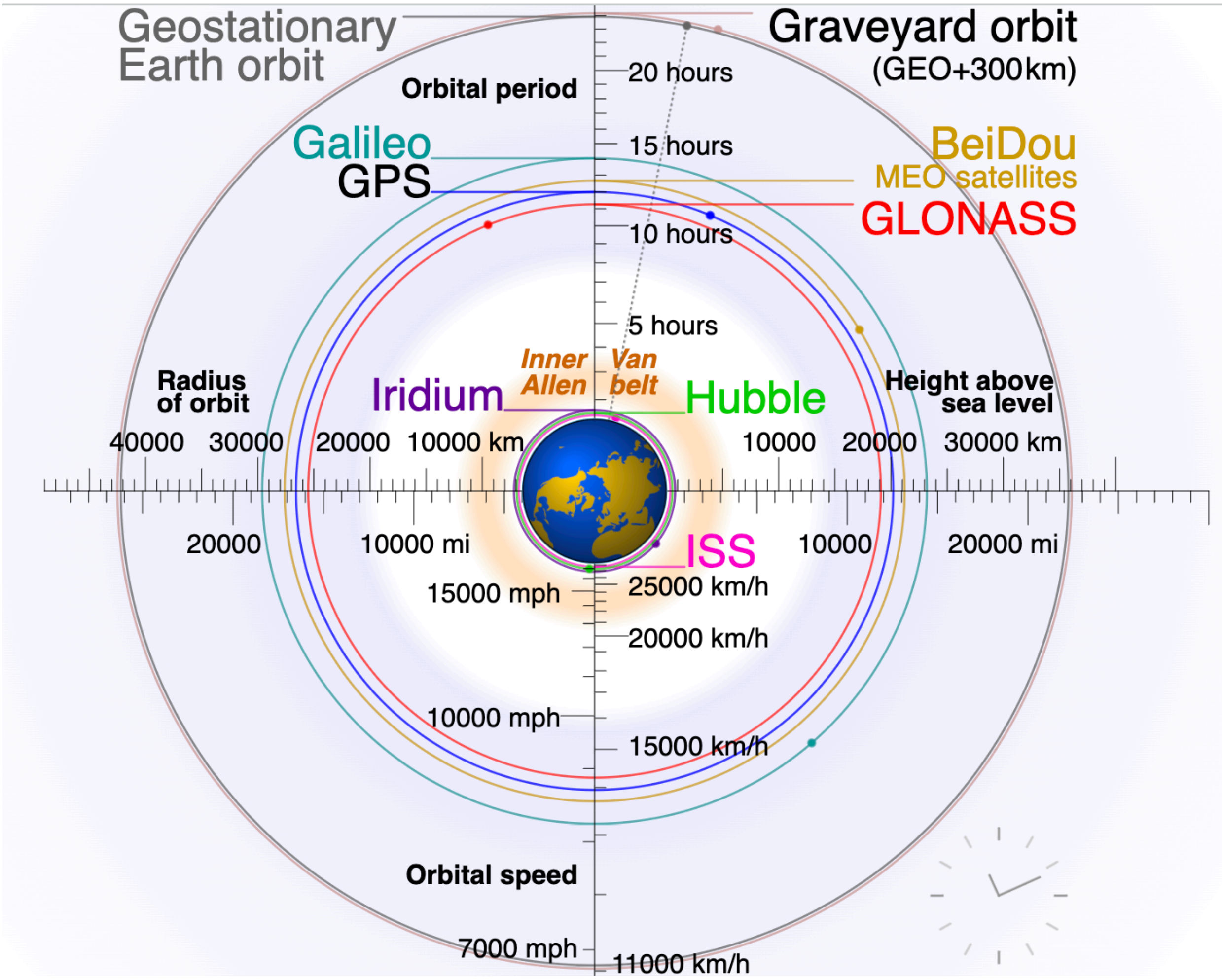


Figure 87. Graveyard Orbit or Orbital Junk[261]

5.1.2 *GSO Weather and GPS Satellites*

There are also spectrum policy questions around the geostationary orbit (GSO) weather satellites and the global positioning system (GPS) which reside higher above the earth's orbit in order to stay stationary in as the earth rotates. The FCC opened a notice of proposed rulemaking in August 2022 to gather comments on the use of GSO satellites (in addition to NGSO satellites) in the 17.3-17.7 GHz band.[262] This band is part of the extended Ka-band for fixed-satellite service (FSS) which includes 17.3-18.3 GHz (space-to-Earth), 18.8-19.4 GHz

[261] Graveyard Orbit, https://en.wikipedia.org/wiki/Graveyard_orbit.

[262] In the Matter of Amendment of Parts 2 and 25 of the Commission's Rules to Enable GSO Fixed-Satellite Service (Space-to-Earth) Operations in the 17.3-17.8 GHz Band, to Modernize Certain Rules Applicable to 17/24 GHz BSS Space Stations, and to Establish Off-Axis Uplink Power Limits for Extended KaBand FSS Operations, and Amendment of Parts 2 and 25 of the Commission's Rules to Enable NGSO Fixed-Satellite Service (Space-to-Earth) Operations in the 17.3-17.8 GHz Band, Report and Order and Notice of Proposed Rulemaking, Aug. 3, 2022, FCC IB Docket No. 20-330, IB Docket No. 22-273, https://www.fcc.gov/document/fcc-updates-17-ghz-rules-support-spectrum-satellite-broadband.

(space-to-Earth), 19.6-19.7 GHz (space-to-Earth), 27.5-28.35 GHz (Earth-to-space) and 28.6-29.1 GHz (Earth-to-space) bands.[263]

Federal users of weather data provided by GSO satellite operators and GPS satellite operators have expressed concerns about new uses from wireless licensees in adjacent bands. The Lightsquared/Ligado boundary has been ongoing for two decades,[264] while the Spectrum Frontiers issues arose most recently with NOAA and NASA concerns in the U.S.'s participation in the 2019 World Radio Conference (WRC).[265] In these cases, the spectrum bands at issue are the Spectrum Frontiers bands (24, 32, and 37 gigahertz (GHz)) and in the L-Band (generally 1-2 GHz, and more specifically, 1176.45 MHz (L5), 1227.60 MHz (L2), 1381.05 MHz (L3), and 1575.42 MHz (L1) frequencies for the Global Positioning System (GPS)).

In the case of the Spectrum Frontiers FCC Auction 102, the FCC held the auction as planned on 24 GHz in 2019, releasing 2,909 licenses,[266] despite concerns from NOAA and NASA, as discussed in a Congressional hearing[267] and a GAO report that followed.[268]

In the matter of the L-Band, studies and proceedings have been ongoing for two decades. The debate is whether terrestrial transmitters may interfere with signals from GPS satellites in adjacent bands used by federal users such as DOD, FAA, NOAA, and others.[269]

These satellite operators seek spectrum license approvals from the U.S. regulator but also need international approvals at the ITU and WRC due to the global nature of satellite operation and orbit paths.

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[263] *Id*. at ¶ 2.
[264] Matteo Luccio, "The Ligado Saga Continues," GPS World, Oct. 13, 2022, https://www.gpsworld.com/the-ligado-saga-continues/.
[265] GAO, Report to the Committee on Science, Space, and Technology, House of Representatives, Spectrum Management: Agencies Should Strengthen Collaborative Mechanisms and Processes to Address Potential Interference, June 2021, https://www.gao.gov/assets/720/715338.pdf.
[266] FCC, Auction 102: 24 GHz, https://www.fcc.gov/auction/102/factsheet.
[267] U.S. House of Representatives, Committee on Science, Space, and Technology, Hearing: Spectrum Needs for Observations in Earth and Space Sciences, July 20, 2021, https://science.house.gov/hearings/spectrum-needs-for-observations-in-earth-and-space-sciences.
[268] GAO, Report to the Committee on Science, Space, and Technology, House of Representatives, Spectrum Management: Agencies Should Strengthen Collaborative Mechanisms and Processes to Address Potential Interference, June 2021, https://www.gao.gov/assets/720/715338.pdf.
[269] Congressional Research Service, "Spectrum Interference Issues: Ligado, the L-Band, and GPS, May 28, 2020, https://www.everycrsreport.com/files/2020-05-28_IF11558_d707240653ab5b7068590d74023f373f1f7a7172.pdf.

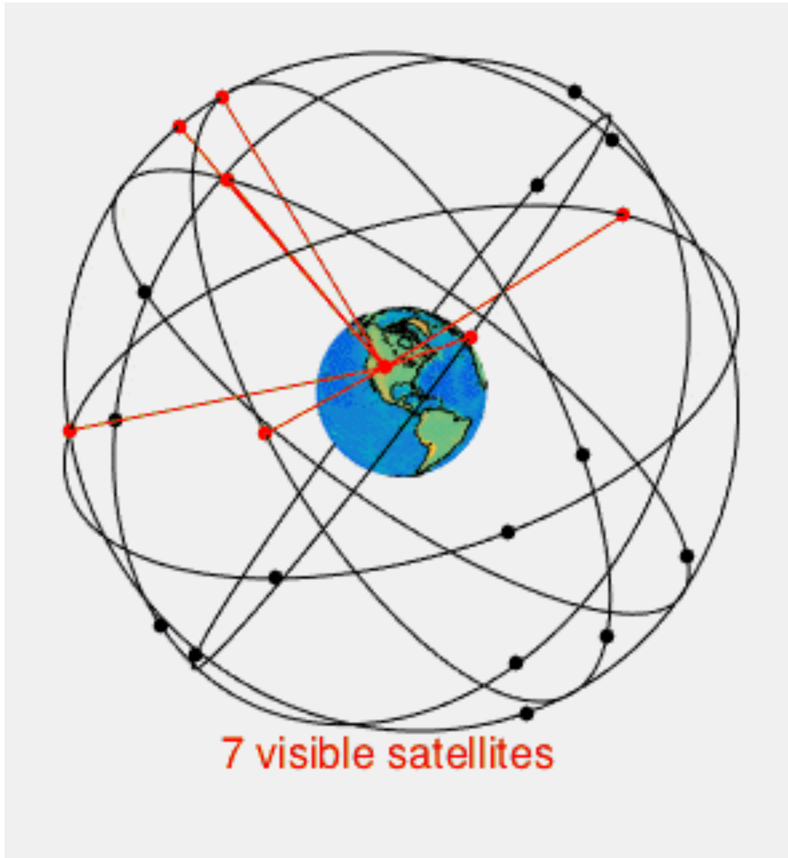

Figure 88. 24-satellite GPS constellation in motion with the Earth rotating[270]

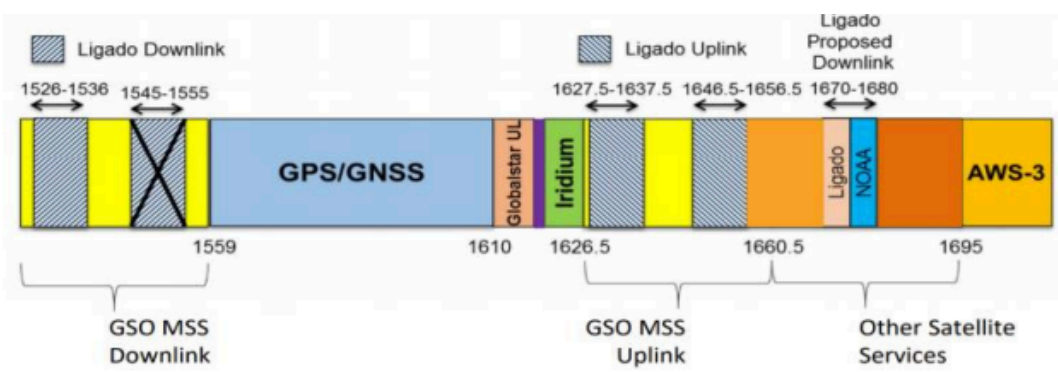

Figure 89. Band Plan for L-Band and Ligado Proposal[271]

[270] Global Positioning System, https://en.wikipedia.org/wiki/Global_Positioning_System.
[271] Congressional Research Service, "Spectrum Interference Issues: Ligado, the L-Band, and GPS, May 28, 2020, https://www.everycrsreport.com/files/2020-05-28_IF11558_d707240653ab5b7068590d74023f373f1f7a7172.pdf, citing graphic source, "Impact of Ligado's Proposal on SATCOM, Aviation and Weather Data Users (Coalition Deck)," September 2019, https://ecfsapi.fcc.gov/file/10906015584180/Coalition%20Deck%20for%20Sept.%204%202019%20FCC%20meetings.pdf.

5.2 Local Governance

In more local and smaller geographic areas, wireless operators are using other configurations of licenses and networks to connect users on the radio spectrum. The business models that can arise from such local governance are built around different types of spectrum rights available in these local area.

5.2.1 Private or Enterprise 5G

Private or Enterprise 5G networks are private mobile networks offered as managed services in local areas such as industrial parks or factories or warehouses. These networks are built on spectrum bands such as Citizens Broadband Radio Service (CBRS) Generally Authorized Access (GAA) spectrum tier in the U.S. (CBRS, LTE band 48).[272]

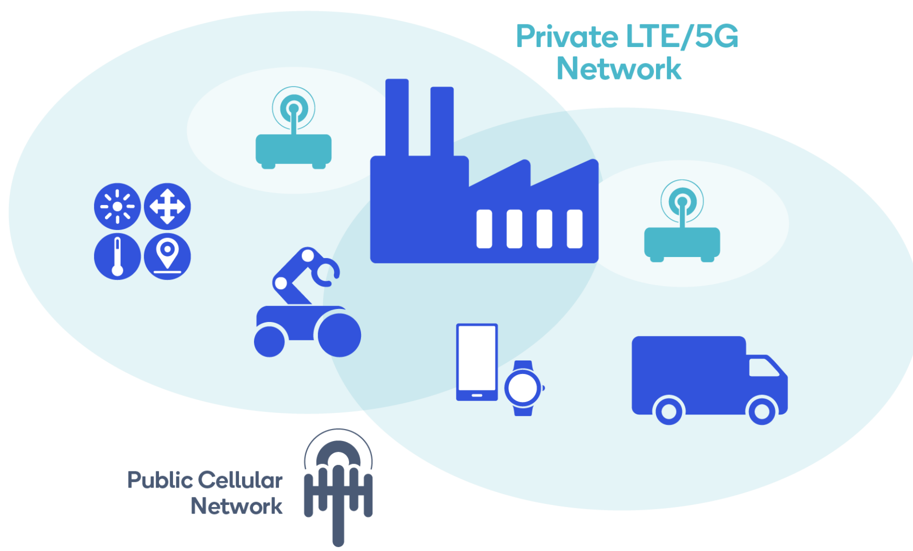

Figure 90. Private LTE/5G Network Diagram[273]

[272] AWS Private 5G FAQs, https://aws.amazon.com/private5g/faqs/.
[273] Qualcomm, What is a Private LTE/5G Network?, Aug. 14, 2019, https://developer.qualcomm.com/blog/private-lte5g-networks-primer-developers.

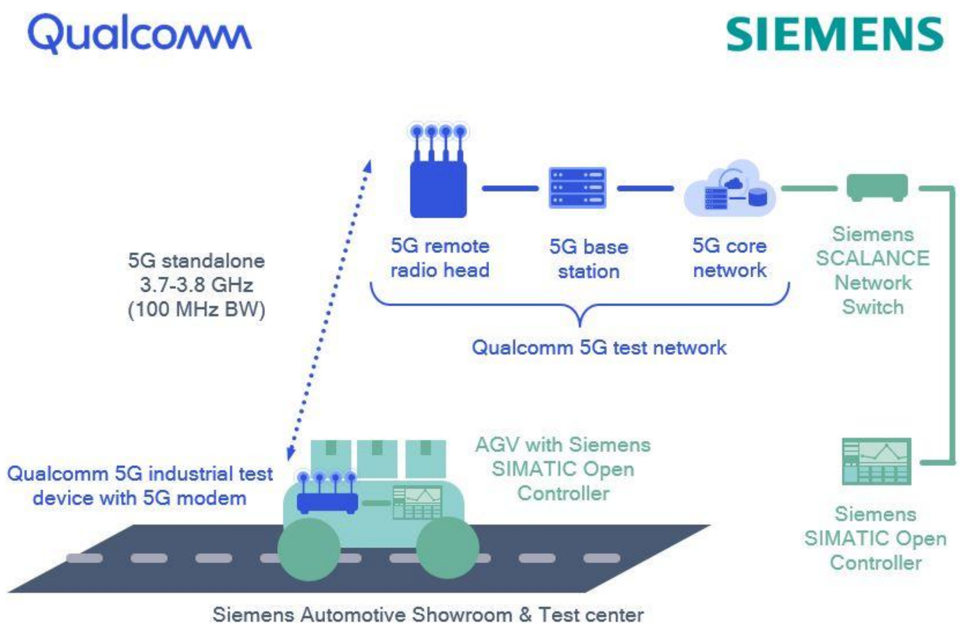

Figure 91. Private 5G Network for Industrial Applications[274]

Recall our earlier discussion of the CBRS band and the SAS/PAL licensing regime. Many of these private 5G networks run on these bands, but have to avoid interfering with incumbent systems which include fixed satellite systems.

The new developments that we see today and going forward are more of this type of coordination between types of radios, terrestrial, fixed, satellite, that involve more than one band and geography and altitude and device manufacturer and commercial operator.

[274] Alan Weissberger, Siemens & Qualcomm Create Private 5G Network for Industrial Applications, Nov. 27, 2019, https://techblog.comsoc.org/2019/11/27/siemens-qualcomm-create-private-5g-network-for-industrial-applications/.

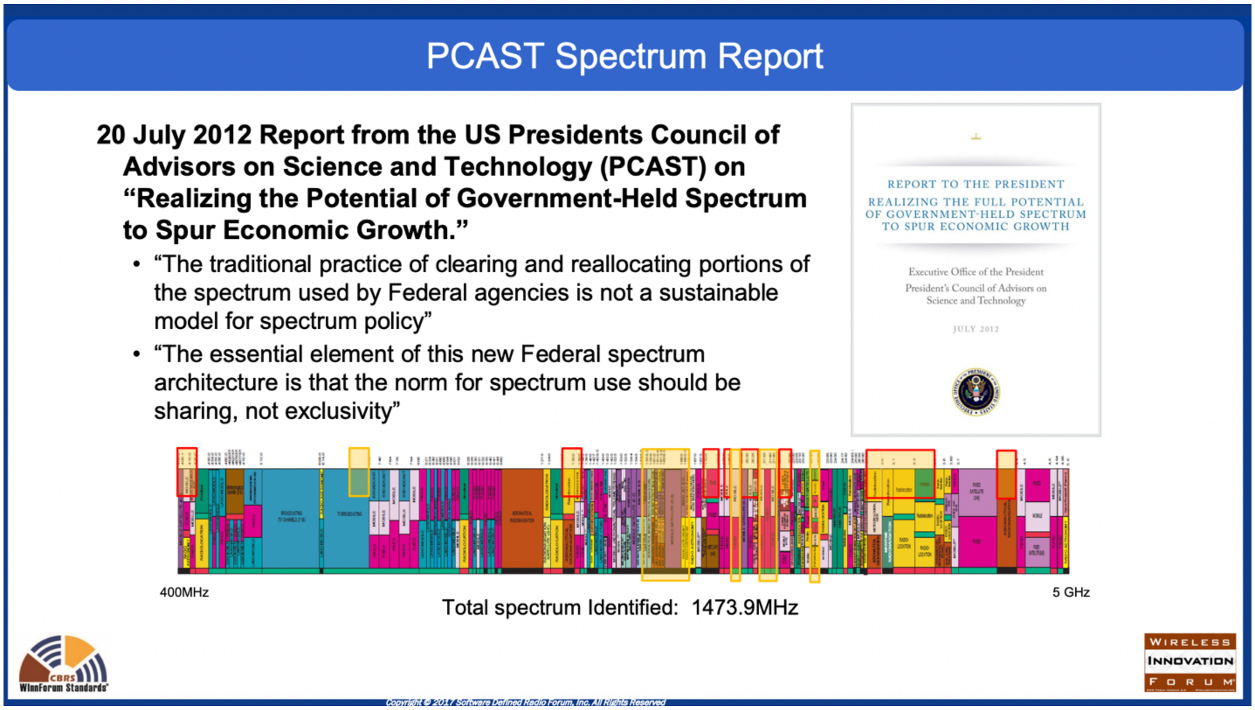

Figure 92. 3.5 GHz Band among the 1.4 GHz of Federal Spectrum Identified by PCAST[275]

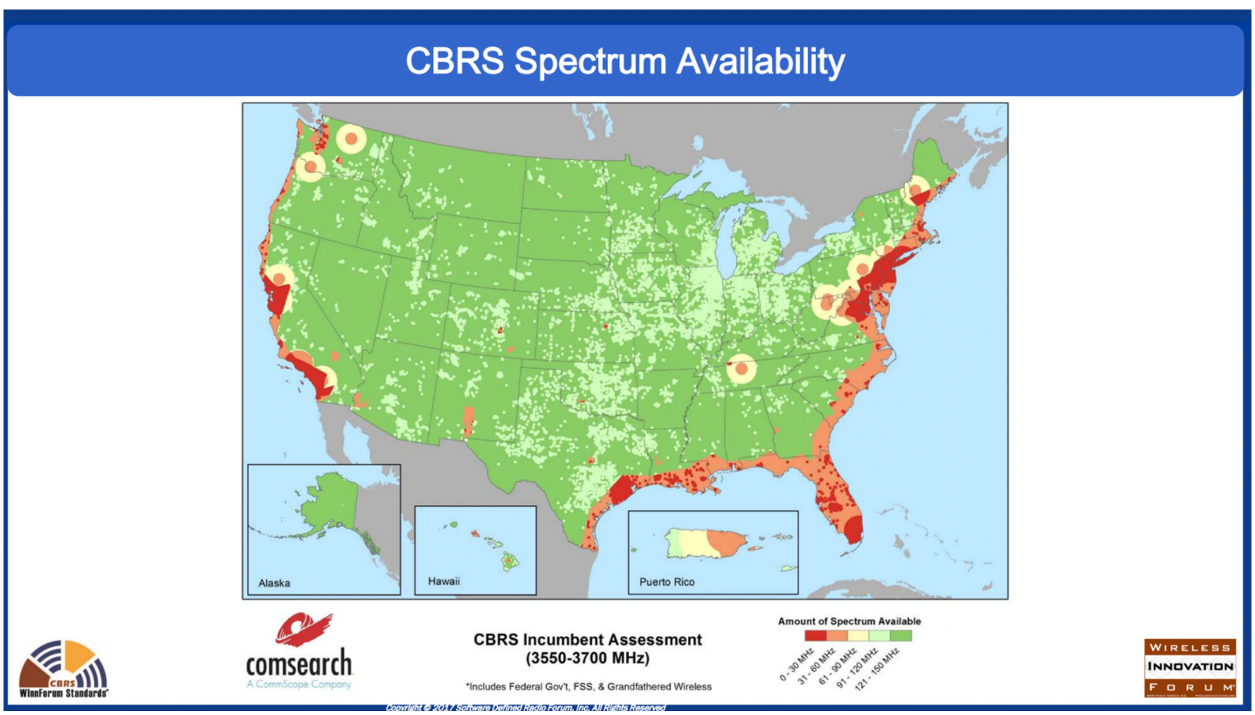

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Figure 93. Federal Incumbents in 3.5 GHz using Fixed Services[276]

Figure 94. 250+ Participants and 60+ Organizations in CBRS[277]

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6 Conclusion

This course examined spectrum economics and market tools such as auctions, secondary markets, unlicensed bands, and experimental licenses. Course material covered the foundations of spectrum valuation, allocation methods, and economic concepts. Students were given two assignments, a research paper and a presentation, to discuss a spectrum auction and to teach other students about a headline event in spectrum policy.

7 Final Assessment Questions

The following questions will test students' comprehension of the material from this course. Answers are available in a separate document for instructors.

True or False Questions:

1. T/F = Spectrum licenses are treated as tangible assets on the balance sheets of wireless companies.
2. T/F = Companies are free to trade and swap spectrum licenses after they win them at auction without reporting to the FCC.
3. T/F = The value of federal spectrum is difficult to compare to commercial spectrum because of a lack of prices and market transactions.
4. T/F = The only way to resolve spectrum interference conflicts between agencies and industries is to escalate the decision to the President of the United States.
5. T/F = Low-earth orbit satellites pose no interference risk to terrestrial or geostationary satellites.
6. T/F = The United States can set policies on spectrum rights without the need to coordinate with international standards bodies.
7. T/F = Before the FCC started implementing competitive auctions for spectrum licenses in the mid-1990s, the FCC used voting methods to determine how to distribute spectrum licenses.
8. T/F = Without the research of Nobel prize winning economists, spectrum auctions and the current wireless regulatory regime may not have been as successful as it has been.
9. T/F = Radio spectrum as a resource degrades over time and once it's used, cannot be restored. F = radio spectrum is an intangible asset that can be cleared of radio transmissions if devices cease to send signals over the frequencies.
10. T/F = If more spectrum bands were unlicensed and shared, it would maximize the value of the radio spectrum.