Powering the Mobile Revolution: Principles of Spectrum Allocation

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EXECUTIVE SUMMARY

A mobile revolution is profoundly changing information technology. A dramatic shift from old technology norms built around fixed-location systems to new mobile devices, wireless networks, and location-centric applications has the potential to reshape society and the economy. In 2011 more smartphones were sold than personal computers, and by 2015, tablets will outsell personal computers as well.[1] The new mobile technology increases economic efficiency and enables innovation, creating jobs and increasing prosperity. By the FCC's estimate, mobile technology is "creating 1.5 million new U.S. jobs and offering tremendous potential to improve education, health care and public safety."[2]

Regulators require a comprehensive set of spectrum management principles.

The continued progress of the mobile revolution depends on advances in semiconductor technology, software, and spectrum reallocation. The most important of these inputs from a policy perspective is spectrum; the United States faces a "looming spectrum crunch" unless regulators can find 500 megahertz (MHz) of new spectrum for mobile applications in the next ten years to complement smaller cells and continued advances in signal processing technologies.[3] Progress toward the 500 MHz goal has so far been mixed, as regulators oscillate between forward steps and backward ones. In order to be effective, legislators and regulators require a comprehensive set of spectrum management principles to guide spectrum policy decisions.

The United States leads the world in the adoption of 4th Generation LTE technology, but it lags the rest of the developed world in repurposing spectrum from legacy systems to LTE. Breaking the spectrum logjam depends on more liberal spectrum policies, better informed principles of spectrum rights, a better understanding of spectrum technology, and a great deal of hard, detailed work on the management of specific spectrum bands.

Nations that lead in the race to modernize spectrum policy stand to win the economic race for the jobs and innovation that are directly created by the new technologies, obviously, but they also stand to improve their economic performance a second time by replacing wasteful and antiquated information systems with more robust, pervasive, and efficient ones. In other words, they gain once by doing things they've never done before and again by doing the old things better.

Historically, spectrum allocation has been an ad hoc, piecemeal system driven by the logic of the moment: A commercial enterprise or government agency with an idea requested a spectrum allocation from the relevant regulator (the FCC in the case of commercial use, and the NTIA for government agencies). If the regulator saw merit in the idea, the regulator looked into its inventory of unassigned radio frequencies and allocated the best available fit. In some cases, the process of spectrum assignment has been initiated by the regulator itself; sometimes to good effect (Wi-Fi™) and sometimes not (satellite phones).

It's now clear that spectrum allocation and management is an ongoing process that will benefit from guidance by a set of fundamental principles. Rather than simply re-assigning spectrum from legacy systems to mobile networks, policymakers need to reform the system that has created a critical shortage of spectrum in the most dynamic sector of the economy while over-allocating spectrum to wasteful and obsolete systems. The spectrum crisis is an opportunity for fundamental reform in the logic of spectrum assignment.

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

1. Sharing: Prefer assignments that serve multiple users, as commercial networks do, over those for single uses.
2. Application Flexibility: Prefer assignments that support a variety of applications over those that support a single application.
3. Dynamic Capacity Assignment: Prefer networks that allow capacity to be adjusted on demand to those that allocate capacity statically.
4. Technology Upgrade Flexibility: Permit technology upgrade without permission.
5. Aggregation Efficiency: Prefer large allocations over small ones to minimize guardband losses.
6. Appropriate Facilities-Based Competition: Seek an ideal number of networks, a number that is likely to be larger than two and smaller than six in most instances.
7. High-Performance Receivers: Favor systems of high-performance receivers over those that can't tolerate common sources of RF noise.
8. All Relevant Dimensions: Allocate "patches" of spectrum by frequency, power level, place, transmission direction, beam spread, modulation, coding, and time.
9. Promotion of New Technologies: Use rules modification rather than exclusive allocation as a means of enabling the next generation of spectrum technologies.
10. Maximize Redeployment Opportunities: When upgrades to existing systems free up spectrum for new ones, as was the case in the DTV transition, require the upgrade.

These allocation principles flow from empirical knowledge of the nature of spectrum, the current state of the art in radio engineering, and the likely timeline of new developments in radio engineering. They are explained in more detail in the main text.

Application of these principles to spectrum allocation disputes will help resolve case-by-case disputes in an optimal manner. Ideally, we should be able to score each spectrum dispute according to the number of principles it follows. This method enables us to determine the extent to which regulators are moving spectrum policy forward or backward. The examination of selected current controversies illustrates this method of analysis at work.

The demand for spectrum is largely created by new wireless applications. The most important example of the demand is the vast pool of applications that have been created for smartphones and intelligent infrastructure such as the "smart grid." Demand for wireless data capacity—bandwidth—roughly doubles year after year.

Bandwidth is often compared to highway capacity, but a better analogy is food production: We can always build more roads, but we can't increase the supply of arable land or of spectrum. We increase the food supply by bringing more acreage into agricultural use, by improving agricultural technologies such as genetically engineered seed, chemical fertilizers, herbicides and pesticides, and by employing sound management practices. Similarly, wireless bandwidth is increased by putting more patches of spectrum to use, developing technologies that increase bits/hertz usage efficiency, and managing network traffic responsibly. Each of these three practices is necessary, and each produces widespread societal benefits.

Spectrum research and development is extremely important, but in the short to medium term technology is not going to resolve the spectrum crunch on its own. Research is advancing along two principal lines:

1. Researchers on the Software-Defined Radio/Cognitive Radio (SDR/CR) field are developing techniques that allow easier access to unused or lightly-used patches of spectrum. These techniques are an alternative or a supplement to traditional regulator practices that assign spectrum to license holders who may not use their allocations fully at all times. In practice, SDR/CR needs to be connected to an authorization database such as the White Spaces Database that provides go/no go information to prospective network operators, and the decisions that his database implements flow from a spectrum allocation policy.

   This branch of research is frequently touted as increasing spectrum efficiency, but this description needs clarification. SDR/CR actually aims to improve *allocation efficiency* by enabling a larger pool of potential users to contend for access to the spectrum. While this can be beneficial, it does not improve *usage efficiency*, the amount of information per unit of spectrum (bits/hertz) that can be transmitted and received over a given patch of spectrum.

2. Research on spectrum efficiency develops techniques that allow for greater bits/hertz *usage efficiency*. This line of research concentrates on techniques that govern the ways that bits are represented on wireless networks, the nature of antennas, and the coding systems and scheduling systems that enable multiple users to share a given patch of spectrum in an orderly manner.

   Most of the practical advances in the use of RF spectrum by commercial and other public systems are the result of research on *usage efficiency*: Packet radio, modulation systems such as Orthogonal Frequency Division Multiplexing (OFDM) and Quadrature Amplitude Modulation (QAM), Multiple-Input Multiple-Output (MIMO) antenna systems, and scheduling/coding systems such Code Division Multiple Access (CDMA).

However, spectrum research doesn't absolve policymakers from identifying more spectrum for wireless data systems. To the contrary, SDR/CR technology depends on spectrum allocation policy as it is primarily a means of implementing complex, multi-level allocation policies. Advanced research on usage efficiency is not currently mature enough to make allocation decisions unnecessary, even if it may be someday. If and when that were to occur, policymakers would still be required to address the vexing problem of the billions of less advanced systems that remain on the air with a transition plan to better technology.

Consequently, lawmakers and regulators concerned with spectrum allocation have no choice but to meet the *current* spectrum crisis by making better use of *current* technology. This requires repurposing and reallocating the pool of spectrum best able to meet the needs of the mobile revolution, a job that is best undertaken by adopting principles that reflect the best understanding of spectrum usage technology as it is today and as it will be in the next five to ten years.

Recent spectrum controversies don't always reflect clear and consistent decision making. Grading the decisions that have been made or will be made soon in this area yields the following results with a scoring system that ranks each decision on a scale ranging from +10 to -10, where +10 is most desirable:

Lawmakers and regulators concerned with spectrum allocation have no choice but to meet the current spectrum crisis by making better use of current technology.

- Leave DTV Channel 51 live while imposing interoperability on 700 MHz B and C block license holders: -8
- Take DTV Channel 51 off the air: +8
- Remove 800 MHz internal guard bands: +10
- Convert government fixed point microwave to fiber backhaul: +10
- Replace Military Tactical Radio Relay with fiber: +10
- Move government video surveillance to a commercial carrier: +6
- Adopt PCAST spectrum sharing recommendation: +5
- Reassign LightSquared spectrum to wideband GPS: -1
- Adopt FCC Medical Body Area Networks plan: 0
- Allow Verizon to purchase SpectrumCo licenses: +7

Policymakers should generally strive for decisions that earn six points or more, and avoid decisions that earn less than three points in the absence of extenuating circumstances not captured by our grading system.

The spectrum agenda needs to proceed along two parallel time lines: In the short term, policymakers need to make more spectrum available for use by high-demand applications such as mobile broadband, and for the long term they need to support basic and applied research on spectrum to relieve capacity constraints. There is no downside in assuming that the spectrum crunch is real and that the long-awaited technical advances that promise to resolve it will not arrive for a very long time. There is an enormous potential downside in assuming that a technology solution that does not require re-allocating spectrum is just around the corner, however. The prudent course is to deal with today's problem today while actively supporting the technology that we will use tomorrow.

SPECTRUM FUNDAMENTALS

This report offers a spectrum allocation grading system that reflects operational principles in modern mobile broadband networks, the facts of wireless engineering, and established principles of economics. This is a data-based policy framework, but empirical data only goes so far in policy debates in this era of "tabloid" tech policy influenced by traffic-hungry blogs that sensationalize technology news.

The warnings of a "looming spectrum crunch" voiced by the FCC, the White House, and the wireless technology community are routinely criticized in the popular press, by the tabloid tech blogs and within the tech policy establishment as self-serving industry propaganda that ignores technology advances such as cognitive radio.[4]

Software-Defined Radio/ Cognitive Radio (SDR/CR), a fifteen-year-old idea, has become the poster child for "new technologies" offered as the solution to the spectrum crunch by pundits who declare radio interference a myth that disappears as radios become smarter.[5] These forecasts are eerily similar to George Gilder's claims of a looming bandwidth glut in the 1990s that would make "bandwidth too cheap to meter."[6]

Cognitive radio, a fifteen-year-old idea, has become the poster child for "new technologies" offered as the solution to the spectrum crunch.

For example, cell phone pioneer Marty Cooper touted SDR at a recent meeting of the FCC's Technological Advisory Council:

> "If you look at the future of what is happening to cell phone designs, we're getting within our sights the possibility of building a cell phone that's totally software configurable. And when that happens, it will be possible to reach for any channel that exists for any specific user. And when you combine that with (you knew I was going to say smart antennas) you now can get not only wide frequency coverage but geographic coverage. And when you achieve that (and it's going to take ten years) all of the work that you're doing in spectrum allocation is going to be irrelevant. There's going to be so much spectrum that we're not going to know what to do with it all."[7]

Similar claims have been made for many years, each projecting five to ten years into the future and we can expect them to continue with the likelihood of resolution any time soon as small.

In reality, fifteen years and six billion dollars' worth of research and development by the DOD on the Joint Tactical Radio System (JTRS) SDR have failed to produce a practical system because SDR is a bet against Moore's Law, a fundamentally misguided approach:

> Since JTRS started, we've seen some advances in software-defined radio technology. NASA is testing SDR as part of its Space Telecommunications Radio System, and it will put an experimental SDR on the International Space Station. Aspects of SDR technology have been used in Wi-Fi devices and cellular phones—for example, the iPhone. But SDR as conceived by the JTRS effort hasn't been widely adopted in the commercial realm, and remains largely the realm of hobbyists, with kits like GNU Radio.
>
> While JTRS's SDR approach focused on making one radio that could do everything with FPGAs, *it was actually a bet against Moore's Law*—that it would be cheaper and easier to have one radio you could add new waveforms to than simply buying another radio. But it turns out, as the consumer wireless market has proven, that it may be cheaper to make lots of single-purpose radios that plug together and get tossed when there's an upgrade.

> When JTRS began, there was no WiFi, no 3G or no 4G wireless, and commercial radio communications was relatively expensive. But the consumer industry didn't even look at SDR as a way to keep its products relevant in the future. No, ASIC-based digital signal processors are cheap, and new products also tend to include faster chips and new hardware features; people prefer buying a new $100 WiFi router when some future 802.11z protocol appears instead of buying a $3,000 wireless router today that is "future proofed" (and you can't really call anything based on CORBA "future proofed").
>
> Without a solid radio product, then, the Army has started to look at options like tactical cellular networks for short-range communications, using proven commercial technology mounted on vehicles and even aerostats (tethered blimps) to create bubbles of connectivity at speeds the waveforms defined a decade ago can't even handle.[8]

The concept of cognitive radio directly conflicts with regulatory enhancements such as receiver performance standards because it opens the receiver portal wider, exactly what we don't want in cases of GPS/mobile broadband co-existence such as the LightSquared matter.

There are other options on the wireless engineering horizon that will increase bits/hertz efficiency by such a radical factor that the spectrum crunch will certainly become manageable and may ultimately fade from the policy agenda. Rather than focusing on the permission structure for spectrum use, these advances create opportunities for actual concurrent use of the same spectrum, in the same place, at the same time, by multiple parties.

Commercial systems already exist that accomplish this goal in a basic way, such as CDMA. More advanced systems have been demonstrated in the research setting that use quantum effects such as Orbital Angular Momentum (OAM) with the potential to increase spectrum re-use efficiency by several orders of magnitude—perhaps thousands or millions of times better than we can do now. These systems address the problem of spectrum scarcity in the orderly, civilian environment, while cognitive radio is more suitable for combat conditions when its problems are worked out. Both OAM and SDR are many years away from practical use in any case.

In this milieu where claims and forecasts consistently outpace the capabilities of existing technology, it's difficult to evaluate the basis on which predictions about spectrum technology are made. Consequently, we offer some tutorial information on wireless technology to help policy thinkers evaluate some of the technical claims that surround this debate. Following the tutorial, we resume the policy analysis.

What is Spectrum?

The term "spectrum" is used in this report and in the policy discourse generally as shorthand for "the spectrum of radio frequency radiation." The radio frequencies of interest to commercial networking providers span the range of electromagnetic energy from 500 MHz to 4 GHz, although radio frequency spectrum (RF spectrum) in general ranges down to 15 KHz. The following briefly describes key properties of RF Spectrum.

The Nature of Spectrum

Electromagnetic radiation (EMR) is a produced by the charged particles (electrons) in atoms. It is a property of all matter, and manifests as waves of energy. EMR in its pure form consists of sine waves of various frequencies, and the modification of these waves by transmitters allows them to convey information.

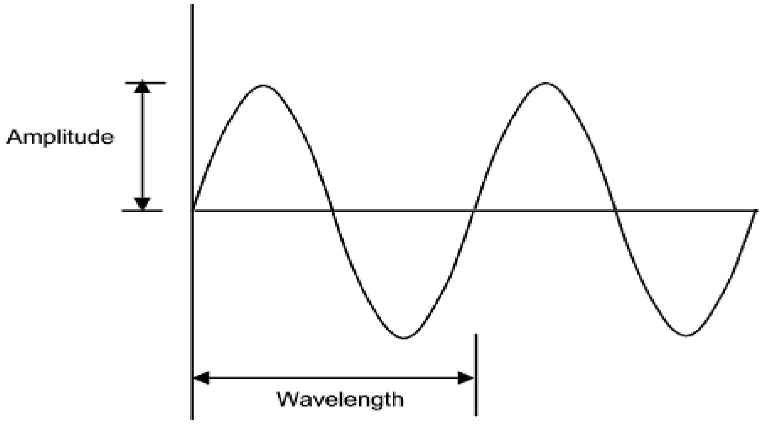

Figure 1: Pure Sine Wave Repeated

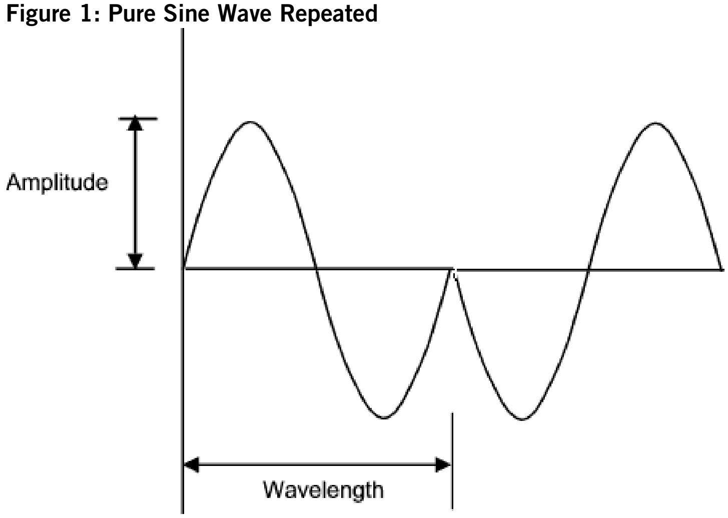

Figure 2: Sine Wave Followed by Inverted Sine Wave

Figure 1: Pure sine wave repeated illustrates the repetition of a pure sine wave, while Figure 2 shows a modification that can be used to carry information. The first sine wave in Figure 2 might be used to convey a bit with value "one," while the second wave could convey a "zero" bit. Of course, real systems are much more sophisticated than this, conveying as many as 1024 bits (or more) with a single modification of the original sine wave.

EMR generally degrades with distance as waves disperse and react to features of the environment and the atmosphere. Spectrum in the 500 MHz frequency has a wavelength of six feet, which allows waves to pass through windows, which are generally much less disturbing to EMR than building walls. Spectrum above 4 GHz range has a wavelength of less than three inches, which causes it to be reflected from (bounced off) most tree leaves. The spectrum between 500 MHz and 4 GHz is most valuable for commercial two-way radio systems such as cellular broadband because of these properties and the size of the antennas that transmit and receive such frequencies.

The Nature of Interference

Radio interference is like a rainbow in the sense that it requires three factors to take place:

1. A transmitter
2. A second transmitter or an obstacle that alters transmissions
3. A receiver located in a specific position

Radio interference is like a rainbow in the sense that it requires three factors to take place: A transmitter, an interferer, and a receiver in just the right place.

Figure 3: Rainbows are Caused by Interference (Credit: Wikipedia)

We see rainbows because the signal transmitted by the Sun is refracted by drops of rain that split visible light into its spectral components, the different colors of visible light. The observer located in just the right place sees the rainbow overlaid on the background of normal visible light, but other observers in other locations don't see the rainbow.

A radio receiver experiences a similar effect when radio interference takes place. In one form of interference, a signal is refracted into elements that arrive at the receiver at different times, one taking a direct path and others taking indirect paths because they bounce off obstacles such as walls, bridges, or foliage. If the receiver is smart, it can recognize that the information carried by the direct signal is the same as the information carried by the indirect signals and recombine them. This capability is exploited by Orthogonal Frequency Division Multiplexing (OFDM) radios.

A more difficult kind of interference is produced by discrete transmitters showering a given receiver with information in the same format at the same time. The information is ambiguous in most instances, because the receiver can't differentiate the ones and zeros until each message is processed, and the messages can't be processed without extracting ones and zeros from the raw energy it receives. We experience this problem in group conversations when two or more people speak at the same time.

Smart radios can disambiguate some of this sort of interference, but not all of it. One approach to smart radio design scrambles messages at the transmitter with a code known to both the transmitter and the intended receiver, so that the application of the code extracts good information and rejects bad. Such systems can even be used to some utility when both messages are intended for the same receiver, as in Code Division Multiple Access (CDMA) systems.

Advances in signal processing will extend the ability of radio systems to focus on meaningful information and reject noise for quite some time to come.

Spectrum Sharing

Radio communication networks share spectrum in two major ways:

1. Regulators assign usage rights to patches of the frequency spectrum in various places to particular operators for years at a time; and
2. Operators assign usage rights to particular users and applications for hundredths of seconds at a time.

The durable access rights assigned by regulators to "raw" spectrum form the basis of the transient access rights to "cooked" spectrum assigned by network operators.

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The term "spectrum efficiency" is used in both contexts, but it has very different meanings when used so broadly. Engineering understands spectrum efficiency in terms of bits per hertz, and this measure is only meaningful in the "cooked" context, after spectrum has been assigned to an operator in a durable manner.

"Opportunistic spectrum access" is actually an advance in the regulatory context rather than in the operational one. It's difficult to measure "bits per hertz" when hertz is an unbounded variable. It's an intermediate between exclusive spectrum licensing (by auction or otherwise) and unlicensed access, but it leans toward unlicensed in practice. The sharing of licensed spectrum is generally more efficient in bits/hertz than unlicensed spectrum: Licensed systems reach 95% utilization, while unlicensed systems such as Wi-Fi™ operate well below 50% utilization. Wi-Fi™ has many advantages, but efficiency is not one of them.

Licensed, commercial networks achieve high utilization by scheduling spectrum access from a common vantage point, a tremendous technical advantage over the "every man for himself" Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) spectrum access system used by Wi-Fi™. Overcoming access inefficiency is a challenge for White Spaces systems when multiple providers seek to utilize common frequencies, but it's not an insurmountable one. In practice, it will be resolved by a combination of game theory and straightforward negotiation.

One concentration of research on spectrum sharing is the "multiple access problem" that addresses the desired use of a given patch of spectrum by multiple parties at the same time. Approaches to this problem include directional radio beams, coding systems that can be easily distinguished, and game theory models for explicit sharing. These technologies are known as beam forming, Spatial Division Multiple Access (SDMA) and Multiple User Multiple Input Multiple Output (MU-MIMO). Commercial systems are developing advanced forms of Sharing by Contract such as “Authorized Shared Access” (ASA), which allows for shared use of spectrum using cognitive radio technologies (geo-location databases, sensing, etc.) based on an individual authorization model of spectrum rights.[9] Market transactions are also a very practical means of addressing this problem.

Drivers of Spectrum Demand

In 2011 more smartphones were sold than personal computers.[10] Only half of Americans have smartphones so far, so the trend toward smartphone and tablet adoption will continue for some time. One day appliances and other devices will come to have smartphone capability built in, so the number of smartphones will exceed the population by several times. This will change the both the Internet and the cellular networks quite dramatically. The Internet is used by some two billion people, but we can expect that number to triple within the next three to five years. The growth in the use of smartphones and the mobile Internet is even more rapid than the boom we saw in Internet growth at the turn of the century.[11]

Smartphone users use many of the same applications that we use on laptop and desktop systems for personal productivity, information browsing, education and entertainment, but they also use applications that are enabled by mobility itself. There has already been a shift in shopping habits during the holiday buying season as smartphone users share information about products, stocks in local stores, lines, and prices.[12] Thanks to web sites such as Zillow and Redfin, shopping for housing is a completely different experience today than it was even two years ago, as buyers can drive neighborhoods, see which houses are for sale or rent, view pictures of their layout, and even analyze their purchase history without leaving the car. Those who walk, run, or cycle for exercise can map their routes, count their steps, monitor their speed, distance, and heart rate, and estimate calorie burn with mobile exercise apps such as Map My Workout, Endomondo and RunKeeper that connect to social networks and cloud computing facilities.

Figure 4: Google Glass (Credit: Google)

In April, Facebook acquired Instagram, a photo sharing service with only 13 employees, for a billion dollars, largely because Instagram has acquired 40 million users in only 16 months of operation. Another social picture sharing service, Pinterest, is the third largest social network only two years after its formation.[13]

“Mobile Augmented Reality” is a new application category that extracts information from massive databases in the Cloud relevant to a user’s location, activity, and preferences; it moves video streams between the user and the Cloud in both directions, sometimes from “Smart Spectacles” that combine a video camera and display screen such as Laster

Technologies' *IEEE Spectrum* 2011 Technology of the Year winner or Google Glass. All of these applications require mobile bandwidth supplied by spectrum and wireless technology—the more the better—and as they are truly mobile there are limited opportunities to offload their spectrum needs to short distance Wi-Fi™ networks. The spectrum needs of tablets are more in line with those of the laptops they're replacing, however as tablets are "nomadic" devices that we use in stationary fashion from multiple locations. The spectrum needs of tablets are generally met with Wi-Fi™ today.

THE SPECTRUM CRUNCH

The National Broadband Plan famously forecasts a need for 300 MHz of spectrum for commercial, mobile networks by 2015, and an additional 200 MHz for various purposes by 2020. Current allocations assign 475 MHz to mobile broadband[14] and 350 MHz to unlicensed Wi-Fi™ and Bluetooth.[15]

The National Broadband Plan famously forecasts a need for 300 MHz of spectrum for commercial, mobile networks by 2015, and an additional 200 MHz for various purposes by 2020.

This estimate is low because we've seen that network applications are generally able to make use of all available bandwidth: Residential broadband connections, for example, are roughly ten times faster than they were in the late 1990s, and many of these connections are unshared.

Figure 5: Augmented Reality in a Contact Lens (Credit: Raygun Studio)

Mobile social networks are using infrastructure initially designed for low bandwidth telephone service. Video sharing applications will consume ten times as much capacity per minute as telephony with the best compression we can use. Cellular networks in major cities are running close to capacity during peak periods already. From 2006 to 2009, the first three years the iPhone was available on the AT&T network, traffic grew 5000%.[16] This figure probably represents users spending five times as many minutes on their iPhones as they spent on their dumb phones, and performing tasks that are ten times as data-intensive. AT&T forecasts a need for eight to 10 times as much data capacity over the next five years as it can carry today.[17] Some of this capacity can be met by improvements in spectrum efficiency (mainly in terms of coding advances), some by increased tower deployment, and some by small cells, but much of it depends on more spectrum.

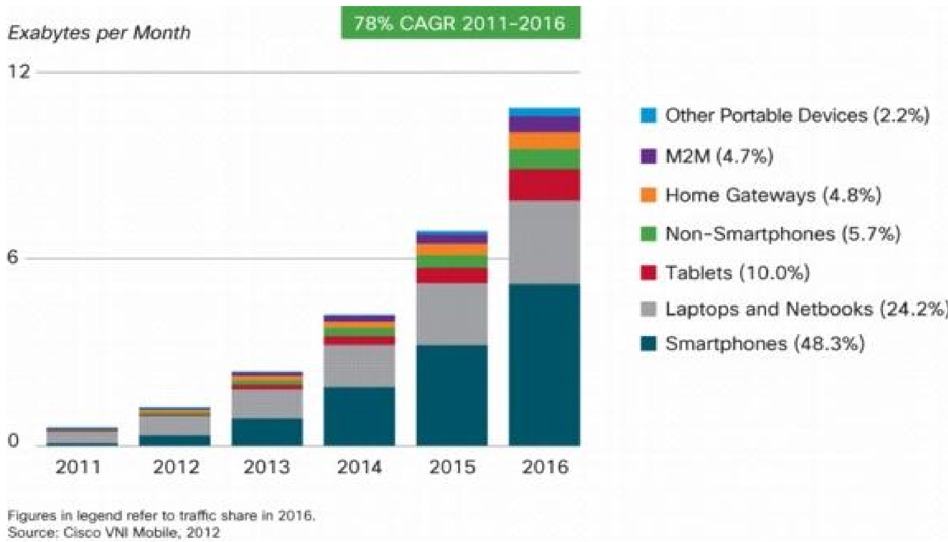

Figure 6: Cisco Mobile Data Forecast by Year and Device (Credit: Cisco)

If we can't find spectrum to meet the needs of mobile users as they transition to smartphones, tablets, mobile social applications, augmented reality, and sensor networks, innovation will stall and economic growth will slow.

The balance between these methods is largely economic. Increased spectrum is the least expensive option, building towers the most expensive, and the costs of more spectrum are ultimately born by users. Some analysts believe that advances in technology alone will meet the demand, but this projection ignores the fact that historical advances in spectrum efficiency follow Cooper's Law, doubling every 30 months, while increases in demand follow Moore's Law, doubling every 18 months.[18] Left to its own devices, technology will fail to meet consumer needs.

The most efficient users of spectrum on a per-user basis over wide areas are the large networks. AT&T and Verizon get by with 0.86 and 0.93 MHz per million subscribers, while Sprint/Clearwire holds 3.72 MHz per million, according to Bernstein Research.[19]

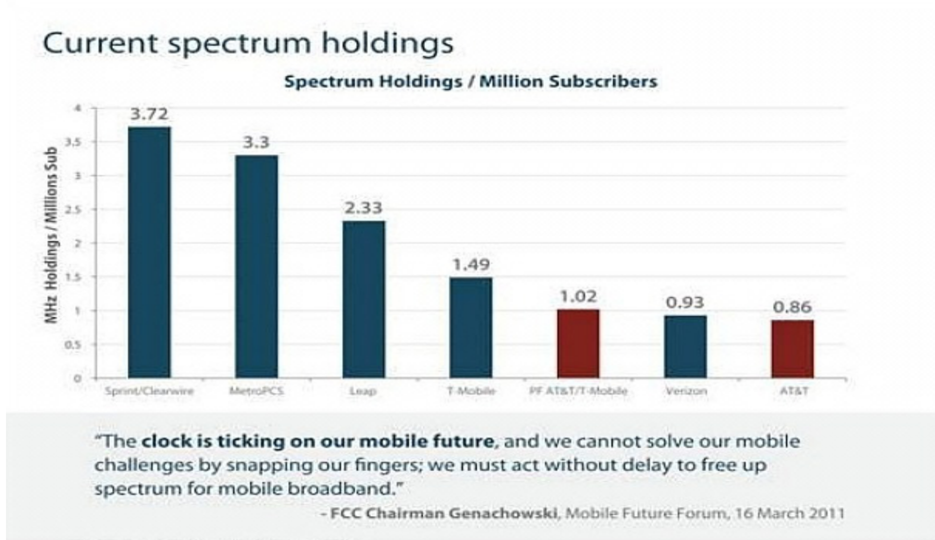

Figure 7: Spectrum Holdings (Credit: Bernstein Research)[20]

If we can't find spectrum to meet the needs of mobile users as they transition to smartphones, tablets, mobile social applications, augmented reality, and sensor networks, innovation will stall and economic growth will slow. The FCC forecasts that these effects will become visible on a broad scale as early as next year, but they're already apparent in New York and San Francisco.[21]

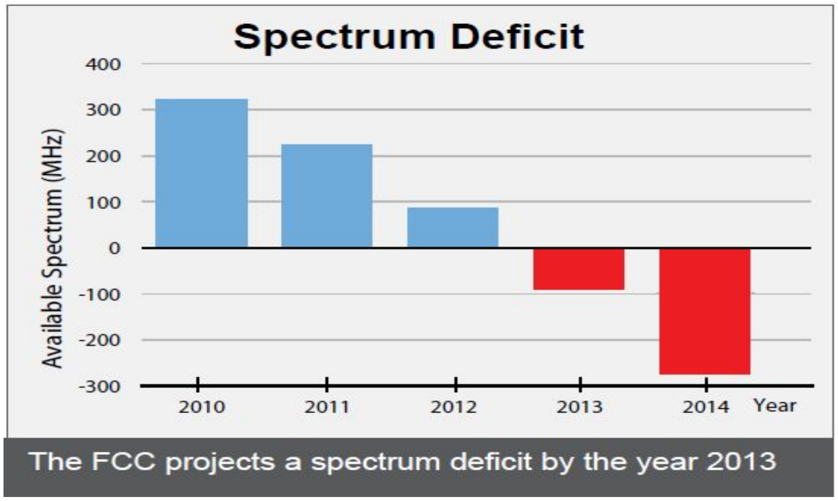

Figure 8: Spectrum Deficit[22]

MEETING THE NEED FOR SPECTRUM

The general problem with spectrum allocation around the world is the 100 year history of assigning spectrum to applications rather than to networks. The following diagram illustrates the complexity of the U.S. spectrum allocation system. A more ideal system would have many fewer allocations, each for a substantially larger amount of spectrum.[23] From the application perspective, spectrum sharing on commercial networks is a solved problem. We don't have one network for Instagram and another for Pinterest, we have one group of networks that handle a wide range of applications. What we're doing with such technologies as Dynamic Spectrum Access and Authorized Shared Access is reversing the effects of historical spectrum allocation policy. When successful, these approaches will create networks that resemble commercial networks in their application support. This is a way of putting the Humpty-Dumpty of primitive spectrum allocations back together again.

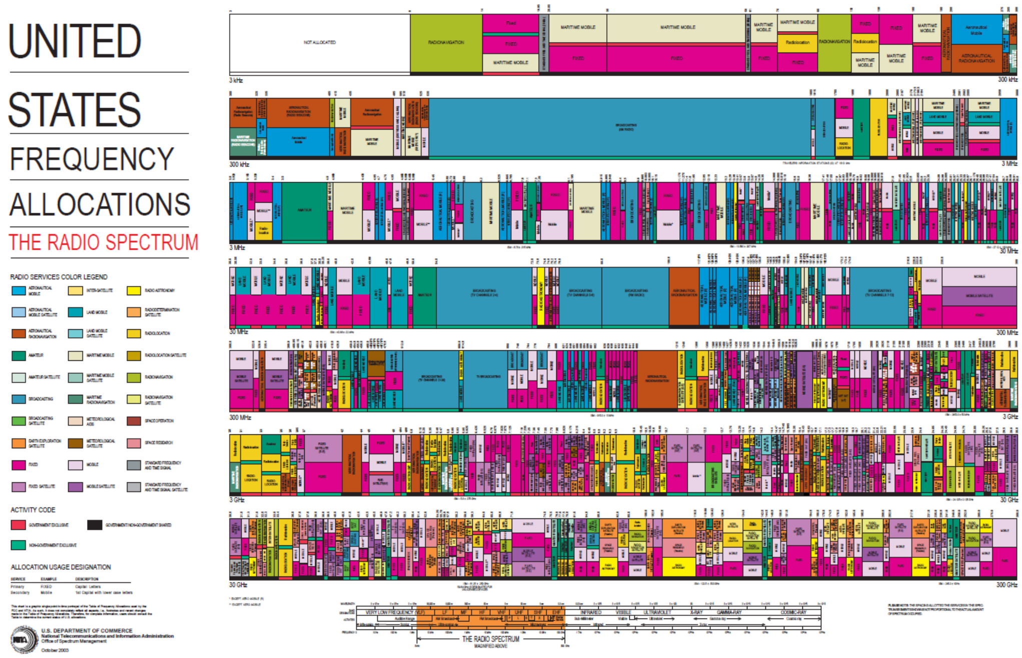

Figure 9: U.S. Frequency Allocations (Credit: NTIA)

In order to meet the need for network capacity, carriers will supply more spectrum per user. The easiest way to do this is to offload the cellular network onto femtocells and Wi-Fi™ networks, but this is a limited strategy because Wi-Fi™ networks are often overloaded themselves, and in the best conditions Wi-Fi™ fails to meet the needs of mobility.

Wi-Fi™ is a nomadic network, not a truly mobile one, and femtocells have similar characteristics. The small cells that will help relieve the crunch are deployed outdoors on frequencies that coordinate with the macro cells on which the cellular network is based. Building micro cells within the macro cellular fabric is a bricks-and-mortar exercise that requires massive investment and zoning approval to be successful.[24]

Technical Means: Improving Usage Efficiency

As previously mentioned, critics of the spectrum crunch construct correctly argue that advances in wireless technology will meet the bandwidth needs of mobile users even if regulators fail to re-allocate spectrum from legacy applications to mobile networks.

This prediction is true because technology will continue to improve for the foreseeable future, so it's inevitable that some future technology will permit the current allocation of spectrum to meet current user needs for bandwidth. The prediction is also false because it fails to account for the time required for such technical advances to be developed and fully deployed as well as for the growth in user demand that will take place along the way.

We can just as easily predict that the Chicago Cubs will win the World Series. In September of 1908, this would have been a sound prediction, but less so fifty or a hundred years later. It's still likely that the Cubs will win the Series *someday*, but we don't know when that day will come.

Cubs fans don't need to know precisely when their team will triumph—as Cubs fan George Will says, they greet every spring like a second marriage, with the triumph of hope over experience—but makers of World Series winner memorabilia do. The key question for spectrum policy is *when* advances in spectrum technology will begin to produce efficiency gains in excess of increases in user demand for bandwidth.

Unfortunately, no one knows the answer to this question. Even Marty Cooper, one the more bullish advocates of the notion that technology alone will solve the bandwidth crunch, doesn't see much happening for ten years.[25] In technology industry terms, the ten year planning horizon is equivalent to "infinity" because few firms plan beyond the next two to three years:

> The five-year planning horizon that used to be typical of traditional strategic plans is no longer feasible. The pace of changes in technology and changes in the business environment warrant no more than three years' planning horizon. Beyond that time frame, it is reasonable to assume that the business environment and available technology will be so different that a new strategy will be required.[26]

The key question for spectrum policy is when advances in spectrum technology will begin to produce efficiency gains in excess of increases in user demand for bandwidth.

Consequently, network operators require the ability to upgrade the actual capacity of their networks without waiting for hoped-for new technologies. In the event that the great breakthrough happens sooner than expected, they're likely to adopt it regardless.

The most curious part of the argument for regulator inaction is the tacit assumption that the current allocation system of spectrum by application is somehow ideal. Our experience with the transition from analog to digital TV contradicts this assumption. When the FCC required TV broadcasters to shift from the analog NTSC standard to digital ATSC, consumers gained access to high-resolution images and sound, and the FCC was able to reclaim half the spectrum previously allocated to analog TV for auction to mobile broadband, to create a public safety network, and for deployment as unlicensed White Spaces systems.

A similar pattern exists across the range of legacy spectrum assignments. The government currently uses 130 MHz for video surveillance, most of it with analog cameras. Converting these systems to digital reduces their spectrum footprint by 75%, and opens the opportunity of sharing with commercial and government systems such as First Net. There is no downside to assuming that the spectrum crunch is real and acting accordingly.

The following reviews some notable opportunities for increased spectrum efficiency and utility and their likely timelines.

Distributed Antenna Systems

In conjunction with the National Association of Telecommunications Officers and Advisors (NATOA) the FCC held a workshop on Distributed Antenna Systems on February 1, 2012.[27] Distributed antenna systems are much more than the name implies.

In fact, DAS simply uses conventional technology on a shared antenna mast, which is already par for the course in wireless network deployment.

These systems allow a particular antenna array to be shared by multiple users, at the expense of digital signal processing equipment in each antenna that is dependent on the particular modulation and coding of the information format in use by each user. They are attractive to community broadband advocates because they allow municipal networks to share facilities used by commercial systems and to municipalities because they reduce the number of unsightly cell towers that must be deployed. They're also attractive to operators because they reduce permitting overhead, but it's hard to argue that they increase bits/hertz efficiency. In fact, DAS simply uses conventional technology on a shared antenna mast, which is already par for the course in wireless network deployment.

Small Cells

LTE enables the deployment of small cells by design. The general notion for LTE network design is to embed small cells in high-density locations within the large cell coverage area.

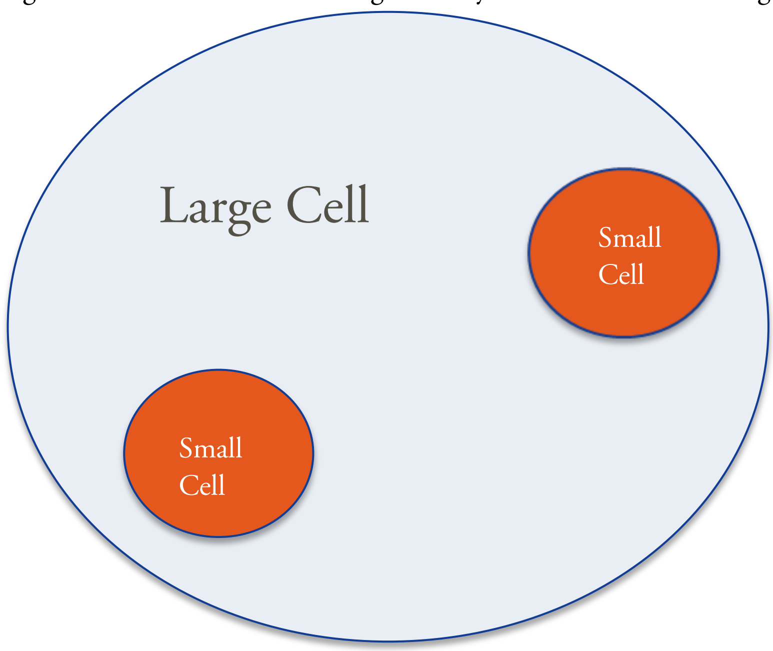

Figure 10: LTE Small Cell Architecture

For this architecture to be most effective, the small cells need to be able to use different radio frequencies than the large cell. If all three cells use the same frequencies, they need to be tightly coordinated to operate at all, and when operating, they fail to meet desired performance goals. Embedded small cells do not eliminate the need for additional spectrum, they're provide a way of using it. Spectrum needs of small cells are taken from alternate antenna sectors today, but this situation isn't ideal.

Personal Cells

Personal cells, or fFemtocells, are a widely used alternative to Wi-Fi™ for local service within a home or office. They're primary useful where both Wi-Fi™ performance and cell reception are poor. They don't significantly address of the needs of mobile users.

Coding Systems

Code Division Multiple Access (CDMA) is a system that uses a combination of spread-spectrum and coding to permit the use of a common set of frequencies by a group of users. CDMA is a very effective system in contrast with scheduled Time Division Multiple Access (TDMA) because it has faster response time. It's also effective by comparison with Frequency Division Multiple Access (FDMA) because it uses more of available spectrum. Most of the benefits of CDMA are already achieved in LTE networks.

Orthogonal Frequency Division Multiple Access (OFDMA) is an alternative to CDMA is uses properties of OFDM to combine data streams from multiple users on a common frequency. Its principal advantages are ease of implementation in systems that use MIMO, and potentially greater immunity to multipath interference. It's primarily used by Wi-Max.[28]

Smart Antennas

Space-Division Multiple Access (SDMA) is a system that effectively sends a radio beam to a receiver in such a focused way that other receivers don't see it. This is accomplished through a combination of multiple antennas that focus on a single partner and coding systems that provide additional per-unit separation such as CDMA or OFDMA.

To be fully effective, SDMA needs to be implemented by both the base station and the mobile device, but mobile implementation increases battery drain. The tradeoff between battery life and signal processing is a feature of all systems that increase bits/hertz efficiency by applying more signal processing, which leads wireless engineers to calculate mobile network efficiency in terms of bits/hertz/battery life.

Twisted Vortex Beams

A promising new technology known as "twisted vortex beam transmission" that uses Orbital Angular Momentum (OAM) is described in an academic paper in *Nature Photonics*. Unfortunately, this system has been poorly explained to the lay public by the tech blogs.[29] Sebastian Anthony of *Extreme Tech* claimed that twisted vortex represents an infinite capacity wireless system:

> According to Thide, OAM should allow us to twist together an "infinite number" of conventional transmission protocols without using any more spectrum. In theory, we should be able to take 10 (or 100 or 1000 or…) WiFi or LTE signals and twist them into a single beam, increasing throughput by 10 (or 100 or 1000 or…) times. For fiber networks, where we still have a lot of spare capacity, this isn't all that exciting—but for wireless networks, where we've virtually run out of useful spectrum, twisted radio waves could provide an instant, future-proof solution. For the networking nerds, Willner's OAM link has a spectral efficiency of 95.7 bits per hertz; LTE maxes out at 16.32 bits/Hz; 802.11n is 2.4 bits/Hz. Digital TV (DVB-T) is just 0.55 bits/Hz.[30]

Samuel K. Moore of IEEE Spectrum provided a more reasonable description of the system:

> Beams with different orbital angular momentum can be transmitted together on the same beam and then distinguished from each other at a receiver as if they had been sent on separate channels.

> The communications technology could find a home in satellite communication links, in short free-space optical links on earth (such as between buildings in a city), or maybe in fiber optic cables (which the engineers say is their next step).
>
> Orbital angular momentum has been studied intensively at optical wavelengths, but recently physicists have been trying to apply it to radio frequencies. Scientists in Europe claimed the first twisted RF communications earlier this year. But others question whether twisted RF is really different from other multiple-input-multiple-output radio techniques.[31]

While the *Nature* article describes a visible light system that operates well beyond the reach of the 500 MHz – 4 GHz range desired for mobile broadband, similar research has been conducted in Italy with an RF system that shows OAM working in the 2.4 GHz Wi-Fi domain as well, a very exciting development.[32]

There is some disagreement about where we are with OAM systems at the moment and the hyping by the blogs doesn't help, but the idea holds enormous research promise. Its first uses will be very basic, point-to-point applications such as short distance backhaul, but a world of possibilities may lie beyond the first step.

Policy Means: Increasing Allocation Efficiency

Policymakers have a number of means to correct inefficient allocation of spectrum usage rights.

Minimizing Guard Bands

The spectrum chart has hard boundaries between allocations, but electro-magnetic energy spills outside its intended boundaries. Regulators require that spectrum users observe quiet zones or "guard bands" at the boundaries of their allocations to minimize this effect, and each guard band is an allocation waste. Guard bands must be wider when a high-energy user such as mobile broadband neighbors a low-energy user such as GPS. Relocating low-energy users to adjoining frequencies reduces this effect, but this is hard to accomplish in practice for both technical and political reasons.

Dynamic Sharing with Occasional Users

Dynamic Spectrum Access (DSA) addresses the allocation inefficiency that arises in the case of occasional users. For example, some military spectrum supports training exercises, so it's not used on a continual basis. In principle, this spectrum can be shared with other users to good effect when training exercises are not underway. Similarly, the White Spaces (dead space between TV channels) can be used by public networks in many areas on a more long-lasting basis, because the practice is to allocate TV stations in each market to non-contiguous channels.

While there's an excellent case for using the stable White Spaces for public networking, it remains to be seen whether the military's training spectrum has the same potential. One question that time-based sharing raises is what the secondary user does when it can't find spectrum to use. Perhaps secondary users will piece together coherent networks out of multiple secondary allocations. Another question concerns network Quality of Service

(QoS). Cellular telephony depends on predictable access to spectrum to ensure voice quality, but systems of non-exclusive access to spectrum are generally unable to ensure QoS. Hence, the viability of the primary cellular application is questionable over DSA systems.

Revoking Legacy Allocations

A third allocation inefficiency arises when a historically popular use of spectrum loses its appeal but retains its allocation. This is the situation with OTA TV, mobile satellite phones, and a number of educational and local government allocations. This kind of allocation inefficiency is best resolved by regulator action to revoke the allocation and allow a more appealing user to take control of the spectrum. This may be accomplished by administrative fiat, by an "incentive auction," or by voluntary license transfer (as in the case of the Clearwire network, largely run on educational spectrum transferred by the original licensee).

While correcting allocation inefficiencies is primarily the job of the regulator, technology can ease the transition from the old to the new user. Frequency-agile SDRs and authorization databases are tools that regulators can leverage in making slow transitions to new allocations.

The most immediate and effective means of making effective use of spectrum that was once allocated to an application that no longer has broad appeal are market-based systems of straightforward license transfer. These solutions encompass the formal auction of spectrum usage rights as well as a direct sale from the old license holder to the new one. The FCC has a system of market-by-market spectrum screens, limits on market concentration that provide guidance on license transfers. This system is meant to preserve competition.

The Value of Unlicensed Spectrum

Unlicensed systems such as Wi-Fi™ and semi-unlicensed systems such as White Spaces networking are not as much about increasing the bits/hertz efficiency of spectrum use as they are about increasing the utilization of spectrum that would otherwise go to waste. This is a tremendous benefit to consumers, of course. Before Wi-Fi™, the 2.4 GHz spectrum was only used by microwave ovens, and it now hosts a variety of applications and hundreds of millions of users.

Wi-Fi™ is very effective at off-loading nomadic use from the cellular network, most dramatically for users of tablets and laptops. White Space networking has the potential to offload voice and text messaging for mobile users as well, but practical deployments of such systems are sparse. AIR.U, a consortium of universities too small to qualify for the Gig.U initiative, announced plans recently to operate pilot networks within the next year.[33] We look forward to evaluating the results of these pilots, but it's too soon to tell how much capacity they will add to the mobile ecosystem and how well they'll mesh with existing systems. The coordination of Gig.U and AIR.U suggest that nomadic users in the participating institutions hope to gain performance upgrades over their current experience on Wi-Fi™ and cable networks.

Wi-Fi™ Alliance members have begun to ship access points conforming to the 802.11ac standard that supports operation in the 5.8 GHz band at speeds up to 1 Gigabit/second.[34] This standard is primarily useful for nomadic applications over short distances on the order of 50 feet. It's not a mobile system, but it can offload voice, text, and video streaming in stationary settings.[35]

PRINCIPLES OF SPECTRUM ALLOCATION

We propose a grading system for spectrum actions based on the current facts about spectrum usage systems and an educated set of predictions about the direction and promise of new technologies currently in development. It consists of ten factors, not currently prioritized or weighted.

1. Sharing: The most desirable allocations are those that can be shared by large numbers of people. Commercial Mobile Networks (CMN) are one very good example of efficient spectrum sharing: The larger networks, operated by Verizon and AT&T in the United States, support approximately 100 million users with 100 MHz of spectrum, for a sharing factor of one hertz per user. Wi-Fi™ has similar efficiency, with some 300 million U.S. users on 300 MHz of spectrum. In contrast, broadcast television consumes 10 hertz per actual user.

2. Application Flexibility: The most desirable allocations are those that can be shared by large numbers of applications. Both CMN and Wi-Fi™ networks host a variety of applications, allowing end users to make the ultimate choice of applications in real time. These networks support the whole range of applications permitted by the Internet Protocol and the roaming limitations of each technology. In contrast, most historical spectrum allocations have been made to single-purpose systems such as AM/FM radio, TV, satellite TV and radio, and taxi networks.

3. Dynamic Capacity Assignment: The most desirable allocations bring supply and demand into balance. Modern networks allow for capacity assignments to follow demand by flexible definition of units of internal allocation (commonly called "channels.") For example, Wi-Fi™ channels can be units of 20MHz, 40 MHz (802.11n) or substantially more (802.11af), while LTE networks can work with channel bandwidths from 2.5 to 40 MHz or more.

4. Technology Upgrade Flexibility: The most desirable allocations are those that can easily be improved. In the old spectrum regime, regulators often stipulated technology choices for spectrum users by fiat, epitomized by the European requirement for carriers to use GSM for 2G phone service. This practice prevents the deployment of more advanced systems such as CDMA and LTE. Rational Allocation permits technology upgrade without permission, and indeed expects that all technologies will have limited lifespans as better technologies are developed that replace older ones.

5. Aggregation Efficiency: The most desirable allocations are those that minimize boundary waste. The fundamental distinction among spectrum sharing technologies distinguishes the sharing done within a particular spectrum-based network and from the sharing between networks. This can be conceptualized as

the sharing of "cooked" spectrum in the first case and "raw" spectrum in the second case. Every network that supports multiple users and multiple applications is an exercise in sharing "cooked" spectrum, and the greater the pool of spectrum for a given network, the greater the potential for sharing. Hence, large allocations have an efficiency advantage over small ones, as they can support large user populations and diverse applications.

6. Facilities-Based Competition: The most desirable allocations are those that promote an efficient level of competition. While a small number of networks leads to more efficient sharing (and to investment efficiency), a larger number of networks produces competition advantageous to consumers, but only up to a point.[36] In the most extreme case, a single network is most efficient from the standpoint of sharing and investment, while an infinite number of networks would produce maximum competition at the expense of efficiency. This principle is therefore in conflict with the previous one and the two must be held in tension as we seek the ideal number of networks, a number that is most likely to be larger than two and smaller than six in most instances. In industries in which a key input is limited, as is the case in mobile networking, the number of sustainable competitors is also limited.

7. High-Performance Receivers: The most desirable allocations are those that require high performance receivers. Spectrum sharing is optimized by high-performance receivers with the ability to tune into the signals intended for them and to reject or ignore all other signals. While spectrum regulation is always written in terms of transmission rights, every statement of transmission rights is inherently a statement about the ability of nearby receivers to function in the presence of such transmissions as the regulation permits. Contrary to the beliefs of some spectrum idealists that the rejection of unwanted signals is simply a matter of digital engineering, every spectrum system is fundamentally analog and must be carefully engineered to work in a specific noise environment. It's proper for regulators to require greater performance of spectrum receivers year after year. Each generation of cellular technology has better noise immunity than the preceding one, for example.

8. Use of all Relevant Dimensions: The most desirable allocations are those that make use of all relevant dimensions of allocation. Traditional spectrum allocations don't fully reflect the variety of ways that spectrum can be used. The traditional methods allocate by frequency, power level, and place, but spectrum can also be distinguished by direction of transmission, beam spread, modulation, coding, and time. As more advanced technologies are developed, allocation principles should come to recognize these dimensions. The TV White Spaces notion is a step in this direction, adding time to the factors that condition spectrum usage rights.

9. Promotion of New Technologies: The most desirable allocations are those that speed the path to new technologies. One of the most important roles the FCC's spectrum policy has played over the years is to create markets for new communication technologies such as satellite, cellular, Wi-Fi™ and ultra-wideband by allocating spectrum for their use ahead of actual network deployment. This function will continue, but in a more subtle way. Rules modification rather than

exclusive allocation is the means of enabling the next generation of spectrum technologies.

10. Development of Redeployment Opportunities: The most desirable allocations are those that can be repurposed as needs change. In line with the notion of rules liberalization and clarification, spectrum policy must recognize that today's problem is one of re-deployment and multiple use rather than new greenfield assignment. As we saw in the LightSquared controversy, incumbents (especially those in the government sector) automatically resist rule changes for adjacent bands with the potential to interfere with legacy systems, but such rule changes are unavoidable. And as we saw in the digital TV channel reallocation, incumbents will resist societally rational reallocations. Redeployment often depends on upgrades to existing systems, and there should not be general resistance to making such changes.

USING THE PRINCIPLES TO ADDRESS CURRENT SPECTRUM CONTROVERSIES

The record in recent spectrum controversies is decidedly mixed between successful, forward-looking resolutions and backward-looking ones that reduce spectrum innovation.

Current and recent controversies over spectrum include disputes over device interoperability in the 700 MHz band, legacy guardband requirements in the 800 MHz band, the dispute between LightSquared and GPS manufacturers, the debate over government applications in the 1.7GHz band, the assignment of application-specific spectrum for medical monitoring equipment, the use of the 700 MHz D block for a national public safety network, and the proposed transfer of 20 MHz of AWS-1 spectrum from SpectrumCo to Verizon.[37] The record in recent spectrum controversies is decidedly mixed between successful, forward-looking resolutions and backward-looking ones that reduce spectrum innovation.

700 MHz Device Interoperability

The FCC is considering new rules for mobile devices that operate in the 700 MHz band per a Notice of Proposed Rulemaking (NPRM) titled "Promoting Interoperability in the 700 MHz Commercial Spectrum." It's unusual for the agency to impose rules on devices built by such firms as Apple, Samsung, Nokia and others, so there is sharp disagreement about whether it actually has the authority to do such a thing. However, it's worthwhile to examine the proposed rules on the assumption that the FCC can find the authority.

The background is somewhat complex. The FCC's last big spectrum auction took place in 2008 when the "digital dividend" freed up some airwaves that had formerly been used by analog television. Digital TV channels can be placed closer together than analog channels were, so a more efficient packing scheme made this spectrum available for sale. The spectrum was arranged in five blocks, called A-E, in two ranges, low and high. Most of the blocks consisted of pairs, separated to allow transmission on one half of the pair while the other half was doing reception, but the E block was unpaired. The D block was not successfully auctioned as the FCC wished to sell a single nationwide license for it and the reserve price wasn't met, but it has since been given to public safety.

The following map shows how the pairing works:

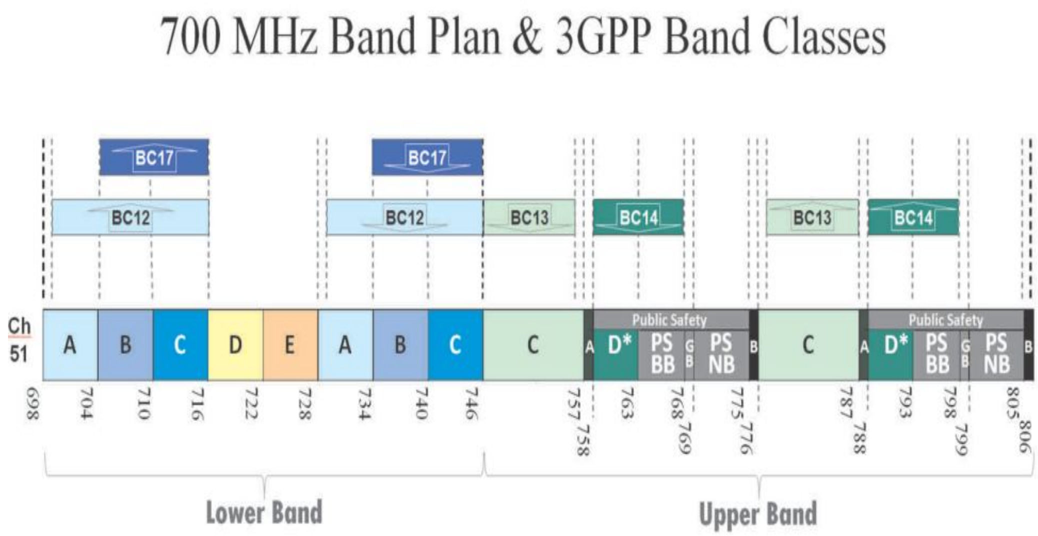

Figure 11: 700 MHz Band Classes (Credit: FCC)

AT&T paid a significant premium to be free of the net neutrality rules and the interference caused by the high power TV transmitters on Channel 51 in the urban markets, and the regional carriers who could live with channel 51 got a discount.

Note that the A block consists of 6 MHz next to Channel 51 at 698 – 704 MHz and another 6 MHz from 728 – 734 MHz, that the E block is a single slice without a pair, and that there is C block spectrum in both the lower band and the upper band, with the upper band (downlink) slices twice as wide as the lower band (uplink) slices.

The A-C blocks sold for wildly different prices because the A and C blocks had significant restrictions that the B block didn't: the A block was directly adjacent to active TV transmitters on Channel 51 is most urban markets, and the FCC imposed artificial net neutrality restrictions on the C block in accord with the fashion of the time. The average prices by MHz per million population ("megahertz pop" in regulatory parlance) were:

Block	A	B	C
Bandwidth	12 MHz	12 MHz	22 MHz
Type	paired	paired	paired
Partition	176	734	12
Price ($/MHz-pop)	$1.16	$2.68	$0.76

Figure 12: Auction Returns[38]

The biggest winner of B block spectrum was AT&T, the biggest winner of C block spectrum was Verizon, and the A block was mainly won by regional networks such as MetroPCS, US Cellular, and Cellular South. AT&T paid a significant premium to be free of the net neutrality rules and the interference caused by the high power TV transmitters on Channel 51 in the urban markets, and the regional carriers who could live with Channel 51 got a discount; Verizon arguably did best of all by accepting the net neutrality rules. The assumption of flexibility played a big role in determining the auction price.

Here's a map of the Channel 51 transmission contour:

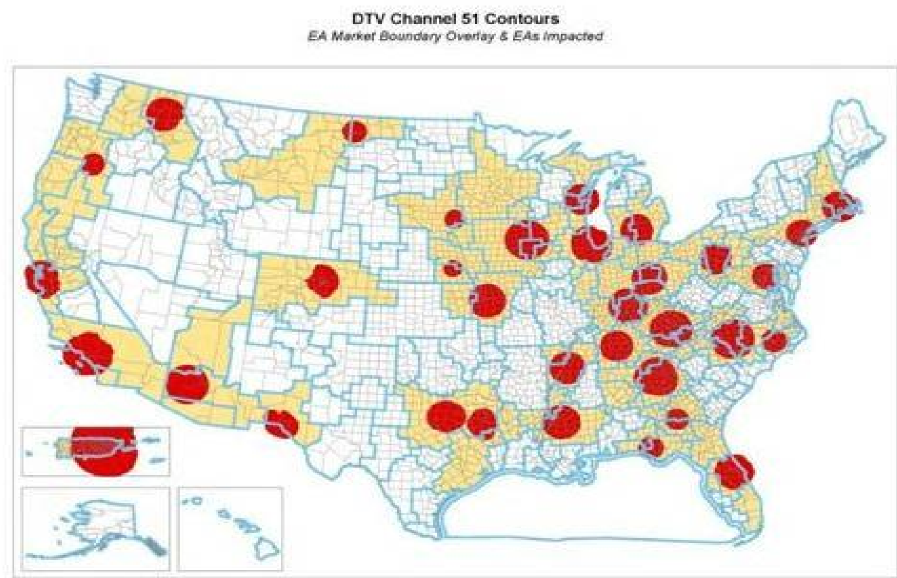

Figure 13: Channel 51 Contours (in red) Against A Block Service Areas (in yellow) (Credit: FCC)

Spectrum is harmonized around the world according to "Band Classes" devised by 3GPP, the standards body that defines such things as LTE, the new 4G standard that's hitting the U.S. market now in a big way and starting to appear in the rest of the world in a much smaller way. There are three band classes of interest for 700 MHz, identified in the first diagram as BC 12, BC 17, and BC 13. Note that Band Class 17 is a subset of Band Class 12 that excludes the discount A Block, and BC 13 is distinct and non-overlapping with classes 12 and 17.

At this stage, AT&T plans to resell devices conforming to Band Class 17 and Verizon to resell devices conforming to Band Class 13 (in the upper C Block). These devices will be able to use their native, licensed networks only, which means they won't be capable of roaming onto other networks (except insofar as these devices may support other frequencies as well). Hence the notion of "interoperability:" 700 MHz devices will not roam or "interoperate" with other band classes and networks but the ones they're built for.

This worries the small carriers who bought A Block spectrum at a discount because they would like to use the same devices that AT&T and Verizon resell rather than more specialized devices tuned to their A Block frequency and also capable of roaming onto the B and C blocks. Cellular South (now known as "C Spire") is the only regional network to offer the iPhone to its customers so the entire group of A Block winners is somewhat disadvantaged in terms of the very best devices, but there are a few Android devices adapted to their networks: MetroPCS offers LTE today with such devices. Chips are available to support Band Class 12 so there is not an insurmountable technical hurdle to building Band Class 12 devices. Making them work well is a different matter, however.

Leaving aside the question of the propriety of the FCC essentially requiring AT&T and Verizon to subsidize handsets for the A Block carriers and focusing in the technical details raises some interesting issues.

We learned from the LightSquared issue that it's never good to be dependent on a low-power signal when you have a neighbor who uses a high powered one. Even though the signals are distinguishable from each other in terms of their patterns of digital bits, the radio energy of a high power transmitter confuses receivers designed for low power signals. Every radio receiver has to operate over a wide range of power levels because signal strength typically erodes with distance. Radio receivers generally amplify received signals to "normal" signal strength internally using an "automatic gain control" circuit that measures received signal strength and boosts the signal by a variable amount to the reference level. When a radio receives two signals at once, one strong and one weak, it boosts both by the same degree but not to the same level. When there is a significant disparity, only the stronger signal can be decoded, so sophisticated digital signal processing techniques are not effective.

As radio waves decay with distance, they give off interference energy above the frequency of the original signal, and this can be significant when the power difference is great between the lower and higher powered transmissions. When multiple transmissions interact, receivers can experience "Inter-modulation" (IM) distortion, defined by Wikipedia as:

> …the amplitude modulation of signals containing two or more different frequencies in a system with nonlinearities. The intermodulation between each frequency component will form additional signals at frequencies that are not just at harmonic frequencies (integer multiples) of either, but also at the sum and difference frequencies of the original frequencies and at multiples of those sum and difference frequencies.[39]

For clarity, the follow page contains a diagram of IM distortion. The diagram shows IM distortion as the two smaller spikes the left and right of the two big spikes that represent the signals. The IM spikes in this example are significantly stronger than the background signals represented by the more solid lines.

There are a few ways to work around IM distortion. The easiest is to raise signal power, which is accomplished in cellular systems by siting towers in a ring around the IM distortion source and by increasing the battery draw in mobile devices. There are limits to this approach because towers are expensive and cellular systems are very low power compared to those TV transmitters on Channel 51.

Engineers hired by the regional carriers seeking to encumber 700 MHz handsets with A Block support claim that three towers close to each TV tower will do the job, but AT&T's engineers put the number closer to 12. Another way is to add filters to the devices, which raise the cost and increase the battery drain, and yet another is to use more sophisticated signal processing, which once again reduces battery life. All of these methods require extensive field testing, so there is a significant overhead in terms of the time to market for new devices.

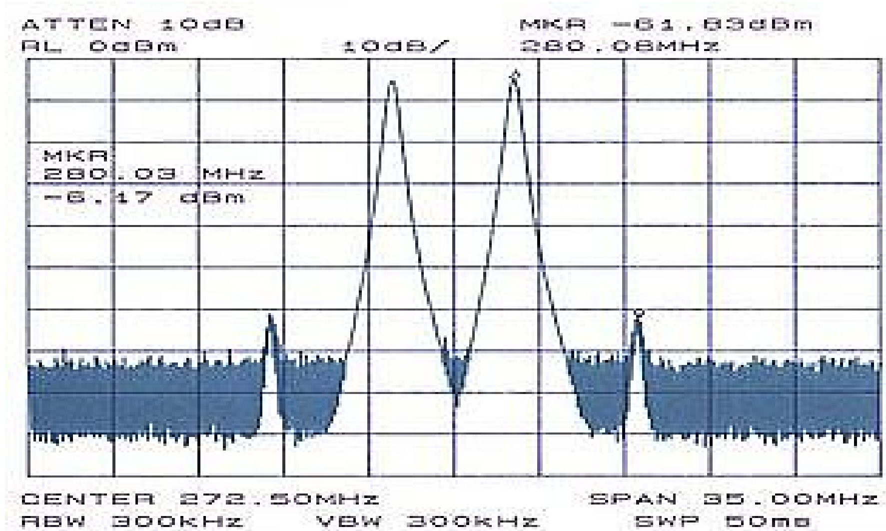

Figure 14: Inter-modulation Distortion (Credit: Wikipedia)

This brings us to this question: Is it reasonable for the FCC to add expense to the smartphones that AT&T and Verizon sell (meaning that millions of consumers would pay more), to reduce their battery life, and to delay the introduction of new devices built by Apple, the Android device producers, and the Nokia/Microsoft partnership in order to enable roaming between regional networks and national ones? "Reasonable" is in the eye of the beholder, of course.

From the point of view of the regional network providers, the proposed interoperability rule costs nothing and impairs the users of the national networks, so it's good. For the national network providers, the rule increases costs and prices, irritating customers, so it's bad. For device manufacturers, it impairs the ability to get new devices to market so it's bad. The "interoperability" mandate will also stress the analog engineering skills of the device makers in an area where they don't need any more problems. Analog engineers are in short supply, which is evident every time a smartphone shows poor antenna performance.

The cheapest and easiest way around this problem would be for the FCC to adopt the same solution they went for in the LightSquared case: They can take Channel 51 off the air. With the interference source gone, Apple can simply build all of their 700 MHz devices to function on the A, B, and upper C blocks without special testing and engineering for the A Block. If the FCC doesn't want to do this, we'll have to evaluate whether their reasons for keeping Channel 51 alive are more compelling than the reasons the device manufacturers have for not wanting to filter the interference it spills into the A Block. The alternatives for current programming on Channel 51 are relocation to another frequency of limiting distribution to cable, satellite, and Internet streaming.

As it stands, the A Block licensees have the power to buy as much interoperability as they want from the companies that build their smartphones. They're going to pay higher prices for these Swiss Army knife phones than the more narrowly tailored phones used by the national carriers, but they got a deal on their spectrum, after all.

As it stands, the A Block licensees have the power to buy as much interoperability as they want from the companies that build their smartphones.

The FCC is looking for precise estimates of the costs of an interoperability mandate, but they're only part of the story given the agency's assumptions. The chief underlying assumption seems to be that the consumer buys a smartphone and keeps it for a decade or more, roaming at will and changing carriers every time a great deal is available. This is clearly not the way the smartphone market works today, or we wouldn't see people camping out at the Apple store to get the newest iPhone.

This proceeding has the feel of "Wireless Carterfone," an attempt to re-live the glory days of 1969 when the courts and the FCC correctly required an interoperability interface to the telephone network. While that decision led to cheaper and more plentiful fax machines, modems, and answering machines, it's not really parallel to the situation we have in the rapidly-changing world of cellular technology. We have to think about how this mandate will affect the roll-out of 5G and 6G services as well as faster and better smartphones even if we can convince ourselves that it makes sense to have the national carriers subsidize the regionals, because it is likely to delay the transition to more advanced systems.

While the issue hasn't been resolved, the part that we're concerned about will either leave Channel 51 on the air or take it off the air. Any interoperability mandate will be mainly conditioned by this decision.

Leaving Channel 51 on the air has the following effects:

1. Sharing: Retarded
2. Application Flexibility: Retarded
3. Dynamic Capacity Assignment: Retarded
4. Technology Upgrade Flexibility: Retarded
5. Aggregation Efficiency: Retarded
6. Facilities-Based Competition: Retarded
7. High-Performance Receivers: Advanced
8. Use of all Relevant Dimensions: Retarded
9. Promotion of New Technologies: Retarded
10. Development of Redeployment Opportunities: Retarded

Total Score: -8

Consequently, leaving Channel 51 on the air scores -8, assuming we weight all factors equally and score +1 for each aspect that advances spectrum utility, 0 for neutral factors, and -1 for each aspect that retards it.

The most compelling alternative is to re-purpose Channel 51 for mobile broadband by joining it with the lower A block. The scores for this outcome are radically different:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Advanced
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Advanced

7. High-Performance Receivers: Advanced
8. Use of all Relevant Dimensions: Retarded
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Advanced

Total Score: +8

Repurposing Channel 51 from legacy over the air (OTA) DTV to mobile broadband scores +8. Given this scoring, there's no need to consider the question of whether an interoperability mandate should be applied to phones supplied by the large carriers on the B and C blocks or the small carriers on the A block, as taking Channel 51 off the air renders that discussion moot.

Advocates of OTA TV insist that taking a TV channel off the air is bad for the public interest, but that argument isn't persuasive. The public's overriding interest in questions of technology innovation is best served by moving networking technology in the direction that our ten factor test indicates: It provides for a better consumer experience, more consumer choice, and greater competition among providers. Leaving spectrum assigned free OTA TV, especially minor channels like 51, does none of these things, and in fact simply serves as a fourth outlet for the same programming, after cable TV, Digital Broadcast Satellite TV, and Internet TV.

800 MHz Guardbands

The FCC recently granted a petition from Sprint for an update of the rules on the use of the 800 MHz Specialized Mobile Radio (SMR) band:[40]

> Sprint has frequencies in the 800MHz SMR (Specialized Mobile Radio) band that so far have been dedicated to the iDEN network, which delivers the narrowband 2G service that Sprint acquired by buying Nextel in 2005. When the FCC carried out a rebanding project several years ago to eliminate interference between iDEN and public safety radios, it decided that services on those frequencies couldn't use channels wider than 25KHz. That channel width can't support anything more than a narrowband service such as iDEN, which delivers average throughput of 20Kbps (bits per second) to 30Kbps.[41]

The SMR network was a push-to-talk "walkie-talkie" network that permitted narrow-band voice communication between subscribers. FCC regulations for the use of the spectrum drawn in 2005 divided the spectrum into 25 KHz (not MHz) channels and further required that each channel have a "guardband" of low energy at the edges. These restrictions were drawn out of respect for expected receiver performance characteristics, and made it impossible for the current owner of the spectrum, Sprint, to implement cellular service. The FCC relaxed but did not eliminate the guardband requirement. Some restrictions remain in place to protect legacy public safety equipment operating in the SMR band until a nationwide public safety network is operational.

This proceeding covered a set of issues very similar to those raised in the LightSquared proceeding concerning the ability of installed equipment to reject the signals generated by the new application. The FCC's resolution took the older equipment off the air, for the most part. In such cases, this is the correct resolution.

Converting the spectrum used by the old SMR network into general-purpose 4G mobile use earns the highest score, +10:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Advanced
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Advanced
7. High-Performance Receivers: Advanced
8. Use of all Relevant Dimensions: Advanced
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Advanced

The best source for additional commercial spectrum is government applications.

Total Score: +10

The alternative (leaving the *status quo* intact) would earn the opposite score on each criterion. Hence, the FCC's action was correct.

Government Spectrum Use: 1.7 GHz Band

The best source for additional commercial spectrum is government applications. Most analysts say that the U.S. government has assigned 300 MHz more prime spectrum to itself than our European neighbors; this spectrum is managed by NTIA.[42] While the U.S. leads the world in the deployment of fourth generation LTE networks, we lag the world in the allocation of spectrum to LTE networks, and this overly generous allocation to the federal government is one reason why.

The recent NTIA report, *An Assessment of the Viability of Accommodating Wireless Broadband in the 1755 – 1850 MHz Band*, is good news and bad news for the reassignment of government spectrum.[43] The good news is that some government agencies are taking the exercise seriously and doing their best to increase the amount of spectrum available for general-purpose commercial networks. The NTIA says the entire band can be made available within ten years, and significant portions of it much earlier.

They caution that some sharing is going to be necessary for quite some time in a few areas, but they're hoping that the sharing is something both the commercial sector and the government can live with. The bad news is that DOD and the FBI still insist they have applications of such importance that they can't live without the allocations of spectrum they currently have. It's likely that the negotiations between the civilian agencies and the NTIA involved spectrum experts while those that took place with the DOD and DOJ involved non-technical administrators. That's at least what the report seems to indicate.

The 1755 – 1850 spectrum band is important because it's been assigned internationally for mobile broadband, so there are tremendous benefits to U.S. firms and consumers if we can use it for that purpose. The estimated relocation costs provided by DOJ and DOD are unreasonably high considering that all the equipment they've currently got should be replaced within five to ten years as a matter of course anyway (and doing so would increase their respective agency performance), and this exercise has already been ongoing for ten years. NTIA notes that the international assignment of paired spectrum differs from the U.S. carriers' proposed use with respect to uplink and downlink, and that this isn't an important difference as the ability to use paired spectrum depends on direction-independent antennas and digital signal processors.

A detailed examination of the assignments follows.

Fixed Point-to-Point Microwave

The first application, fixed point-to-point microwave, should raise a red flag immediately because nearly all its 360 allocations can be probably be replaced by a wireline or commercial alternative. Point-to-point microwave is a virtual wire whose history pre-dates fiber optics and it's a laggard in terms of performance and quality.

The report excuses these allocations as being cheaper or higher quality than commercial or wireline alternatives, but that analysis only works if you value the spectrum at zero. Replacing 95 percent of these allocations with fiber backhaul could end up being a net positive for the government because they could over-provision and lease dark fiber to the commercial sector. The only rational application for fixed point-to-point microwave in most cases is connecting mountain tops in rural areas where there's no plausible case for fiber, but this is probably not the government's typical use case.

Converting fixed point microwave to fiber backhaul and auctioning the spectrum for commercial use earns the maximum score, +10:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Advanced
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Advanced
7. High-Performance Receivers: Advanced
8. Use of all Relevant Dimensions: Advanced
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Advanced

Total Score: +10

Commercial use of this spectrum could involve point-to-point microwave, point-to-multipoint, or mobile, according to the preference of the commercial license holder, and the spectrum could also be deployed to the public on an unlicensed basis.

Military Tactical Radio Relay

Per the NTIA report, "Tactical Radio Relay is a…generic class of transportable fixed microwave systems that support Army, Navy, and Marine Corps training at a number of sites and on tactical operational missions." These systems have a somewhat stronger use case that fixed microwave. The purpose of these allocations should be to connect a training network to a fiber terminal, and it would be very surprising if DOD needs the 579 separate allocations it has for this application to support active training missions. Even if they had hundreds of training missions going on at the same time, they're not in the same place so there's no practical reason for so many exclusive allocations. This is another category of microwave, and there are commercial systems and higher frequencies available to support it that aren't appealing to mobile networks. In fact many of these systems are indistinguishable from commercial mobile broadband systems in function and purpose.

Most of these 579 allocations duplicate commercial systems. Hence the same grading would apply as to the previous application, +10:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Advanced
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Advanced
7. High-Performance Receivers: Advanced
8. Use of all Relevant Dimensions: Advanced
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Advanced

Total Score: +10

Air to Ground Systems

This category includes the military's Air Combat Training System, Precision Guided Munitions, Tracking, Telemetry, and Commanding Systems, Unmanned Aerial Systems, and Aeronautical Mobile Telemetry. These systems are used for training, testing, and operation of fighter/bombers and similar systems. They used dedicated, exclusive spectrum assignments within the U.S. and whatever is available in real combat conditions. It seems that the major problem with these allocations is systems that require specific frequencies on which to operate. Combat systems have to be capable of operating overseas, in countries that have not made specific allocations of spectrum to invading armed forces, so there must be a difference between combat training systems and actual combat systems. A flexible use system that allowed for sharing could free up several hundred allocations and improve the flexibility and utility of real combat systems.

While the details of these systems aren't known in detail, it's safe to assume that they aren't radically different in principle from more generic systems of air-to-ground communication that could be used by the general public through commercial carriers. Transitioning these applications from their present form to a more generic form that shares spectrum and technology with civilian users would earn a high score, and leaving them in the present form would earn a low score.

Video Surveillance

Of all the applications in the NTIA report, this is the most puzzling. The report declares: "DHS, DOJ, and the Treasury state they need to retain up to 30 MHz of contiguous spectrum for surveillance in the 1780-1850 MHz band pending the successful development of new technology and the availability of spectrum in the comparable bands." This is a commendable reduction from the 130 MHz that the government currently uses for video surveillance of American citizens in cases involving suspected terrorists, tax evaders, and other criminals, but video bits are not so special that they need their own network.

Commercial networks can easily accommodate the needs of law enforcement for transporting video bits. We know this because they just as they transport video bits for consumers every day. There is little justification for putting 30 MHz of contiguous spectrum on hold just after allocating the 700 MHz D Block to the nationwide public safety network that's about to be built. The NTIA needs to say "no" to this application, resoundingly. Sharing video transport with commercial systems would earn a score of +6:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Neutral
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Neutral
6. Facilities-Based Competition: Advanced
7. High-Performance Receivers: Neutral
8. Use of all Relevant Dimensions: Neutral
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Advanced

Total Score: +6

Initial PCAST Recommendations

While the ice is beginning to melt around some federal spectrum allocations in the 1755 – 1850 MHz band, the most significant development is not covered by the NTIA's report. This is the public/private initiative to promote effective sharing of spectrum between government, commercial interests, and unlicensed users. The President's Council of Advisors on Science and Technology (PCAST) released an update to its spectrum investigation on May 25, 2012, outlining this plan.[44] The update was followed with a more a detailed and radical report on July 20, 2012.[45]

The PCAST update recommends a system be developed that would allow for the sharing of spectrum currently held by the government through a database system according to three priorities:

1. The primary user—the government—has first right of access.
2. If there is no government demand, the spectrum can be employed by a licensed user.
3. If there is neither a government nor a licensed user, the spectrum can be employed by an unlicensed user.

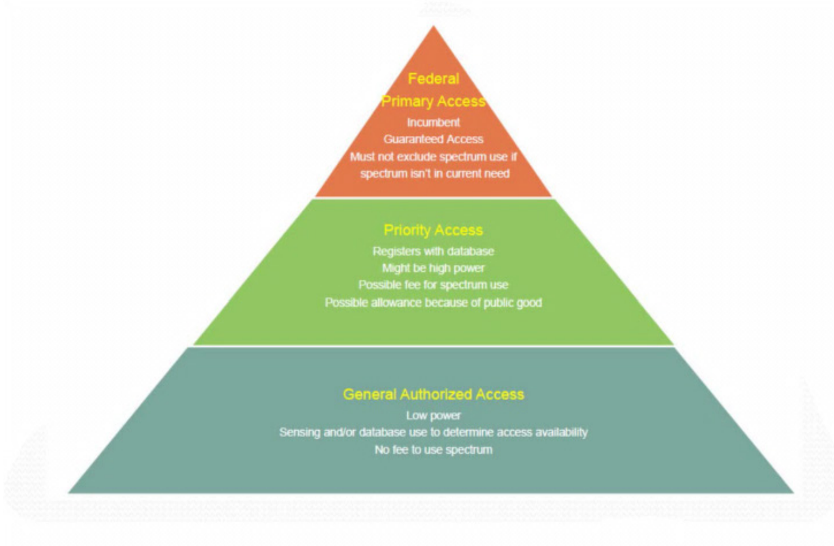

Figure 15: PCAST Sharing Hierarchy (Credit: PCAST)

Spectrum sharing is frequently confused with efficiency in the press and in much policy discourse, but this is a mistake. Sharing can be efficient or inefficient.

The PCAST system described in the update would earn high scores in most criteria, but not top scores. As PCAST recognizes, the system allows government agencies to continue operating current systems that don't permit sharing by simply asserting "Federal Primary Access" privilege to a particular band of spectrum for use by a legacy system at all times. In this scenario, the spectrum would be shared in name only, and this is not a desirable scenario. Federal agencies would still need to be motivated to participate in this system in a positive manner by increasing their use efficiency and reducing their spectrum occupancy time.

PCAST proposes the development of a "Spectrum Currency" system and the creation of a "Spectrum Efficiency Fund" to motivate efficient sharing in recognition of their system's shortcomings. PCAST also recommends the creation of a White House-based Spectrum Management Team (SMT) consisting of the U.S. Chief Technology Officer, the National Security Staff, Office of Management and Budget, National Economic Council and NTIA to oversee management of federal spectrum. The composition of this committee suggests that we may shortly find ourselves with a *Spectrum Czar* who oversees government spectrum use, which would not be a bad thing.

In order for an oversight committee of this sort to be effective, it needs to have the power to suspend and revoke federal usage rights to particular patches of spectrum. Without this power, the committee is simply a paper tiger.

Spectrum sharing is frequently confused with efficiency in the press and in much policy discourse, but this is a mistake. Sharing can be efficient or inefficient, depending in the characteristics of the signals that sharers transmit and receive. While PCAST makes a step forward by taking a stand in favor of spectrum sharing by federal and non-federal users, this step doesn't go very far. We grade the PCAST update +5:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Neutral
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Neutral
6. Facilities-Based Competition: Neutral
7. High-Performance Receivers: Neutral
8. Use of all Relevant Dimensions: Advanced
9. Promotion of New Technologies: Neutral
10. Development of Redeployment Opportunities: Advanced

Total Score: +5

PCAST Spectrum Superhighway

The final PCAST report proposes the creation of a 1000 MHz National Spectrum Superhighway based on Dynamic Spectrum Access (DSA), a poor solution to the immediate spectrum needs of American citizens.[46] The urgent issue for spectrum policy makers is how to manage the ever-growing Federal appetite for spectrum without slowing economic growth and impairing the wireless services that consumers have embraced. While the PCAST update offers suggestions for better managing Federal spectrum, the final report doesn't adequately answer the critical question because it fails to distinguish practical systems from speculative and unproven ones.

The system that it proposes would unduly burden American consumers and network providers by making their entire joint investment in wireless handsets and infrastructure obsolete. At the same time, it would protect all Federal users (primarily the military,) from any disruption to present operations, regardless of how inefficient current systems may be. This is not the proper balance.

The most astonishing claim made by the report is that "the traditional practice of clearing government-held spectrum of Federal users and auctioning it for commercial use is not sustainable." On the basis of this assertion, the PCAST report embarks on a thought experiment toward a new method of allocating spectrum which it terms "a new spectrum architecture and a corresponding shift in the architecture of future radio systems that use it [that] can multiply the effective capacity of spectrum by a factor of 1,000."

Claims of this magnitude should be supported by reams of empirical and analytical data, but the 162 page report offers no data at all to support its presumption that the auction system (which has been employed by the FCC only since 1994) is not "sustainable" or even to define the parameters of "sustainability."

The auction system doesn't need to meet the needs of spectrum users indefinitely, it only needs to provide a rational way to re-allocate spectrum from low-demand and low-value uses to those that the public values more highly until we have practical means of simultaneously sharing spectrum at the same times, places, and frequencies without undue interference.

The only system that has ever been effective at increasing the supply of usable spectrum is one that upgrades legacy systems, such as the old analog TV broadcast system, to up-to-date digital systems with greater bits/hertz information efficiency. The best of these modern digital systems conform to international standards such as LTE and Wi-Fi that foster the creation of supporting industries in silicon chips, handsets, base stations, antennas, and software.

The PCAST report rejects this approach in favor of new technologies that would favor interference tolerance over efficiency: "Reductions in the transmitted bits/Hertz reduce the interference footprint as a ratio of the communications range. Transmit waveforms should transition from maximizing the bits/Hertz in scarce spectrum to instead optimizing for spectrum reuse." Spectrum experts will naturally take issue with this finding, which is also not supported by evidence.

PCAST places enormous faith in the ability of geo-location databases to improve the usability of spectrum, consistent with the proposed White Spaces system that will rely on such databases when deployed. The White Spaces system enables fallow spectrum to be harvested and put to productive use, just as Wi-Fi enables consumers to operate their own wireless networks at home and in the enterprise. But these systems are a complement to commercial wireless networks rather than a replacement. In areas where there is no fallow spectrum in the frequency and power ranges that can be used by consumer devices conforming to international standards, no database or opportunistic access system can supply it.

It's important for legislators and regulators to ensure that consumers have an adequate supply of spectrum for short-distance Wi-Fi networks which are also under stress in many areas. The White Spaces system is likewise a worthwhile system that must be allocated sufficient spectrum to either succeed or fail in real operational settings. But neither the proven value of Wi-Fi nor the potential value of geo-location systems warrants PCAST's rash desire to put all of the nation's spectrum assets in one basket. Advances in technology are often messy and disruptive, so it's much more sensible to continue pursuing a multi-faceted strategy that allows technologies to compete on the basis of the value they offer consumers than to tilt the scales in favor of one and only one system.

Geo-location databases are a very important tool for managing unlicensed spectrum; they offer a means of forcing obsolete devices such as the early Wi-Fi adapters off the air in favor of better and more recent systems. They permit the rapid deployment of networks in emergencies and in unserved and underserved areas. Very importantly, these databases can be used to implement sharing policies that and can handle overload from licensed networks of various kinds.

It's a mistake to assume, however, that these devices mandate any particular policies about spectrum allocation. Geo-location databases are tools for implementing policy, not a form of policy in their own right.

In particular, the Spectrum Superhighway concept proposed by PCAST lacks capabilities to provide mobile voice users with the Quality of Service support that current cellular networks provide. It is thus a step in the wrong direction from the system described the Update. We grade the PCAST Spectrum Superhighway +2, three points less than the Update:

1. Sharing: Advanced
2. Application Flexibility: Retarded
3. Dynamic Capacity Assignment: Advanced
4. Technology Upgrade Flexibility: Neutral
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Retarded
7. High-Performance Receivers: Advanced
8. Use of all Relevant Dimensions: Neutral
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Retarded

Total Score: +2

LightSquared and GPS

On February 14, 2012 NTIA sent a letter to the FCC declaring that "there is no practical way to mitigate the potential interference" between the proposed LightSquared network and GPS.[47] The NTIA letter followed a round of testing in which 25 percent of tested devices were not affected by transmissions from the LightSquared network. These devices had in fact found a way to mitigate actual interference, but the other 75 percent had not.[48] The GPS industry had been on notice since 2003 that changes in the rules for spectrum adjacent to GPS frequencies were in the offing, and had agreed to the proposed rules as late as 2009.[49] While the industry had agreed to a new neighbor in formal filings with the FCC, product engineering practices continued unchanged in most firms, however.

There are two main problems with the design of GPS receivers that affect their ability to operate in spectrum adjacent to a terrestrial mobile broadband network such as the one proposed by LightSquared. The first of these is a design decision made by manufacturers of High-Precision GPS (HPGPS) systems such as the John Deere "StarFire" system to look for three digital signals carried on different frequencies through a common analog filter. John Deere's presentation to the FCC illustrates the problem.[50]

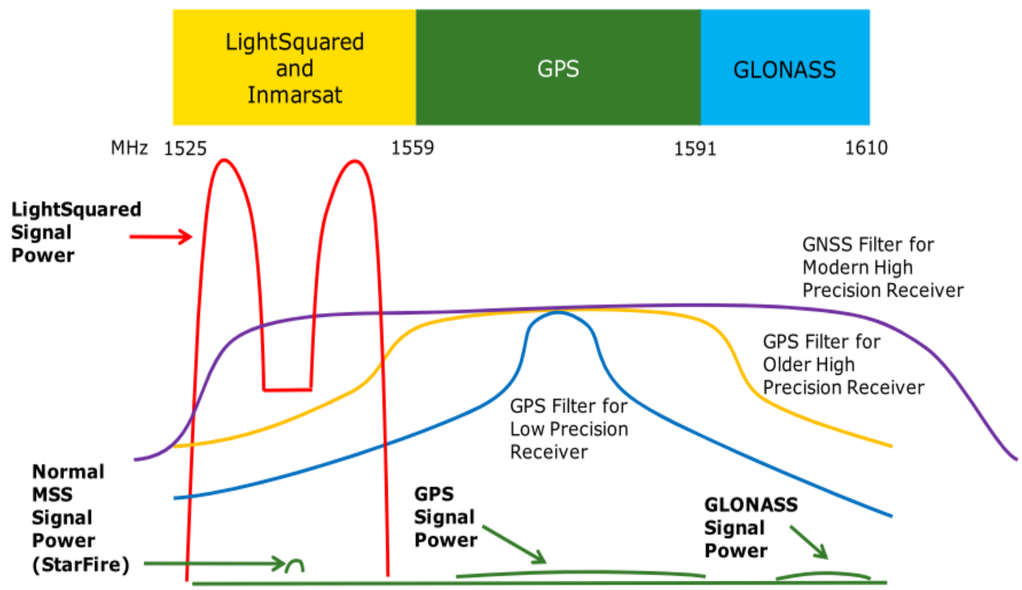

Figure 16: Location of StarFire Augmentation Signal (Credit: John Deere)

As we explained in our filing with the FCC on this matter, the problem that arises in a system such as this one is that the StarFire receiver hears both the GPS signal and the StarFire signal indiscriminately, as illustrated by the curve labeled "GNSS Filter for Modern High Precision Receiver."[51]

Such a front end will amplify the entire range from StarFire to GPS, including the upper LS band (as well as part of the lower LS band, according to Deere's diagram) unless it's equipped with pre-correlator filters that cancel signals in the intermediate bands.

The result of this amplification is to effectively deafen the receiver to both GPS and StarFire, due to receiver saturation that comes about from the amplification of the higher-energy LS signal, a signal that can and should be filtered. This sort of saturation can be overcome by separating the analog front end for the StarFire receiver from the front end of the GPS receiver. It can also be overcome with a notch filter across the upper LS frequency, but HPGPS providers have not needed to employ such filters before now as a practical matter.

In other words, the common analog front end amplifies the LS allocation when it should be filtered, a very bad design indeed and one that blatantly violates design guidelines issued by the DOD's 2008 "Global Positioning System Standard Positioning Service Performance Standard."[52]

A second problem arises with consumer GPS receivers with respect to LightSquared. The GPS signal is very faint at the reception end. Each GPS satellite is located in geo-synchronous orbit 22,000 miles above the surface of the Earth, and each signal is dispersed across a wide geographic area. Because the signal is so weak, many manufacturers of stand-alone GPS receivers (those that are not part of smartphones) have chosen to bend the rules for receiver design by listening to a wider channel than the authorized frequencies for the

GPS signal. As the signal spreads out and degrades in its path through the atmosphere, it flattens and disperses into neighboring frequencies, so a wider reception window captures more signal than one that strictly follows the rules, in the same way that a large window lets more sunlight into a house than a small one does.

But just as large, open windows may permit us to see and hear things that we'd rather not see and hear, so too does the relaxed reception window in the stand-alone GPS receiver permit the device to capture unwanted signals from neighboring services. When the nature of the neighboring service changes, as would have been in the case with changing LS from a satellite-based service to a terrestrial one, a receiver that employs this engineering trick ceases to function. The 75% of GPS receivers who failed the test are designed as just described. The 25% that passed testing are probably smartphones that were designed to capture cellular signals and GPS at the same time, with the appropriate circuitry to disambiguate the two signals. There is consequently no way to re-purpose the LS spectrum without replacing millions of GPS receivers in the United States alone, but LS argues that GPS manufacturers were put on notice in 2003 that just such a wide-scale replacement would one day become necessary, as mentioned.

Many manufacturers of stand-alone GPS receivers have chosen to bend the rules for receiver design by listening to a wider channel than the authorized frequencies for the GPS signal.

Disputes such as this one can only be resolved by setting long term goals and sticking to them, a hard feat to accomplish in a policy milieu where every regulatory action is colored by politics and devoid of a technical framework. The FCC and the GPS industry would do well to devise a second generation GPS system with greater efficiency and noise immunity, and to develop a plan for the phase out of the current system. Fortunately, such planning is underway, although it maintains a "backward compatibility" requirement that's essentially counter-productive as it prevents or retards necessary upgrades to existing, obsolete equipment.[53] The spectrum dividend we reaped from the conversion from analog to digital TV would not have occurred if the new DTV system had maintained backward compatibility with analog TV, after all.

A correct resolution of the LS/GPS controversy would have shared the responsibilities for sharing a general spectrum neighborhood between the two parties and improved them both. The resolution that was reached simply pushed LS into bankruptcy and left the *status quo* intact. Consequently, it earns a low -1 score even though it preserved the functioning of consumer GPS equipment and a poorly-designed HPGPS system:

1. Sharing: Neutral
2. Application Flexibility: Retarded
3. Dynamic Capacity Assignment: Neutral
4. Technology Upgrade Flexibility: Retarded
5. Aggregation Efficiency: Neutral
6. Facilities-Based Competition: Neutral
7. High-Performance Receivers: Neutral
8. Use of all Relevant Dimensions: Neutral
9. Promotion of New Technologies: Neutral
10. Development of Redeployment Opportunities: Advanced

Total Score: -1.

Medical Body Area Networks

On May 24, 2012 the FCC issued an order dedicating 40 MHz to Medical Body Area Networks (MBAN) in the 2360-2400 MHz band.[54] As in in the case of TV White Spaces, the FCC seeks to create a database of registered users and uses for purposes of controlling interference with the licensed incumbent service, which in this case is Aeronautical Mobile Telemetry (AMT).

The MBAN proceeding follows a request from GE Healthcare (GEHC) to modify existing Part 95 rules for "MedRadio" that use spectrum in the 401 – 406 MHz, 413 – 419 MHz, 426 – 432 MHz, 438 – 444 MHz, and 451 – 457 MHz bands, all on a secondary basis. GEHC does not desire much more spectrum than the previous rules allowed; it wants wider channels (as did Sprint in the 800 MHz matter) in a frequency range adjacent to Wi-Fi™ in order to use slightly modified Wi-Fi™ parts to build its sensors and hubs, but the order limits channel width to 5 MHz.

It's also reasonable to ask why the FCC carved out a secondary use in the sweet spot for mobile broadband (500 MHz to 3 GHz) instead of assigning less desired spectrum above 3 GHz.

The FCC's order follows a cross-industry agreement between healthcare firms (GEHC and Philips Healthcare) and the Aerospace and Flight Test Radio Coordinating Council, but no broader group of stakeholders. It's a marvel of micromanagement that specifies the operation of MBAN networks at a non-productive level of detail. Medical sensors using MBAN spectrum are forbidden from communicating directly with each other, for example; they can only pass information to and from sensor hubs. Sensor hubs are similarly forbidden from communicating with each other; they may communicate with medical sensors wirelessly and with hospital local area networks (LANs) by non-MBAN means. These architectural stipulations are completely irrelevant to legitimate interference concerns and would appear to serve secondary interests, if they serve any interests at all. The prohibition of mesh networks is justified by the order on security grounds, but it's a ridiculously crude means of securing a network.

Given the desire of GEHC and other potential builders of MBANs to re-purpose Wi-Fi™ chips for this new service and its adjacency to Wi-Fi™, it's reasonable to ask why the FCC didn't simply add the 40 MHz to the existing Wi-Fi™ allocation with transmit power rules protecting AMT. This would have resulted in a 50 percent increase in spectrum available to Wi-Fi™ users in the adjacent 2400 MHz to 2480 MHz band.

The answer is that the FCC desired to create a system for more orderly sharing of bandwidth than is typical in Wi-Fi™ networks. Although Wi-Fi™ can operate as a highly controlled system with high Quality of Service provision under the Point Coordination Function, this is not a common mode of operation.[55] Essentially, the FCC's MBAN order uses authorization and architecture to specify a mode of operation for MBAN networks that has been described in a more effective and efficient way at a higher level of system design by LAN standards. It fortunately leaves complex questions of frequency, time, and coding allocation within the MBAN allocation to the imagination of the user even if it ties their hands with respect to the direction and routing of communications.

It's also reasonable to ask why the FCC carved out a secondary use in the sweet spot for mobile broadband (500 MHz to 3 GHz) instead of assigning less desired spectrum above 3

GHz. There are, after all, Wi-Fi™ chips that operate in both the 3.6 GHz band (802.11y) and in the 5.8 GHz band (802.11a, 802.11n, and 802.11ac). This question is not addressed by the order, but the FCC is certainly aware that spectrum in this range is prized by both licensed and unlicensed users.

As it is, MBANs will probably not be authorized in Arecibo, Puerto Rico because of potential interference with radio astronomy operations, and in other areas they will operate at low power so as not to cause too many problems for amateur radio operators and the aforementioned incumbent AMT services. Consequently, the MBAN order is large step backward in terms of the logic of spectrum allocation, although it's not as bad as it might have been since use of the spectrum is controlled by an authorization data base that allows for the implementation of additional rules. The order is not at all straightforward.

Allocation of spectrum in such a historically backward way—it's an order that hearkens back to the era in which the FCC allocated by application instead of technical characteristics—earns a low score of 0 in our system:

1. Sharing: Advanced
2. Application Flexibility: Retarded
3. Dynamic Capacity Assignment: Neutral
4. Technology Upgrade Flexibility: Retarded
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Neutral
7. High-Performance Receivers: Neutral
8. Use of all Relevant Dimensions: Advanced
9. Promotion of New Technologies: Retarded
10. Development of Redeployment Opportunities: Neutral

Total Score: 0

Verizon/SpectrumCo Transaction

On January 11, 2012, the FCC opened a docket to review the proposed sale of 20 MHz of spectrum in the AWS-1 band from the "SpectrumCo" cable company joint venture (and from former SpectrumCo member Cox Communications) to Verizon Wireless, a joint venture of Verizon Communications and Vodaphone.[56]

The cable companies purchased the licenses in order to build a mobile broadband network that would compete with AT&T, Verizon, T-Mobile, and Sprint, but soon discovered that the skills required to do that were outside their expertise; as a result, the spectrum is currently lying fallow.

Verizon offered to buy the SpectrumCo licenses as part of a complex transaction that would also allow them to bundle mobile phone service with cable broadband for sale to their customers, and which would also allow the cable companies to offer similar "quad play" bundles to their customers. A great deal of the discussion of the transaction focuses on the bundling aspect, but that's really quite distinct from the spectrum transaction. The

FCC has business examining cross-marketing deals, but the rules that apply are very different from those that apply to spectrum.

Verizon has an immediate and pressing need for more spectrum because it has aggressively deployed LTE across the U.S. Verizon Wireless is now the world leader in LTE deployment, and the U.S. as a whole has 70 percent of the global LTE users.

The FCC has been urged Sprint and T-Mobile and friendly interest groups to block the transaction, although a recent transaction with T-Mobile has muted their criticism. With these technical and political facts at work, it's unacceptable to allow these 122 licenses to go to waste. The FCC has tools to examine spectrum concentration known as "spectrum screens" that should be applied to the transaction without modification that makes it more difficult for the carriers who are investing most heavily in new technology to reap marketplace advantages. We urged the FCC to approve the spectrum transaction and to review the separate business deal between the parties on its own.[57]

Assuming that the transaction is approved without destructive conditions, it would earn a high score of 7 simply for allowing currently unused spectrum to be put to use in a highly productive way:

1. Sharing: Advanced
2. Application Flexibility: Advanced
3. Dynamic Capacity Assignment: Advanced
4. Technology Upgrade Flexibility: Advanced
5. Aggregation Efficiency: Advanced
6. Facilities-Based Competition: Neutral
7. High-Performance Receivers: Neutral
8. Use of all Relevant Dimensions: Neutral
9. Promotion of New Technologies: Advanced
10. Development of Redeployment Opportunities: Advanced

Total Score: +7

This transaction compares very favorably against the MBAN and LightSquared matters.

THE SPECTRUM RESEARCH AGENDA

As Figure 9 indicates, the general problem of spectrum policy today is fragmentation: Regulators have assigned every patch of desirable spectrum but demand continues to rise. Technology continues to improve, but advances will be most effective if fragmentation is corrected. The easy way to do this is to take spectrum away from low-value applications (such as the government's dedicated video surveillance frequencies, many lightly-used satellite services, and over-the-air TV) and assign it to high-value commercial networks by auction. Sharing is inherent in commercial networks; it's how they make money and they're very good at it. Research on better ways of using spectrum will allow policymakers to correct inefficient historical allocations and enable more effective sharing in the future.

Allocation Efficiency

Unlicensed radio systems are most effective over short distances: Bluetooth and Wi-Fi™ are their signature accomplishments. These systems manage spectrum access at the network edge using "contention" systems that become less efficient as network distances and data rates increase. Licensed commercial systems employ centrally-managed spectrum access controls that are effective at a broad range of speeds over longer distances, but at the cost of much greater planning and more complex infrastructure.[58] Each approach has distinct benefits and ideal deployment scenarios: We would not want to build nationwide networks with Wi-Fi™, and we would not want to centrally manage Bluetooth connections between smartphones and headsets.

Figure 17: Actual Overhead of IEEE 802.11n Carrier Sensing for Single Packets Sent at High Rate[59]

In addition to the spectrum sharing that licensed commercial networks and unlicensed networks already do, research has developed (and will continue to develop) systems that coordinate spectrum use among networks themselves. The best known of such systems are the Dynamic Spectrum Access (DSA) and Authorized Shared Access (ASA) systems described previously. These systems simply coordinate spectrum access among and between network operators where idle spectrum exists and sharing agreements of some kind are in force.

In order for these systems to function, the pool of idle spectrum can be used by capable devices when certain conditions are met and an operator claims the spectrum, either with government permission (as is the case in the White Spaces systems), or in accord with a commercial agreement between network operators in other cases, or in terms of an informal agreement in yet other cases. The act of claiming the spectrum makes the network operational, and once this takes place, the process of network operator-mediated sharing among applications follows, with potentially as much efficiency as commercial licensed networks exhibit over a broad range of operating conditions.

These systems will prove beneficial in the short to medium term, until we reach the point where there is no longer any idle spectrum to claim and assign dynamically. At that point, advances in spectrum sharing will depend on more advanced and more beneficial technologies that that allow a single frequency to be shared among multiple *simultaneous* users. We don't do this today, and we won't do this with DSA and ASA.

In DSA and ASA systems, as with common commercial systems, users take turns accessing spectrum in round-robin fashion, typically for a few milliseconds at a time. In other words, conventional packet radio systems, whether licensed or unlicensed, fixed or dynamic, only permit the transmission of one packet of data at a time in a given place, time, and frequency.[60] DSA and ASA systems reduce to the effects of this fundamental limitation by marshaling more spectrum to each location. The next stage in spectrum engineering is systems that allow for multiple packet transmissions in each time and place on the same range of spectrum.

The most fertile test bed for DSA operations research is the vast pool of lightly-used and locally-used government spectrum. Many government systems that use spectrum only do so occasionally and in specific locations, so this spectrum is ripe for use by both commercial and non-commercial systems in other times and places. The IEEE 802.11y variant of Wi-Fi™ is a good example of the dynamic sharing of government spectrum.[61]

Usage Efficiency

Truly simultaneous spectrum use requires transmissions to be effectively focused or cloaked from each other so as not to create discernible interference; these systems can be called Simultaneous Shared Access (SSA). One way of doing this is Space-Division Multiple Access (SDMA), a system that effectively sends a radio beam to a receiver in such a focused way that other receivers don't see it. Another system for simultaneous sharing would be an advanced form of Code Division Multiple Access (CDMA), a system that scrambles transmissions so that only the intended receiver can unscramble them, and other potential receivers automatically filter them out. Current CDMA systems reduce the data rates of simultaneous transmissions relative to theoretical capacity; advanced CDMA would be less limited in this respect.

The next stage in spectrum engineering is systems that allow for multiple packet transmissions in each time and place on the same range of spectrum.

Yet another method is Ultra-Wideband (UWB), a system that uses very wide radio channels "underneath" conventional narrow channels. While conventional cellular channels are 5, 10, or 20 MHz wide, UWB channels are spread over 500 MHz each, so the UWB energy is very faint to cellular receivers. UWB transmissions are also pulsed to as to appear more like sporadic noise to conventional receivers. Therefore, UWB transmissions blend into the background noise filtered by narrowband receivers by design. Of these three approaches, only CDMA has proved a commercial success so far, but its sharing efficiency is less than expected.

As previously mentioned, Orbital Angular Momentum (OAM) multiplexing systems also show tremendous promise for achieving SSA. These systems appear to be infinitely scalable, which is the Holy Grail of spectrum sharing.

Research spending should focus on Simultaneous Sharing. It would be prudent to organize research funding for simultaneous sharing under a coherent National Science Foundation program. The best way to do this may be to create an NSF Engineering Research Center (ERC) for simultaneous sharing similar to the research centers that already exist in the Microelectronics, Sensing, and Information Technology area, such as the ERCs for Integrated Access Networks, Extreme Ultraviolet Science and Technology, Collaborative Adaptive Sensing of the Atmosphere, and Mid-Infrared Technologies for Health and the Environment.

A report released by the White House Council of Economic Advisors in February 2012, *The Economic Benefits of New Spectrum for Wireless Broadband*, touts the benefits of "research on standards, technologies, and applications to advance wireless public safety communications." While such research is clearly necessary and beneficial, we should acknowledge that it is low-risk applied research with a known outcome. In addition to applied research, we need to support pure research on SSA that can potentially push the boundaries of mobile networking to the next stage.

The research agenda can be organized on a timeline between short-, medium-, and long-term initiatives, as follows:

Short term	Reallocation by auction or license transfer
Medium term	Dynamic Allocation and Sharing
Long term	Simultaneous Shared Access using OAM or similar means

Table 1: Timeline of Initiatives

When SSA is fully developed and non-SSA receivers are replaced by SSA-capable ones, the problem of spectrum allocation and management will become much simpler than it is today.

GOING FORWARD

The spectrum crunch created by the exploding adoption of smart phones and data-intensive applications is real and immediate. The ability of commercial LTE and LTE Advanced networks to keep pace with demand is a gating factor what will either accelerate innovation in the mobile space or retard it. This ability depends on continued technology innovation, but it also depends on the repurposing of the spectrum currently allocated to legacy wireless applications to newer forms of technology. Currently, only 20 percent of the spectrum in the range from 500 MHz to 3 GHz is assigned to mobile broadband networks, and the justification for continuing to use the remaining 80 per cent for legacy purposes is thin in many instances.

In the future, advances in wireless technology will enable more efficient bits/hertz utilization of spectrum assigned to mobile networks, and regulator bypass will enable more spectrum to be used opportunistically. While these technologies are certain to come to pass in some form, the timeline for their maturity it not consistent with present needs for additional spectrum. Consequently, spectrum policymakers must be mindful of three time lines for spectrum allocation:

1. The present crisis which actually began in 2007 with the release of the first iPhone and growing use of smart phones; and

2. The medium term period where we learn how to achieve efficient sharing among occasional, opportunistic, and authorized users of common spectrum allocations; and

3. The longer term scenario in which major advances in wireless technology will be ready for deployment in ten years or so.

The solution to the present crisis involves making the best use of the technologies that are suitable for immediate use and enhancements to the regulatory system that enable opportunistic use and shared access where it's practical. The longer term scenario is served by a combination of research support and spectrum policies that allow for flexible use as new technologies come to the fore that can be implemented in due course.

The spectrum of the greatest interest for commerical systems is assigned to a variety of uses already, many of which will function just as well below 500 MHz or above 4 GHz. For clarity, we include the detail on the allocaiton in this range from the NTIA chart. Sharing these frequencies has the most utility for general public users of smartphones and similar systems.

Spectrum policymakers must be mindful of two time lines for spectrum allocation, immediate and long term.

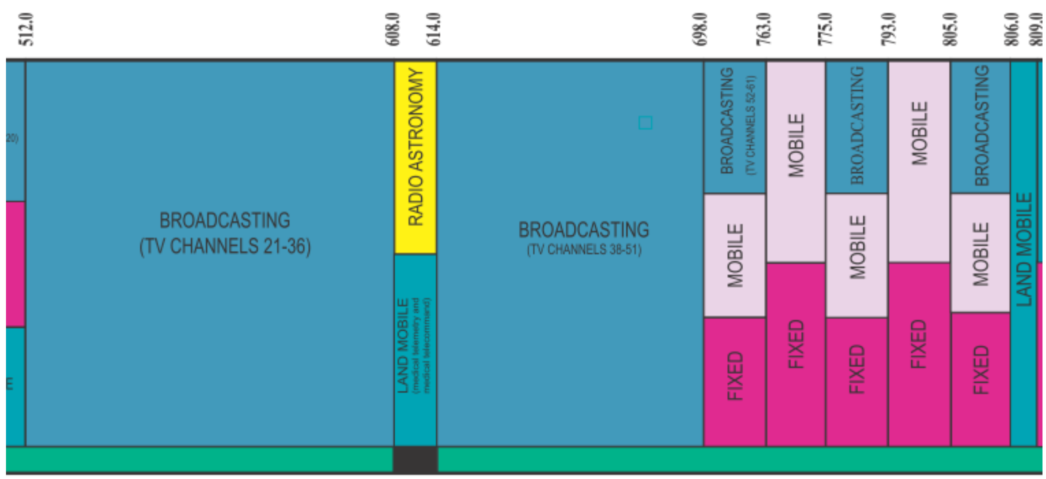

Figure 18: 500 MHz – 809 MHz (Credit: NTIA)

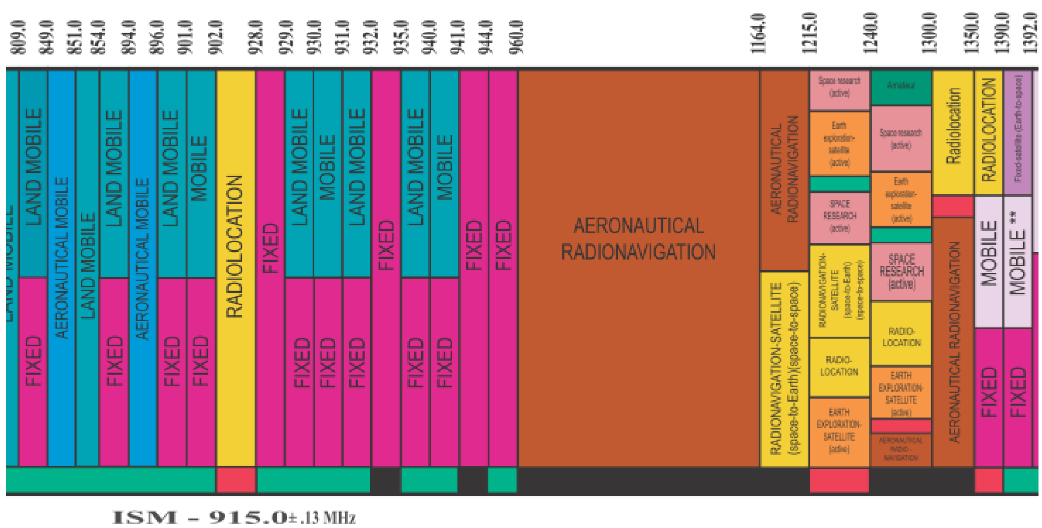

Figure 19: 809 MHz – 1392 MHz (Credit: NTIA)

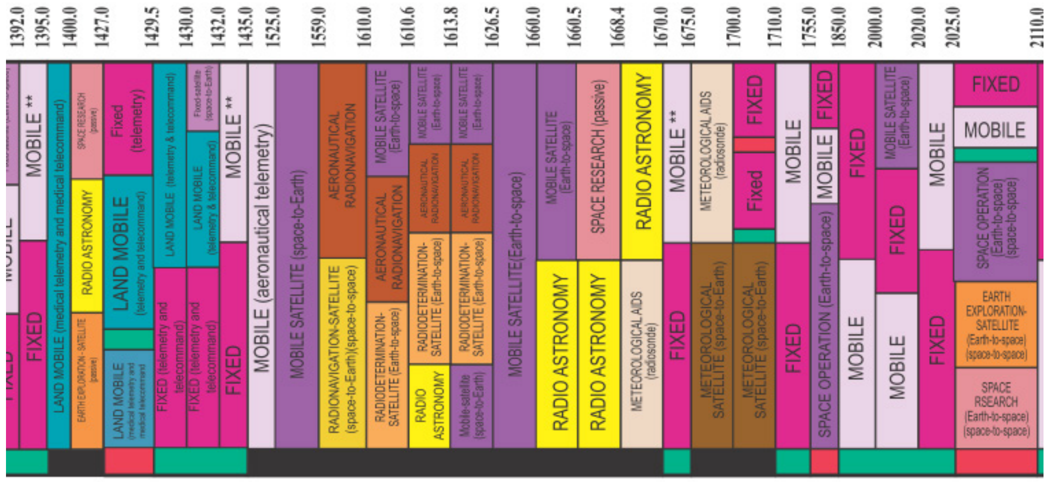

Figure 20: 1392 – 2100 MHz (Credit: NTIA)

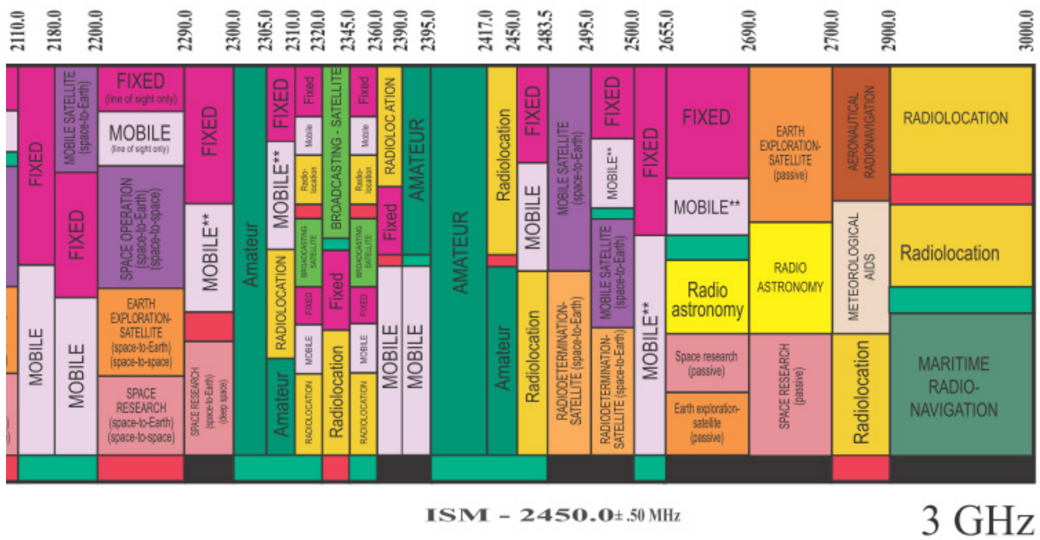

Figure 21: 2100 – 3GHz MHz (Credit: NTIA)

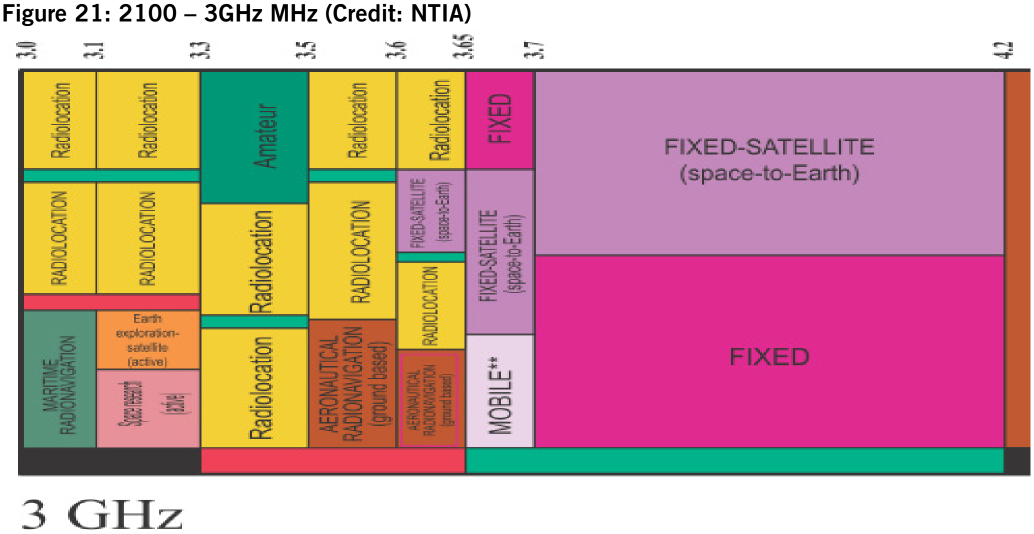

Figure 22: 3 GHz – 4 GHz MHz (Credit: NTIA)

CONCLUSION

Despite the many challenges we face in converting our system of spectrum assignment from one of administrative fiat to a pragmatic and dynamic system of continual economic stimulus, the rewards are great. The nations that lead the way in the deployment of advanced technologies stand to reap the benefits that increased efficiency and innovation brings to economic growth.

While it has become routine for policy analysts to bemoan the United States for its position in traditional rankings of wired broadband adoption (where we lag because of low rates of household computer ownership) and speed, we're the clear leader in LTE adoption.[62] LTE is very significant step in the evolution of mobile networking not only for its radio technology but also because it's a system entirely based on Internet Protocol that stands to not only increase the capacity of mobile networks but to make the Internet itself a more reliable and robust system.

We should not delude ourselves into believing that a magic technology is going to drop out of the sky any day now that will resolve spectrum conflicts once and for all without any work on the part of policymakers. Policy has to work with reality.

Continued leadership in LTE depends on the continued release of spectrum to the most successful commercial networks through reassignment of government applications and the transfer of licenses from declining systems such as MSS and OTA television broadcasting to high-value mobile broadband. Leadership in the systems that will take the place of LTE and LTE Advanced depends on increased investment in the technologies for simultaneous spectrum sharing that will ultimately relieve the spectrum crunch once and for all. We should not delude ourselves into believing that a magic technology is going to drop out of the sky any day now that will resolve spectrum conflicts once and for all without any work on the part of policymakers. Policy has to work with reality.

Since the introduction of the iPhone in 2007, mobile data traffic on the AT&T network in the U.S. has increased by 8000 per cent. Android is the fastest growing smartphone platform, and on average Android users consume even more data capacity than iPhone users. The National Broadband Plan recommended the use of incentive auctions to re-allocate 120 MHz of radio frequency spectrum currently assigned to broadcast television to mobile broadband. The reasoning for this recommendation is very clear: The demand for mobile broadband has grown rapidly since the advent of the iPhone, while the demand for broadcast television declined sharply since the advent of cable TV. High-demand systems such as mobile broadband should have first call on spectrum in the 500 MHz – 3 GHz range.

Incentive auctions are a general purpose mechanism that's meant to accelerate the reassignment of spectrum the FCC has licensed to specific users for specific periods of time, but they're not enough; direct license transfers and commercial sharing agreements are also important. Exclusive use of spectrum by government agencies must be scrutinized for opportunities to upgrade applications to modern standards and shift them to commercial networks where feasible, and sharing of spectrum between government and commercial users must be implemented in other cases.

A thorough, detailed review of legacy spectrum allocations must be an ongoing part of the duties of the FCC and NTIA for the foreseeable future. Ongoing research and a more sophisticated approach to spectrum reallocation are needed to ensure that the U.S. maintains leadership where were currently lead and that we regain it in other areas of spectrum technology.

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