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The Spectrum Opportunity: Sharing as the Solution to the Wireless Crunch

KEVIN WERBACH
The Wharton School, University of Pennsylvania

AALOK MEHTA
University of Southern California

Introduction

We face today a set of policy choices that will define the landscape of the connected world and the United States' place within it. The popularity of smart phones, tablets, and other mobile devices has caused demand for wireless connectivity to skyrocket. Although growth in wireless usage is a longstanding phenomenon, the recent explosion of wireless data traffic is unprecedented, transforming the marketplace in just a few years. Demand will grow for the foreseeable future as wireless systems become increasingly central to social, economic, and political life.

This creates a major public policy imperative. Technical improvements and network upgrades alone will not satisfy this accelerating demand; any sustainable solution will involve expanding access to spectrum for mobile data. Otherwise, limited wireless capacity could become a major drag on U.S. job creation, competitiveness, innovation, community development, and important advances in education, health care, and public safety.

The question is how. All useful frequencies are already assigned, either to government or commercial users. In the National Broadband Plan (Federal Communications Commission, 2010a), the Federal Communications Commission (FCC) established an ambitious goal of freeing up an additional 500 megahertz (MHz) of spectrum for mobile data, but these efforts have run into obstacles. The problem is not a lack of resolve but the cold reality that clearing existing licensees off the spectrum, moving them and their users somewhere else, and auctioning the frequencies to new licensees is increasingly costly, contentious, and uncertain. An approach based entirely on taking frequencies from someone and transferring them to someone else will not maximize capacity over the long term.

What is needed is a change in orientation. Policy makers should acknowledge what engineers already recognize and businesses are already implementing: The future of spectrum is about various forms of sharing. Exclusive rights are still desirable, even essential, in some contexts. However, they will exist within a larger matrix of sharing arrangements to maximize available capacity. Such a policy approach allows the most users and devices to benefit from the airwaves rather than simply picking winners. At the same time, it will extend the long tradition of wireless communication as a mechanism for innovation and free expression.

In this article, we explore the history of spectrum policy and review advantages and disadvantages of current management practices in light of current technological and economic trends. The evidence suggests that not only is spectrum sharing becoming more important and feasible, but that a framework that makes sharing the default approach offers significant political, economic, and societal benefits. Exclusive-use licenses will still be desirable in many circumstances, but they should have the burden of proof.

The new normal of spectrum sharing may be difficult at first to accept. However, with today's technology, sharing arrangements can be structured to meet the requirements of many categories of users. Conversely, taking spectrum from government or private incumbents and selling it to wireless data providers is far simpler in concept than in execution today. Policy makers should follow the lead of the President's Council of Advisors on Science and Technology (PCAST) and the FCC, both of which have offered recent proposals to reorient spectrum policy around sharing.

Part 1. The Evolution of Spectrum Policy

What Is Spectrum?

Spectrum refers to wireless frequencies used primarily for communication. Wireless communications systems have been commercially viable for more than a century, beginning with broadcast radio and proceeding to television, satellite communications, cellular telephony, and myriad other uses. These industries today touch virtually every American and generate a vast amount of economic activity. However, spectrum differs in important ways from other essential inputs for economic growth and innovation.

As Coase (1959) recognized more than half a century ago, spectrum is no more a definite "thing" than the color palette of visible light in a rainbow; it is an abstraction that reflects technological choices and legal rules. As a result, the effective capacity of the spectrum is a constantly moving target. Frequencies that were unusable in 1970 are now being intensively exploited, for example, while systems that originally reflected state-of-the-art efficiency later become profligate spectrum hogs.

In the first instance, the federal government defines allocation rules for using the spectrum, and assignment rules under which particular entities gain the rights to use it. The goal of spectrum policy is to manage the public airwaves in a way that maximizes societal benefits. For wireless communication, this involves two dimensions: the volume of communication and the value of that communication. All things being equal, more communication is better than less, whether expressed in terms of simple quantity (more television channels or more cellular phones operating at the same time), capacity (higher data rates, allowing for faster connections and richer transmissions such as video), or reliability (messages reaching their destinations consistently).

Of course, all things are not equal. Airwaves have different propagation characteristics based on their frequencies, and transmissions are affected by physical features such as mountains and buildings. Two systems may have different characteristics, making them hard to compare: more throughput versus more reliability, for example. A change that increases capacity may increase costs, require new equipment, or displace existing users. And some uses are inherently more valuable than others. A lifesaving 911 call should not be displaced by a YouTube entertainment video, even though the video carries more bits. (The trouble is that real-world value choices are rarely so clear-cut.) Finally, a decision optimized for today may block investment or innovation that delivers significantly greater benefits tomorrow.

Every spectrum allocation is thus a bet on the future, involving complex trade-offs. Originally, the government simply added new services at increasingly higher frequencies, where no existing systems operated. For several decades, all frequencies with desirable propagation characteristics have been allocated to either commercial or governmental users. Modern spectrum policy therefore involves a process of continual reallocation, as new systems replace old.

Since the early 1990s, the primary mechanism for deciding who can use reallocated spectrum has been auctions. Although in theory licenses could be assigned through some other mechanism, the ability of auctions to generate up-front revenues is overwhelmingly appealing. Auction revenues can be used to pay for clearing and relocation costs, and the remaining proceeds go directly to the U.S. Treasury. In an environment of fiscal austerity, such revenues are a powerful inducement. However, the one-time financial returns of auctioning spectrum should be distinguished from the ongoing direct and indirect benefits of usage of that spectrum.

Licensed Versus Unlicensed

When transmissions by one wireless system make the operation of another system more difficult, it is called interference. Historically, the most practical means to minimize interference was to split the spectrum into frequency bands and allocate exclusive licenses to transmit in those bands. Each station on AM or FM radio in a given market, for example, is broadcasting simultaneously but using a different frequency band, allowing them to coexist. Within each band, transmissions not by the licensee are prohibited as "harmful interference."

Granting licensees control over slices of spectrum precludes some communication that would not, in practice, cause interference. The amount of such underexploited capacity is quite significant. A recent European study found average spectral occupancy—a measure of the "fullness" of a spectrum band—below 10% (Forge, Horvitz, & Blackman, 2012), and other spectrum surveys report similar results. Historically, however, all nations decided in favor of the greater certainty of licenses. There was seen to be no other viable way to prevent ruinous interference. As a result, frequency-based exclusive licenses take up much of the usable spectrum.

The primary exceptions for communications are scattered segments available on an "unlicensed" basis since the mid-1980s. In bands such as 2.4 GHz and 5 GHz, for example, anyone is free to use the spectrum. Rules are put in place about allowable devices and uses; often these include stipulations that receivers must accept and make do with any interference in the band. In fact, the 2.4 GHz band was once considered a waste area of spectrum because it was choked with interference from industrial devices and microwave ovens. After being opened to unlicensed use, however, the band now houses uses as diverse as WiFi, Bluetooth, cordless phones, radio frequency identification chips, and more. The combination of

FCC Part 15 rules for unlicensed devices and technical standards such as the IEEE 802.11 specifications for WiFi enable these systems and other activity in the bands to coexist.

Unlicensed technologies support increasingly huge markets. In 2012, there were 2 billion Bluetooth devices and 1.5 billion WiFi-enabled devices shipped globally (Meeker, 2012). In markets including mobile broadband, health care, and machine-to-machine communications, unlicensed devices have rapidly taken over a significant market share (Benkler, 2012). The coming "Internet of Things," which will connect tens of billions of devices and sensors, will be even more heavily dominated by unlicensed connections (Thanki, 2013).

For several years, academics have argued the relative merits of the licensed and unlicensed approaches (Benkler, 2012; Hazlett & Spitzer, 2006; Werbach, 2004). Advocates of unlicensed allocations point to the success of WiFi and argue that open access promotes greater innovation as well as democratizes the airwaves. Proponents of licenses counter that only with exclusive control will companies have the certainty to attract capital and make necessary investments for large-scale commercial services. They argue that unlicensed allocations only make sense for "junk" spectrum and short-range services like WiFi, where low power reduces the likelihood of interference and thus minimizes conflicts between simultaneous users (Hazlett & Spitzer, 2006).

Rethinking Sharing

The licensed/unlicensed debate misses the point, however. Both approaches have a place, but they represent two ends of a continuum of sharing. A frequency can be licensed and still shared, for example, if licenses are limited in the scope of the rights they grant. Similarly, unlicensed allocations can be designed to occupy an entire band, as with WiFi, or structured to coexist with other systems. The real question is whether the baseline assumption of spectrum policy should lean toward exclusivity or sharing.

In a sense, all wireless communication involves sharing. Dividing spectrum into frequencies was, in effect, a mechanism to share capacity among unrelated systems. Geographic limitation of spectrum assignments is another kind of sharing. Signal strength restrictions ensure that, for example, a TV station in Los Angeles and one in San Antonio can broadcast on identical frequencies without interfering.

Even within exclusive licenses, sharing has a place. Cellular phone systems are able to reuse the same spectrum by handing off calls whenever a device moves closer to another tower. The next-generation LTE Advanced standard allows multiple carriers to aggregate their capacity for greater performance. In a multiple virtual network operator arrangement, a cellular licensee allows another provider to piggyback on its spectrum by paying a wholesale rate. And virtually all licenses allow for very low-power devices or geographically limited secondary users that are unlikely to cause interference. A recent European study concluded that just 11% of frequencies under 3 GHz were truly exclusively licensed, mostly for radar systems (Forge, Horvitz, & Blackman, 2012); the pattern in the United States is likely similar.

In recent years there has been an explosion of technical innovation around spectrum sharing. The full implications of these developments have not been fully incorporated into spectrum policy debates. Some examples include:

- Software-defined radios that allow devices to change frequencies and modulation schemes dynamically.
- Mesh networking to relay communications from one device to another.
- Heterogeneous networks that overlay short-range "femtocells" and WiFi access points onto conventional cellular networks.
- Secondary markets in which service providers or devices can acquire rights only for a short period of time.
- Systems using databases, either on the devices themselves or through fixed beacons, to instruct devices about available frequencies in a particular area.

Spectrum-sharing mechanisms can be mapped along two dimensions (Peha, 2009; Weiss & Lehr, 2009): coordination (whether devices affirmatively cooperate or simply coexist) and hierarchy (sharing among equals or in primary/secondary relationships). In the discussion below of the relative benefits of sharing versus spectrum clearing, we refer to the full range of possible arrangements, with the recognition that different approaches will make sense in particular cases. However, we emphasize primary/secondary cooperation mechanisms that are likely to be most prevalent in the near term.

Cooperative approaches hold the greatest long-term potential for capacity increases. They can take advantage of the collective intelligence of all devices in the manner most adaptive to existing local conditions, or they can use real-time markets to reallocate spectrum rights. Such systems also involve the greatest computational and economic challenges and require agreements to implement particular protocols. Moreover, existing licensees, whether governmental or private, typically demand guarantees that sharing will not excessively degrade the quality of service on their networks.

To address these concerns, sharing regimes can be structured to operate around existing rights holders. Unlicensed bands, which involve coexistence where no device has greater interference protection than any other, are an option where there is no incumbent service. Otherwise, the greatest opportunity lies in the quadrant of primary/secondary coexistence. Already many examples exist in which one licensee of a frequency is defined as the primary user and other, typically a low-power service, as secondary. The secondary user cannot interfere with the primary user, and it has no protection against interference by that system. This approach can be expanded more broadly to include different classes of primary, secondary, tertiary, and other services within a set of frequencies. Solving the coordination issues involved in sharing is not trivial, but it is becoming easier as devices become more computationally powerful.

Even when spectrum is not shared at the license level, devices today can use multiple radios to create de facto sharing mechanisms. Most smart phones and tablets include WiFi capability. Through these connections, licensed operators are already offloading large percentages of data traffic to unlicensed WiFi nodes. Comcast alone operates more than 55,000 WiFi hotspots. A Comcast executive recently testified that WiFi was now the most popular method of accessing the Web and is a critical form of access during disasters such as the Boston Marathon bombing (Eggerton, 2013).

Confirmation of this trend came from Cisco's most recent Visual Network Index report, widely used as the leading forecast of Internet traffic growth, which dramatically increased earlier projections for WiFi offloading (Cisco, 2013). The new report found that nearly half of all mobile data traffic would flow over unlicensed access points by 2017. Some experts estimate that even that remains a significant understatement (Deans, 2013). New standards for seamless handoffs between access points will expand this phenomenon.

The story of wireless systems today is thus at least as much about sharing as it is about exclusivity. Driven primarily by market forces and technology, vendors and service providers are developing ever more sophisticated ways to exploit the latent potential of spectrum through sharing. However, spectrum policy has not fully incorporated this development.

Part 2: The Spectrum Challenge

The U.S. government has been allocating spectrum for over a century, since the passage of the first Federal Radio Act in 1912. Today, however, it faces an unprecedented challenge. Skyrocketing demand and limited options for creating new supply create the potential for a crisis. Fortunately, this challenge is also an opportunity.

The Data Boom

The history of spectrum policy tells a repetitive story of capacity exhaustion solved by expansion or reallocation. Television, satellites, advanced radars, microwave links, airplane communications, pagers, mobile phones, and many other developments required new capacity. In every case this was achieved with only moderate difficulty. The situation today is different. Improvements in miniaturization and computing have led to unprecedented penetration of reliable wireless connectivity and affordable mobile computing devices, both domestically and globally. And whereas most wireless communication used to involve broadcasting a single transmission to many recipients, today the market has shifted toward far more intensive two-way data conversations among billions of people.

It is instructive to remember that the first iPhone, which kicked off the smart phone boom, was introduced in just 2007. By mid-2013, the installed base of smart phones and tablets worldwide exceeded that of personal computers, and by 2015, there will be twice as many smart mobile devices in use (Meeker, 2012). Overall, analysts predict that by 2020, connected wireless devices worldwide will nearly triple, rising to 24 billion from the current figure of 9 billion (Machina Research, 2012).

The speed of adoption is breathtaking. Apple's iPad hit 100 million units shipped two and a half years after launching. That is triple the growth rate of the iPhone, itself one of the most transformative consumer electronics devices. Android smart phone shipments are growing even faster, and with smart phones representing only half the mobile phone market in the United States (comScore, 2013) and one-sixth of the market worldwide (MobiThinking, 2013), there remains room to grow. At the end of 2012, 29% of U.S. adults reported owning a tablet or e-book reader, up from less than 2% three years before (Meeker, 2012).

Simultaneously, mobile phone service providers have transitioned from voice to data companies. Mobile data demand is expected to grow substantially each year for the foreseeable future, with mobile traffic doubling between the end of 2011 and the end of 2012 and growing by 28% in the last quarter of 2012 alone (Ericsson, 2013). Total data transmitted on mobile broadband networks in 2017 is expected by Cisco (2013) to be nearly 13 times that in 2012. Much of that growth is being driven by mobile entertainment. Verizon Wireless reports that video currently makes up 50% of its mobile traffic and is growing rapidly; by 2017, that figure will expand to two-thirds of all network traffic (Marek, 2013).

Worldwide, twice as many people access the Internet via mobile broadband connections as fixed lines (International Telecommunication Union [ITU], 2012), and mobile usage represented 13% of total Internet traffic in November 2012, up from 1% three years before (Meeker, 2012). Mobile broadband subscriptions are growing at an annual average rate of 40%—faster than any other information or communication technology market (ITU, 2013). In India, mobile broadband already represents a majority of total traffic, a pattern likely to be replicated in the developed world before long (Meeker, 2012). Qualcomm (2012) expects mobile data demand to grow 1,000 times between 2012 and 2020, creating a need for a ninefold increase in available spectrum capacity, even after taking into account new or developing wireless technologies.

This may be just the tip of the iceberg. Machine-to-machine interactions that would allow for remote environmental monitoring, cheap smart grid systems, automatic health care data aggregation, whole house automation, and a plethora of other innovative services are expected to grow 24-fold between 2012 and 2017 (Cisco, 2013). By 2020, there will be an estimated 12 billion such connections worldwide—some half of all mobile connections (Machina Research, 2012). In total, these mobile connections are expected to lead to $2.5 trillion in new global revenue and another $2 trillion in cost reductions and service improvements (Machina Research, 2012).

As mobile computing expands, wireless will become the predominant way that most people and companies access the Internet. As such, it is key to all of the many benefits discussed in the U.S. National Broadband Plan (Federal Communications Commission, 2010a) and other sources, including not just expanded business and wealth creation but also e-governance, telemedicine, public safety and emergency response, and more efficient energy usage.

Future growth predictions in fast-changing technology-based industries are inherently uncertain. However, the general trend is undeniable: rapid growth in data-connected mobile devices and increased usage intensity over the next decade. The basic uncertainty lies in how that demand will be met.

Responses to the Wireless Crunch

To address this tidal wave of demand, the National Broadband Plan (Federal Communications Commission, 2010a) recommended freeing up 300 MHz of spectrum within 5 years and 500 MHz over 10 years. About half the spectrum identified for reallocation is currently held by private licensees—primarily television broadcasters—with the remainder controlled by federal agencies. Later in 2010, the Commerce Department outlined its reallocation vision, identifying approximately 115 MHz of federal spectrum to be made available in the next 5 years and as well as a long-range plan for reaching the 500 MHz goal (U.S. Department of Commerce, 2010a; 2010b). In fall 2012, FCC Chairman Genachowski (2012) declared that the FCC was on track to meet the broadband plan recommendations, although significant implementation and other challenges remain.

The most significant chunk of capacity will likely come from "incentive auctions," which were proposed in the National Broadband Plan and authorized by the Congress in the Middle Class Tax Relief and Job Creation Act of 2012. Many television broadcasters receive virtually all of their revenues from cable or satellite distribution or have ceased operations as the percentage of Americans watching over-the-air signals dwindles below 20%. Nonetheless, even though they explicitly have no ownership rights, broadcasters are reluctant to give up their spectrum licenses, which cover frequencies considered to be "beachfront" spectrum due to their ability to travel long distances and penetrate building walls and other obstacles. Incentive auctions give broadcasters a share of auction revenue if they voluntarily relinquish their licenses.

Incentive auctions are a novel win-win solution that has the potential to unlock significant quantities of underused spectrum. However, the auctions pose enormously complex economic and political challenges, and it remains on open question how much spectrum such auctions will make available, especially in urban areas that make the most intense use of wireless broadband and also host the most lucrative television markets.

The other frequencies that have been marked for potential reallocation are generally spectrum reserved for use by various government departments, such as for radar, military communications, and air traffic control operations. As the commercial importance of wireless communication has expanded and technologies became available to serve these agency missions more efficiently, there have been several cases in which federal spectrum was cleared and then sold to commercial companies. For example, half of a 90 MHz band that sold for auction in 2006 for $13.7 billion came from federal spectrum (PCAST, 2012).

The National Telecommunications and Information Administration (NTIA) of the Department of Commerce, which oversees federal spectrum, has been working diligently and coordinating with the FCC to repurpose spectrum from government to private use for wireless broadband. However, clearing additional federal spectrum is proving exceptionally difficult and time-consuming. Government and defense agencies use spectrum to support important mission objectives, and making necessary equipment replacements and reconfigurations to support further spectrum transitions can be extremely costly. NTIA concluded that repurposing the 95 MHz of federal spectrum most amenable to clearing—the 1755–1850 MHz band—would still cost some $18 billion and take 10 years (U.S. Department of Commerce, 2012).

The U.S. General Accounting Office (2013) has concluded that the Department of Defense underestimated the actual relocation costs of the recently cleared 1710–1755 MHz band by almost $500 million, or 50%.

Although most of the emphasis since the National Broadband Plan has been on clearing frequencies for reauctioning, regulators are also making inroads into additional shared or unlicensed wireless capacity. For example, the FCC (2008b) is moving forward with unlicensed use of "TV white spaces," unused gaps in the frequency bands allocated for television broadcasting. Significant swaths of this spectrum lie fallow, especially in rural areas, because the original allocations assumed the technical characteristics of 1950s televisions and the number of stations in large urban markets. New technology, however, is expanding the ability of radios to sense their spectral environment and adjust operations in response. The FCC and private parties spent several years testing whether devices could access empty TV bands without harming existing broadcasts (Federal Communications Commission, 2008a). Ultimately, the FCC authorized TV white space radios with the requirement that they check an online database of existing broadcasters before transmitting. The FCC (2011) has subsequently authorized several database providers.

Because white space devices are unlicensed, the spectrum where they operate does not generate auction revenue. This provoked objections from some quarters in Congress. As ultimately passed, the legislation authorizing incentive auctions does not tie the FCC's hands on making unlicensed white spaces available. However, the technical design of the auctions and associated decisions about how to repack remaining stations into blocks of contiguous frequencies will determine how much effective capacity is available in the TV white spaces.

As technology and market conditions have evolved, other new opportunities for sharing have arisen. A significant portion of the 5 GHz unlicensed band is the result of a 1997 spectrum-sharing arrangement requiring devices to select frequencies to avoid interference with military radars. In early 2013, the FCC proposed expanding the 5 GHz band to further support certain unlicensed uses (Federal Communications Commission, 2013).

The PCAST Report*: *The Battle Lines Are Drawn

The FCC and NTIA are not the only governmental entities developing new approaches to increase wireless capacity. PCAST (2012), the president's science advisory board, was tasked to consider the best mechanism to reallocate federal spectrum for commercial uses. It recommended creating a 1,000 MHz superhighway by sharing federal spectrum with commercial users instead of focusing on clearing bands out to reauction for exclusive use. The core conclusion of the PCAST report is that "the norm for spectrum use should be sharing, not exclusivity" (PCAST, 2012, p. vi).

Under the PCAST proposal, frequencies currently controlled by federal agencies would be subject to a hierarchical spectrum access system that offered three tiers of interference protection: incumbent access (which would be protected from harmful interference from other users); secondary access (which would be subsidiary to the federal users but have protection against other private users); and general authorized access (similar to unlicensed systems today, with no guaranteed interference protection). These policies could be enforced by a database system, similar to the one now being deployed for TV white spaces. The FCC (2012b) has proposed an initial experiment in the 3.5 GHz band using such an approach.

The PCAST proposal focused on federal spectrum because of the group's charge and the difficulties already apparent in clearing and reallocating bands now under the control of government agencies. It offered other proposals such as a synthetic "spectrum currency" to encourage agencies to use spectrum efficiently and make capacity available to the commercial sector. Other authors have similarly focused on federal spectrum in advocating expanded use of sharing (Feld & Rose, 2010; Pickard & Meinrath, 2009). However, there is no technical reason a shared spectrum approach cannot also be used for reallocation of underutilized commercial frequencies.

The PCAST report provoked an intense response. The major wireless carriers criticized its emphasis on sharing as unrealistic and a distraction from the real work of spectrum clearing (CTIA, 2012). One commentator declared that "spectrum 'sharing' has become code among federal authorities to stall for more time" (Downes, 2012), and a Republican staff memo for a House Energy and Commerce Committee argued that "sharing should be reserved for cases in which Federal clearing is impossible" (Eggerton, 2012). In a hearing before that committee, Rep. John Skimkus (R-IL) summed up the opposition: "Having it is better than sharing it. Give it to the dang private sector and see if they can turn a profit" (quoted in Gross, 2012, para. 11).

The severity of the opposition to the PCAST report suggests that we have reached a decision point. As described in the previous section, sharing and exclusivity have long coexisted in the wireless world, with sharing becoming more prevalent as a technical approach over time, including within licensed bands. The explosive growth in wireless demand raises the stakes. Policy makers must decide whether to emphasize clearing or sharing to meet future capacity needs.

Part 3: Sharing as the New Normal

Clearing and reauctioning are necessary pieces of a response to the looming wireless crunch. But are they sufficient? The answer is no. Overemphasis on spectrum clearing will waste opportunities for productive spectrum sharing. This would be a major mistake. Although there is intuitive appeal in Rep. Skimkus' assertion that "having it is better than sharing it," on closer observation, the process of clearing and auctioning spectrum has significant limitations. Spectrum sharing, conversely, has significant benefits that have not been fully included in the policy calculus. Especially when considering the importance of spectrum for innovation, new businesses, free expression, and civic benefit, sharing mechanisms deserve at least as much emphasis as spectrum clearing.

The burden of proof should be on proponents of clearing to show that the benefits of greater exclusivity outweigh those of expanded sharing. There are multiple reasons why that might be true, such as the control necessary to guarantee quality of service or to overlay heterogeneous networks into an integrated service. Those potential benefits, however, should be weighed against the advantages of sharing.

Shortcomings of Spectrum Clearing

The clearing approach has real benefits. Decades-old legacy systems may be wildly inefficient in their use of spectrum. The revenue that auctions generate cannot be ignored, and economic theory suggests that companies' willingness to pay for spectrum will reveal their true demand. Auction revenue may help to convince incumbents such as broadcasters and federal agencies not to create roadblocks that could slow or stop reallocation efforts. Exclusive-use licenses give operators greater certainty, which may be particularly important for services with a large geographic footprint or that require high power and high reliability. And in theory, if given the freedom to resell or subdivide its rights, a licensee will have incentives to do so when such arrangements would be efficient.

Despite these apparent benefits, relying on spectrum clearing creates significant problems: Timely availability of new spectrum capacity is unlikely; clearing causes problems of spectrum access for small and nascent companies; and excessive exclusivity undermines overall efficient use of spectrum.

There is no "new" spectrum to clear. Almost all spectrum that has value for communications is already allocated to existing users, supporting a bewildering array of contemporary applications. Although some of this spectrum is being used with less intensity than other portions, any reallocation involves transplanting existing users in some way. Those users, whether commercial or governmental, are operating systems in which they have made investments, where users have devices in the field, and which are bound up with either financial or mission commitments.

Reallocating spectrum is slow and expensive, and only likely to become more so. Because of the density of existing uses, spectrum clearing involves the time-intensive, expensive process of negotiating with current license holders and upgrading or replacing equipment designed for specific frequency bands. The transition to digital broadcasting for terrestrial television, for example, cost the United States hundreds of millions of dollars and took far longer than anticipated. Overall, the past five spectrum reallocations in the United States have taken from 6 to 13 years each, with three taking a decade or longer (Federal Communications Commission, 2010a, p. 79). And the spectrum bands most amenable to reallocation have already been auctioned off. The process will be longer and more expensive for current bands under consideration.

Exclusivity encourages spectrum "territoriality." Companies that acquire cleared spectrum with exclusive rights have incentives to use it efficiently. The evolution of licensed cellular technology shows a continual progression of innovations to wring out more capacity. The problem arises when transmissions in one band manifest as interference in another band. The FCC is mandated to regulate transmitters, not receivers, even though poor-quality receivers effectively create interference. Without the incentives created by sharing, there may be insufficient pressure to deploy receivers that are robust to interference from transmissions in other bands, even when that would expand the overall utilization of the spectrum. The global positioning system industry was recently able to block LightSquared from deploying a new wholesale mobile broadband network because of such interference concerns (Federal Communications Commission, 2012c), showing that even when devices are unlicensed, allocations that do not contemplate sharing from the outset can be problematic.

Exclusive-use licenses today are almost always granted via auctions, which generate government revenues and, in theory, assign spectrum to those who value it most. A decision to clear frequencies for exclusive use is thus tantamount to a decision for auctions. In the current economic and technological environment, auctions create additional difficulties beyond those inherent in exclusive rights.

Auctions artificially favor large, incumbent providers. Auctions favor large, established companies, with prices for new spectrum licenses of decent size running into the multiple billions of dollars. This creates a "valley of death" that favors large incumbents and stifles opportunities for new entrants or nontraditional players (Marshall, 2012). At the same time, incumbents will often have the option to invest in infrastructure such as towers or backhaul that would achieve the same result as acquiring more spectrum, but will choose to purchase additional spectrum instead. New providers, on the other hand, cannot enter without access to spectrum.

Auctions artificially favor certain business models. Both sharing and exclusive use can create significant governmental revenues. Even purely unlicensed WiFi systems generate billions of dollars annually through taxes on equipment sales and fees for hot spot roaming services such as Boingo. The difference is that exclusive-use auctions ensure the largest up-front payment. Companies that make those payments then need to implement business models that recoup them. This typically involves maximizing airtime charges, tethering devices to service contracts, and potentially implementing restrictions on certain applications or services. Most of the FCC's Open Internet regulations, which place limitations on such blocking behavior for wired broadband connections, do not apply to wireless broadband systems (Federal Communications Commission, 2010b).

Auctions create incentives for anti-competitive behavior. Large incumbents may purchase spectrum to warehouse for potential future needs or to prevent potential competitors from emerging (Benkler, 2012). Even if, by itself, the spectrum being auctioned is more valuable to a new entrant, the incumbent may be willing to pay more for it, thereby foreclosing competition.

Spectrum clearing efforts should continue where feasible, but they should not be the only path forward. New technological developments and a refined understanding of spectrum point to solutions that can increase the efficiency of wireless usage and avoid many of the potential pitfalls of exclusive-use licenses.

Why Sharing Pays

Existing spectrum policies were developed when greenfield spectrum was relatively available for new wireless applications. Now that that spectrum is, for the most part, extremely scarce, new policies are needed, just as planners in many urban regions have shifted their zoning policies to help urban cores thrive despite a lack of new land to develop. Fortunately, both technology and economists' understanding of how communities can share resources effectively have also evolved tremendously.

Several strong reasons exist to include spectrum sharing in a comprehensive response to the wireless crunch.

Sharing increases efficiency and reduces waste. Based on pilot deployments and initial tests, TV white spaces are an example of how sharing can increase intensity of use. Television "guard band" spectrum is dark, despite growing demand, by government fiat. Unlicensed white space devices can fill in these spectrum holes by finding unused frequencies in their local area and transmitting at power levels that do not interfere with high-power television services. The fact that unlicensed devices must be robust to potential interference also increases spectrum efficiency. Low-quality unlicensed receivers cannot rely on the protection guarantees of an exclusive license and therefore will not be widely adopted.

Sharing could offer more, and more useful, dividends to governments. There is no doubt that spectrum auctions are potentially lucrative. However, focusing on short-term revenue curtails the overall benefits of spectrum to the government. The cost of relocating existing federal users may match or exceed the anticipated revenue from auctions. Furthermore, focusing on auction revenue ignores the financial benefits of alternative systems that are not represented by an up-front license payment. One estimate calculated these benefits as $50 billion annually in the U.S. (Consumer Federation of America, 2011), and a comprehensive analysis in Europe concluded that shared access to spectrum generates welfare benefits exceeding several hundred billion dollars (Forge et al., 2012).

Sharing could generate recurring revenue. Under the plan outlined by PCAST, federal spectrum would be shared under various short- and medium-term, flexible licenses. These could provide a substantial source of recurring revenue to the government. Moreover, this allows the government to recapture gains as spectrum increases in value, just as local governments are able to adjust annual property taxes in response to rising land values. Under a system of single-user spectrum licenses that can be resold on a secondary market, on the other hand, the government does not have an easy way to reap dividends from increases in the value of spectrum.

Sharing ensures that spectrum is more accessible, to more people. The airwaves are a public asset, but for as long as wireless telecommunications technology has existed, public access to those airwaves has been limited. Fears of interference led to private enclosure of spectrum. However, anyone using a public park in a major city should recognize the benefits of making even extremely scarce and valuable assets open to the public. The rationales for such spaces are even stronger in the case of the spectrum, which now serves as a primary medium for expression and communication for billions of people worldwide. Spectrum sharing represents the best method for making more spectrum accessible to individuals, small businesses, and innovators.

Open and shared spectrum offers benefits for nearly all groups. More openly accessible spectrum makes privately licensed spectrum more valuable, just as a neighboring public park can increase the desirability of a plot of land, because everyone—including exclusive-use license holders—has access. Offloading of mobile traffic onto WiFi is just one example; in this way, mobile operators are able to shift lower-priority communications off of their licensed bands and reserve these frequencies for the more quality- and time-sensitive messages most suitable for exclusive-use frequencies. Shared spectrum also creates incentives for technological innovation that benefits all spectrum users, because many of the advances in sensing the surrounding environment and extracting information amid interference also improve performance in exclusive-use systems.

All this is not to say that shared spectrum systems are without their problems. The computational overhead involved in simultaneous use makes shared systems less useful for low-latency applications, although the surprising ability of unlicensed WiFi devices to support voice and even video effectively suggests this may be a limited concern. Many of the growth areas for mobile data, such as the Internet of Things (Thanki, 2013), are more delay-tolerant. Several other factors might tip the scales in favor of exclusivity, including cost and complexity of devices with the capability to operate in a shared environment; the propagation characteristics of the spectrum, with low frequencies traveling longer distances and penetrating walls and trees; and the need for certainty to justify investment in towers and other infrastructure. Setting shared access as a default will encourage advocates of exclusive-use allocations to advance these arguments and assess them on a case-by-case basis rather than merely assume clearing is the best approach.

The Feasibility of Spectrum Sharing

Wireless operators and trade organizations have complained that calls for spectrum sharing policies, such as the PCAST proposal, only serve to delay the process of clearing new spectrum to auction (CTIA, 2012; Information Technology and Innovation Foundation, 2012). They assert that sharing is unproven and represents a mere aspiration about future potential. These arguments, however, represent two fundamental misunderstandings.

First, a greater emphasis on spectrum sharing is not mutually exclusive with spectrum clearing. Where clearing and reauctioning is most feasible and advantageous, it can still be used. Also, there is a range of possibilities under a spectrum-sharing model. A spectrum access system for a particular band providing for very limited secondary and general authorized access would look quite similar to some existing exclusive-use allocations. And both approaches require incumbent spectrum holders to give up some of their exclusive control; sharing is by no means equivalent to the status quo.

Second, as described throughout this article, spectrum sharing is hardly a pipe dream. The key technologies and operational models are well proven. For example, the ability to shift frequencies to avoid interfering with incumbent systems was a core part of the 5 GHz standards for Unlicensed National Information Infrastructure (U-NII) devices established 15 years ago (Federal Communications Commission, 2013).

The vision of a fully "cognitive" radio, which could avoid interference purely through spectrum sensing and real-time frequency hopping or changes in modulation, remains the subject of research and development in the lab. However, the PCAST proposal is far more modest. It describes an architecture very similar to the one the FCC has developed over the past decade in its TV white spaces proceeding. Rigorously tested white space devices are coming to market today and require no exotic technology. They make use of cheap computational power and location-based databases, which are already features of today's smart phones and tablets. Even low-end mobile phones on the market today contain powerful computers with multiple radios and spectrum access modes.

The use of a database infrastructure greatly reduces the technical demands and reliability assumptions for mobile devices making flexible use of spectrum (Werbach, 2010). Such frequency coordination, for example, is key to the recent FCC approval of secondary use of the 2360–2400 MHz band for indoor medical body area networks (Federal Communications Commission, 2012a). The FCC (2013) and NTIA (2013) are both exploring the technical feasibility of expanding U-NII rules (which include dynamic frequency selection) to the 5350–5470 MHz and 5850–5925 MHz bands, which would create a 750-MHz band of contiguous spectrum available for unlicensed operation; industry standards for high-speed wide-band technology that can take advantage of such large chunks of accessible spectrum are currently under development. And despite constant predictions of impending collapse, WiFi and other unlicensed systems have continued to operate in an environment of unrestricted sharing. Spectrum sharing is not a futuristic fantasy; it is a widespread reality today.

Even the major wireless carriers recognize the importance of sharing arrangements and the high costs of clearing new spectrum. For example, AT&T Mobility, T-Mobile, and Verizon Wireless recently announced a collaboration with the U.S. Department of Defense to test the possibility of sharing the 1755–1850 MHz band, using a combination of commercial low-power mobile broadband uplinks and government air combat training systems, aeronautical mobile telemetry, satellite command and control, and small unmanned aerial vehicles (Goldstein, 2013).

Similarly, the FCC's recent proposal to implement PCAST recommendations in the 3.5 GHz band highlights the fact that the primary obstacles to denser usage of spectrum in many bands are regulatory, not technological. The 3.5 GHz band currently supports satellite and radar operations that make geographically limited use of the spectrum band but preclude concurrent use for cellular networks. According to the proposal, a three-tier sharing system could be implemented in the near future in this band by utilizing existing small-cell devices and extending the TV white spaces database model. "We believe that current database technology can be used to achieve dynamic frequency assignment while mitigating interference between devices in the same frequency band," the FCC writes, although it also acknowledges that such a "Spectrum Access System as applied to the 3.5 GHz Band would implicate some novel issues," including "a new generation of this dynamic database technology" (Federal Communications Commission, 2012b, para. 58).

Major wireless equipment vendors also recognize that sharing arrangements are essential to meet growing demand. Qualcomm, which primarily sells technology powering licensed cellular systems, has, among other solutions, called for the creation of an Authorized Shared Access system (Qualcomm, 2012). Through ASA, commercial operators would be able enter into an exclusive sharing arrangement with incumbent users, particularly government agencies, on globally harmonized spectrum bands. This, along with the increasing availability and decreasing costs of small-cell devices such as femtocells, would allow for intense densification of wireless infrastructure and much more efficient use of higher-frequency spectrum bands, Qualcomm says.

New spectrum-sharing technologies will likely be developed as fast as or faster than new spectrum can be cleared, given the intense commercial and government interest in such technologies. Key innovations such as spread spectrum and orthogonal frequency division multiplexing were deployed on unlicensed systems before licensed cellular networks (Thanki, 2013). Next-generation cellular networks and new wireless networking standards in development, such as IEEE 802.11ac, will feature advancements in smart antenna technology that will allow more data to be transmitted over the same frequency band.

Fundamentally, the dismissal of spectrum sharing reflects the conceptual difficulty of spectrum. Although most of us use mobile devices constantly, we still have a hard time coming to terms with the physics of wireless communication. Congested spectrum is not the same as an overused pasture, to use a common metaphor for what happens when communal resources are opened to general use. In the pasture, too many cows eating grass will literally destroy the ground, making it unusable. But radio spectrum works the same way as listening to a conversation in a loud room. No matter how noisy the environment, a conversation is not destroyed—it just becomes harder and harder to hear. In the same way, interference does not destroy the information carried via spectrum; signals just stack on top of one another, increasing the effort required to extract communications (Computer Science and Telecommunications Board, 2011).

Technologies of spectrum sharing are becoming more sophisticated in both licensed and unlicensed systems. The best approach to use in any case can be debated, but sharing should not be written off at the outset as a technological fantasy.

Conclusion

Spectrum policy should refocus on the goal of maximizing the volume and value of usable capacity. Sharing mechanisms must be an important part of that effort. Another way to frame the imperative is that spectrum policy should make a commitment to *users* of spectrum rather than merely to spectrum *holders*. Whether the policy goal is to promote private investment or citizen empowerment, greater use of potential wireless capacity is the ultimate objective. Changes in who controls frequencies are a means to that end.

Approaches that emphasize spectrum clearing to the exclusion of spectrum sharing will, in effect, leave capacity on the table. Furthermore, an environment of predominately exclusive rights will be less conducive to new forms of competition, out-of-the-box innovation, community engagement, and diversity of applications. The history of communications media is rife with examples in which openness was sacrificed for economic feasibility. In the 21st-century wireless environment, such a trade-off is unnecessary, but only with the right policy choices.

The U.S. government is turning over every possible stone to identify, clear, and reallocate underutilized spectrum bands. However, given the more intensive uses of those bands and the lengthy time lines of recent reallocations, there is no guarantee that substantial amounts of new spectrum will go to auction anytime soon. Ultimately, regulators will have to make decisions on how to move toward more effective spectrum use in the face of uncertainty—both on whether new spectrum can realistically be cleared in the near future and how quickly proposed sharing mechanisms can be developed and implemented. If history is a guide, those decisions will shape wireless communication for decades to come.

Relying more on spectrum sharing will open up new opportunities for investment and innovation in wireless systems and offer more flexibility in the face of changing technology and societal demands. Such an approach holds the best hope for turning the wireless crunch into a spectrum opportunity.

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