How New Technologies Can Turn a Spectrum Crisis into a Spectrum Opportunity

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Executive Summary

Wireless networking has revolutionized how we use technology, allowing even casual users to connect their computers, entertainment devices, and home automation systems. Wireless technologies have also dramatically altered the workplace, enabling networking for business meetings and for mobile workers. In the public sphere, these technologies have been used to provide Internet access in public spaces and automate governmental functions such as meter reading and security monitoring.

Wireless networks depend on radio frequency spectrum. In the United States, most spectrum allocation is done through licensing and those allocations have historically been constrained by the complexities of detecting and preventing interference. In recent years, however, intensifying use of finite spectrum resources has led policymakers and network providers to consider novel approaches to spectrum allocation and to adopt new technologies, such as smart radios and online databases, that reduce interference and allow for more spectrum sharing. Using more radios and new radio designs will also lead to more intensive use of limited spectrum resources.

It is increasingly important to get spectrum policies right as demand for wireless data traffic soars and the devices and information in our environment become more interconnected. This means pursuing innovative technologies that enable spectrum to be used at different times, locations, and frequencies more efficiently. It also means allowing spectrum to be shared in mixed-use scenarios and identifying underutilized spectrum bands.

This paper explores current models of spectrum management, the technologies that use spectrum, and the limitations of current spectrum management policies. It argues that regulatory mechanisms should be designed to exploit the capabilities of new technologies. These technologies include cognitive radios, which enable use of noncontiguous chunks of spectrum; spectrum-sensing technologies that allow bands to be shared by multiple users; online databases that automate spectrum allocation; and networks that can dynamically control their transmission power, allowing spectrum bands to support more efficient modulation.

In addition to describing these new technologies, this paper identifies a number of spectrum bands—particularly bands that abut current unlicensed allocations and which have favorable propagation characteristics—that could be early targets for new spectrum management approaches.

Future innovation in an increasingly digital world—new technologies, new kinds of services, new business models—will depend on the expansion of the total wireless bandwidth available to people and machines and on the ubiquity of high-speed networks. Policymakers should simultaneously pursue several approaches to deal with the growing spectrum crisis: allowing access to more spectrum, using a mix of spectrum allocations, enabling complementary shorter-range and wide-area networks, and increasing reliance on automated solutions. None of these approaches alone can address the growing demand for wireless broadband.

Introduction[1]

Wireless radio devices were invented about 140 years ago, with widespread commercial application coming four decades later. The initial application of radio for broadcast news and entertainment revolutionized the world, much as the Internet has done more recently. During the 100 or so years that radio has been used, different strategies for sharing the radio waves have been employed, ranging from an early free-for-all to court-ordered allocation and then eventual regulation by national agencies such as the U.S. Federal Communications Commission (FCC) as well as international agencies and treaties.

It is increasingly important to use spectrum as efficiently as possible as demand for wireless data traffic increases and as we bring about an "Internet of Things"—the interconnection of all the devices and information in our environment. The FCC has projected strong growth in mobile data traffic from 2009 levels—by a factor of five by 2011, a factor of more than 20 by 2013, and a factor of 35 by 2014 (FCC 2010b). By one estimate, there will be 50 billion connected devices by 2020.[2]

Most radio spectrum is currently allocated through licensing, and much of the licensed spectrum is used for communication, from cellular systems and police radios to RADAR, satellite downlinks, and GPS broadcasts. Spectrum allocation has historically been constrained by the complexities of detecting and preventing interference, but in recent years new technologies (such as spread-spectrum radios) and wireless networking protocols (such as those used in Wi-Fi) have emerged that can automate how radio spectrum is shared and can reduce interference.[3] These technologies have led to an explosion of applications, from cordless phones to Bluetooth headsets and near-ubiquitous Wi-Fi networking. These are just early

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[1] This paper was made possible with support from Microsoft Research.

[2] See Ericsson press release quoting its president and chief executive officer Hans Vestberg, April 13, 2010, available at http://www.ericsson.com/thecompany/press/releases/2010/04/1403231.

[3] Chapter 8 of *Blown to Bits: Your Life, Liberty, and Happiness after the Digital Explosion* (Abelson 2008) has a very readable overview of the history of radio spectrum allocation, regulation, and technologies.

examples of how technological advances have allowed for more efficient use of spectrum and have expanded the use of wireless devices. They enable increased use of unlicensed and "lightly licensed" approaches to allocation in which spectrum can be shared in a mixed-use scenario and underutilized spectrum can be put to use.

Revolutionizing the way that spectrum is managed is essential to meeting the future need for high-speed wireless broadband and enabling new wireless applications. This will entail pursing technologies that enable spectrum to be used at different times, locations, and frequencies more efficiently.

Regulatory mechanisms should better reflect the capabilities of new efficiency-enhancing technologies. Policymakers should simultaneously pursue several approaches: allowing access to more spectrum, allocating a mix of spectrum bands, enabling complementary shorter-range and wide-area networks, and increasing reliance on automated solutions. None of these approaches alone can address the growing demand for wireless broadband.

Today, there are new mechanisms, including "Internet managed" spectrum databases, software-defined cognitive radios, and wide-spectrum radios, that can greatly increase spectrum utilization. Many existing spectrum allocation methods can be better handled by *online databases* or *distributed allocation systems* that allow for more dynamic use of underutilized spectrum. Internet-managed radio networks can accommodate new uses while preserving the functions of incumbent users. New radio technologies, such as software-defined cognitive radios, allow wireless systems to use disparate spectrum bands and enable many innovative uses of wireless networks. New radio designs are emerging that can make use of a wider range of spectrum blocks and often make use of several parts of the spectrum at one time. Rules governing when and where spectrum can be used should both embrace the capabilities of existing technology and chart a regulatory course that allows emerging technologies to be used as soon as they become commercially available.

The best targets for novel spectrum management techniques for broadband networks are those underutilized spectrum bands that abut current "unlicensed"

allocations and which offer opportunities to trade off different spectrum for different tasks and circumstances. A variety of factors should be considered in determining whether spectrum blocks are underutilized and therefore appropriate targets for secondary uses. Spectrum occupancy studies can provide important information in making those determinations. There are a number of other criteria for selecting the spectrum to be devoted to Internet-managed unlicensed models, including the geographic extent to which the spectrum is used, the ability to use the spectrum without interference, and the cost of interfering with or relocating existing users. Some examples in the United States might include:

- The 420-450 MHz band, currently used for a combination of public and governmental land-mobile, amateur and federal applications as well as private land-mobile radio;

- In addition to the recently allocated UHF TVWS spectrum (portions of 54-72, 76-88, 174-216, 470-512, 512-608 MHz), some of the additional spectrum that arises from consolidation of existing TV channels;

- Portions of the 960-1215 MHz radio navigation and amateur bands because of their proximity to the 900 MHz Industrial, Science, and Manufacturing (ISM) band and TVWS;

- Controlled use of the 2360-2400 and the 2500-2655 MHz bands because of their proximity to the existing 2400 MHz ISM band; and

- Controlled use of the 2900-3100 MHz and 3550-3650 MHz bands because of their proximity to the lightly licensed 3650-3700 MHz band.

How Spectrum Is Allocated

Understanding how spectrum can be better used requires understanding how it is currently allocated and the technical reasons behind those allocations—as well as how new technologies are influencing spectrum allocation and will continue to do so into the future.

The nature of spectrum and the need for international cooperation have resulted in a complex international effort to coordinate spectrum use. International spectrum policies are set by the Radio Regulations, an international treaty ratified by member

states of the International Telecommunications Union (ITU), a United Nations agency. The ITU organizes spectrum management by geographic region in an effort to harmonize spectrum use across borders, facilitate international commerce, and find efficiencies by ensuring that new technologies can operate across multiple countries. The ITU also promotes spectrum (and, more broadly, telecommunications) policy, management, and education.[4]

Although the ITU attempts to coordinate policies, individual countries set their own spectrum allocation policies.[5] Broadly speaking, there are three models of spectrum management: Administrative, Market, and Commons. In the Administrative model, governmental organizations typically dictate where spectrum can be used, by whom, with what equipment, and with what modulations or radio devices. The Market approach uses auctions of spectrum licenses or spectrum leases to allocate specific spectrum bands in a specific geographic area. This model moves more of the decision making to the participants in the spectrum market. The Commons model allows a variety of devices to access specific spectrum bands across broad geographic areas. Those devices are typically certified and must obey specific regulations, but they do not operate under the control of a licensee. (Variations on the Commons approach are also used; see Freyens [2010] for an overview of Australian policy.)

The Administrative and Market approaches both allow exclusivity of access. Spectrum is either licensed, whereby specific frequency ranges are reserved for specific purposes or users, or lightly licensed, whereby spectrum is allocated through site-specific licenses that are easier to obtain but may be limited in duration and may provide rights that are secondary to primary users of the spectrum . The

[4] The ICT Regulation Toolkit at http://www.ictregulationtoolkit.org provides an overview of ITU regulatory practices and goals.

[5] In this paper, I use the word *allocation* to encompass a variety of scenarios, ranging from licensed, exclusive-use allocations to more flexible allocations involving licensed primary uses and secondary unlicensed uses (as described later).

Commons model uses unlicensed allocation, whereby devices are certified but the users and their devices do not have any exclusive rights to spectrum.

Many countries use multiple regulatory mechanisms—for example, in the United States, the National Telecommunications and Information Administration (NTIA) uses an Administrative mechanism for government use of spectrum, while the FCC uses a combination of approaches for nongovernmental use of spectrum. However, broadly speaking, spectrum policies across the world are similar even though the policies for specific frequencies may differ.

Most spectrum is licensed, and much of the licensed spectrum is used for person to person communications (either cellular systems or "land mobile radio" such as radios used for police and taxi services). Some of the licensed spectrum is devoted to specific applications—for example, in the United States, the 173.075 MHz frequency is allocated for the LoJack vehicle recovery system. Other allocations are designed to exploit specific physical properties of spectrum bands, such as those used for RADAR and radio telescopes; still others are used for satellite downlinks, GPS broadcasts, and other air or ship radio-location systems.

A number of spectrum occupancy studies in the United States (McHenry 2004, Strickling 2009, Shared Spectrum 2010), Europe (Valenta 2010, Wellens 2009), and other regions have demonstrated that only a fraction of the available spectrum is in use at any one time. This is true even over multi-day periods that include significant public events that would be expected to engender significant communication on cellular, police, taxi, and other land mobile radios, such as the 2004 Republican National Convention in New York City. Much activity and research is ongoing to determine whether unoccupied or underutilized spectrum could be used for new applications, such as rural broadband, machine-to-machine communication, and enhanced data networks for consumers, businesses, and governments.

> Only a fraction of the available spectrum is in use at one time, even over multi-day periods.

We'll briefly examine licensed, lightly licensed, and unlicensed spectrum allocation. Then we'll discuss the opportunities for dynamic spectrum access, which allows for more flexible use of traditional spectrum management techniques.

Licensed Spectrum

Many spectrum allocation rules have specific limitations based on the propagation, or reach, of different spectrum bands. For example, Figure 1 shows the effective radio range of a 3500 MHz radio and a 700 MHz radio in the area surrounding Buckhannon, West Virginia, if both radios are mounted at the same location and use the same transmission power. These plots were developed using Radio Mobile software[6] in combination with United States Geological Survey topographical maps. The software uses the Longley-Rice model that approximates the physics of radio propagation (OET 2004).

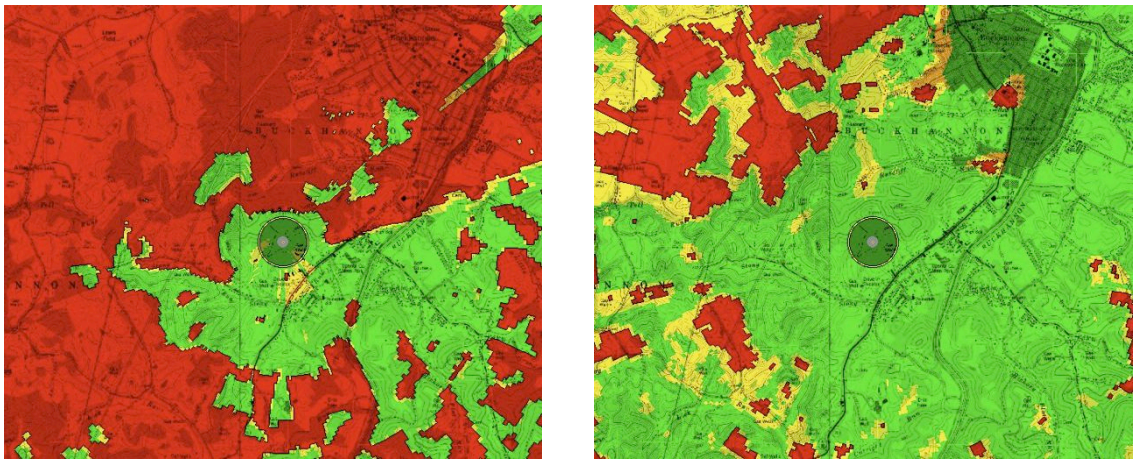

Figure 1. Comparative propagation for 3500 MHz (left) and 700 MHz (right) radios.

In the Figure 1, red indicates poor reception, green indicates good reception, and yellow is in between. Despite the fact that the hypothetical radio tower (indicated by the circle) is on a hill, the rolling hills in the region pose problems for 3500 MHz signals because those signals cannot reflect or diffract around objects such as hills. This figure also illustrates why certain spectrum is called "beach-front property"—

[6] Available at http://www.cplus.org/rmw/english1.html.

more favorable propagation characteristics can increase the area served at the same power.

Regulators usually specify the allowed EIRP (effective isotropic radiated power) for licensed frequency allocations; the EIRP accounts for tradeoffs in power, antenna size, and mounting location. The goal of those regulations is to reduce the interference to and from nearby users of the same spectrum.

Kobb (2001) has published a comprehensive index of spectrum allocations compiled from FCC and NTIA documents as well as documents from international organizations such as the ITU. Licensing systems have often dictated which technology can use which spectrum bands. For example, to ensure that land mobile radio systems are compatible, the spacing and modulation of channels for those radios has been specified. New technologies that have improved the efficiency of spectrum use have enabled occasional reassignments, such as the recent transition to digital TV in the United Kingdom and the United States and the current narrowing of land mobile radio channels from 25KHz to 6.25KHz.

Lightly Licensed Spectrum

The use of some spectrum bands has been liberalized through the use of lightly licensed regulation schemes. For example, in the U.S., the 3.65 GHz band is used for satellite communication and RADAR systems. In 2004, that band became a mixed-use band that allows access by fixed wireless access (data) networks in geographic areas where satellite and RADAR systems are not used. (The same band is used for fixed wireless access in other countries.) This gives the networks significantly higher power levels, making them suitable for “last mile” connectivity. This licensing mechanism includes a requirement for contention-based protocols (like those used in Wi-Fi) to limit interference.

The lightly licensed mechanism for the 3.65 GHz band provides new spectrum over much of the United States, although large portions are excluded because of

grandfathered uses such as satellite communication and RADAR systems, as shown in Figure 2.

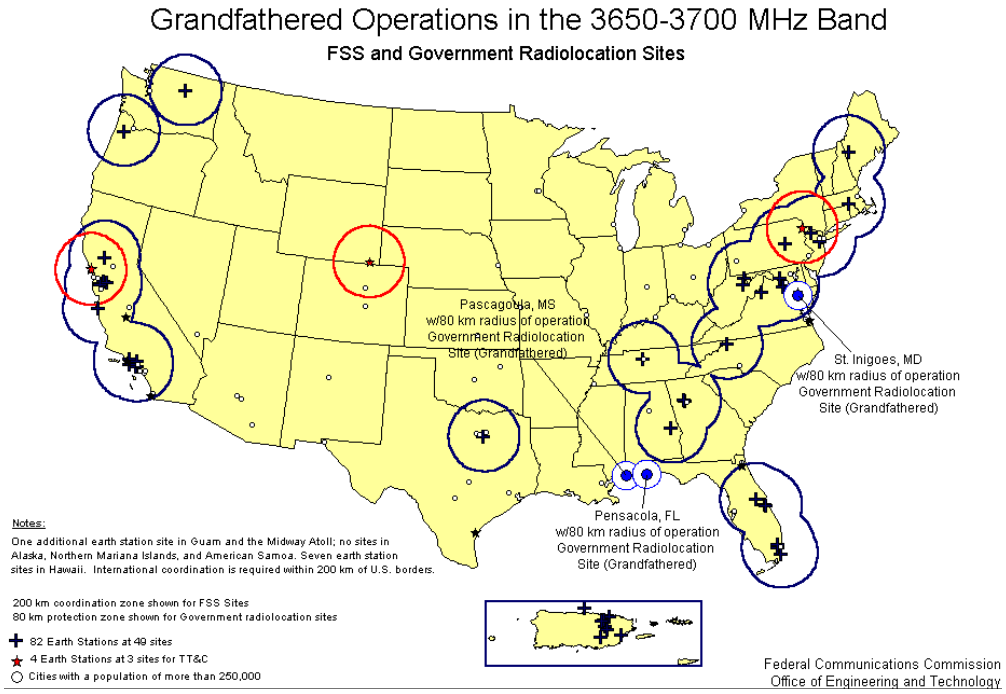

Figure 2. Spectrum use in the 3650-3700 MHz band.

Under a lightly licensed scenario, sharing of spectrum is facilitated through use of a "database" of nonexclusive allocations, to limit interference and protect existing applications. For the 3.65GHz band, the database is accessed manually. This is an example of spectrum "geo-fencing"—restricting spectrum use to a specific geographic area. Although this lightly licensed approach is less time consuming, less complex, and less expensive compared to most applications for licensed spectrum, the manual database management process means that lightly licensed spectrum cannot be used for mobile applications because the geo-fence is checked as part of the license application rather than when the device is used.

Unlicensed Spectrum

Allocation of spectrum bands for specific purposes may depend not only on characteristics such as propagation but also on potential natural interference or

unavoidable interference. The ISM bands are parts of the spectrum where noise is generated by many sources. For example, the 2.4 GHz ISM band (used for Wi-Fi networks) receives interference from microwave ovens, rendering it less useful for reliable communication.[7] However, that frequency range is good for short-range communication (where, for example, a homeowner could control the source of interference, the microwave oven) or with devices that can tolerate interference.

Many devices are covered by the rules governing unintentional radiators (e.g., microwave ovens) and unlicensed devices (e.g., Bluetooth or Wi-Fi). In the United States, these are called FCC Part 15 devices, and they must accept other interference (i.e., you can't complain if your Wi-Fi network doesn't work when the microwave is on). Designation of ISM bands is not consistent around the world. For example, the U.S. designates 902-928 MHz as an ISM band, but that band is used in much of the world as part of the GSM 900 MHz cellular phone standard.

In the last 20 years, unlicensed spectrum use has expanded, usually in the ISM bands. This is technically the Commons model, which allows the use of unlicensed devices in certain bands. The key enabler of unlicensed devices is spread-spectrum transmission, which allows a number of devices to share a single channel without interference. (The signal of any one transceiver appears as low-level noise to the other receivers, but the radio receivers are able to disentangle the signal of one transceiver from another.)

Even when different radios can "hear" each other, protocols and etiquettes can allow the shared use of that spectrum. Protocols include the definition of how a particular wireless standard, such as WiFi, WiMAX or LTE are constructed and communicate. Etiquettes include mechanisms that allow wireless networks using different underlying technologies or protocols to cooperate for common goals. These etiquettes are similar to those used in speech in a crowded room—don't talk if it's

[7] The interference is intrinsic to the microwave oven—it arises because water molecules can be "excited" by a 2.4 GHz RF source, causing the water in food to heat. Shielding in microwave ovens is intended for human safety—it reduces the noise, but the oven can still interfere with local Wi-Fi communication.

too noisy, explicitly address the other party, identify yourself, take turns, and talk no louder than needed.[8] Coupled with the low-power restrictions on devices used in unlicensed bands, unlicensed allocation is increasingly popular for private wireless networks used by consumers, businesses, and government groups. Early experiences with unlicensed allocation have spawned new demand for machine-to-machine communication, including smart-grid power monitoring, home and industrial automation, and entertainment devices —all components of the Internet of Things. Some of these networks (e.g., ones that link video devices) often use considerably more bandwidth than "human-centric" networks.

Controlling interference is important both for high-performance wireless networks and for other devices that use the same spectrum. Sometimes the "controls" to limit interference are part of the spectrum allocation or rules for allowed use. For example, in the United States, the UNII[9] 5 GHz spectrum allocation has different antenna and power limits for each band. The rules for each band are designed to reduce interference, with some bands being restricted to indoor use to avoid interference with legacy uses of those bands (e.g., hearing aids and transportation networks). Part of this band is used by 802.11a Wi-Fi unlicensed devices for data networking.

Two of the UNII bands require that devices constantly check for the presence of incumbent RADAR systems. If such systems are detected, the device must not use the band and will usually switch to another band. This is an example of *dynamic frequency selection* (DFS)—the check is based on measurements made by the radio. In both Europe and the United States, dynamic frequency selection is mandated for devices that use the UNII bands, such as those that use 802.11a Wi-Fi.

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[8] The technical terms for the equivalent protocols in Wi-Fi are *carrier sense/multiple access* (CSMA), *destination and source addresses*, *contention-based packet protocols*, *and transmit power control*. Each of these has many variants or alternatives, but the analogy to conversational etiquette is fair.

[9] The Unlicensed National Information Infrastructure spectrum, which contains four bands: UNII-1 (5.17-5.25 GHz), UNII-2 (5.25-5.35 GHz), UNII-2-extended (5.47-5.725 GHz), and UNII-3 (5.725-5.825 GHz).

Dynamic Spectrum Access

New technologies can enable more flexible use of traditional spectrum management techniques. The first step involves automating the licensing and database mechanism used in lightly licensed schemes. This is happening in countries around the world as part of the transition from analog TV to digital TV signals. Digital TV reduces the bandwidth needed for existing broadcast TV. In the U.S., some of the remaining spectrum has been devoted to cellular services (the 700 MHz auction), and part of it has been made available as unlicensed spectrum using innovative technologies and policies (FCC 2010c). As indicated earlier in Figure 1, the propagation characteristics of these frequency bands make them very useful for long-range networks and for better in-building coverage.

New technologies can enable more flexible use of traditional spectrum management techniques.

The FCC splits the TV spectrum across multiple channels, as partially shown in Figure 3 below. Some TV channels are not used, and even where TV stations are actively used, guard bands are used to reduce the risk of channels interfering with one another. These guard bands and the unused channels constitute the TV White Spaces (TVWS).

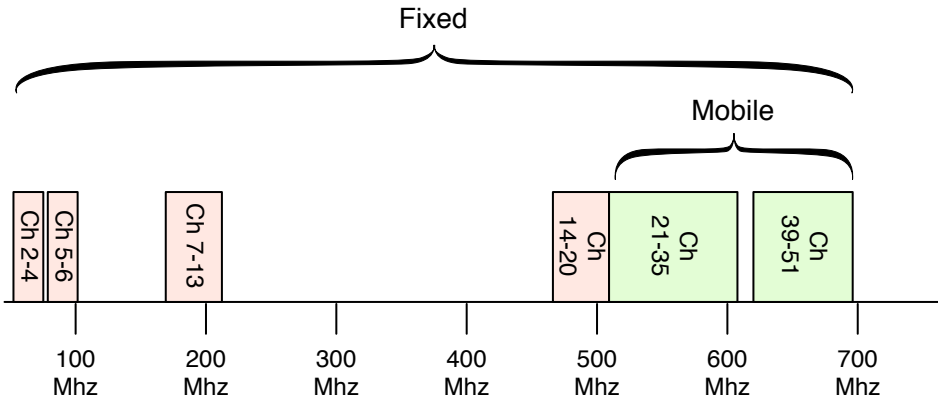


Figure 3. TV White Spaces spectrum in the United States.

The FCC has released comprehensive regulations allowing unlicensed use of the TVWS. It divides TVWS access into two sections (shown in pink and green in Figure 1) in which fixed applications or both mobile and fixed applications are allowed. The FCC's rules ensure that existing licensees, such as broadcasters, licensed wireless microphones, radio astronomy, and some mobile radio networks, are protected from interference by requiring TVWS devices to rely on automated, dynamically updated databases or to use sensing technology that indicates when those frequencies are being actively used by other applications.

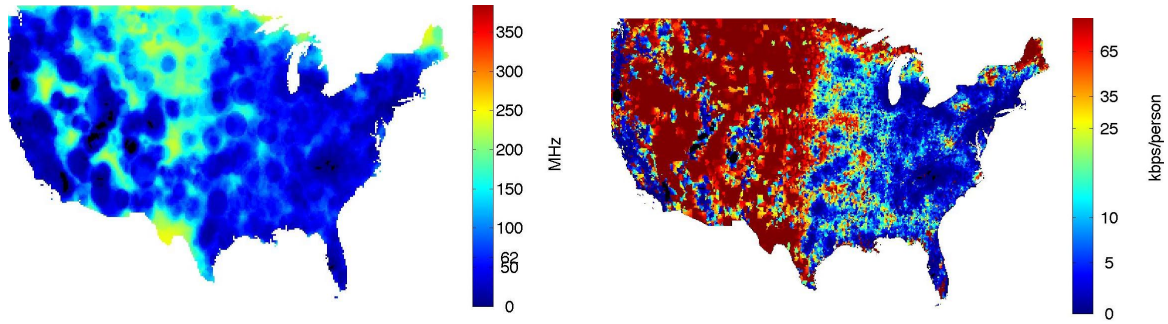
Other countries are considering similar use of the TVWS for unlicensed use (referred to as license-exempt use in many countries outside the United States). For example, the UK Ofcom has concluded that license-exempt access to the TVWS spectrum should be permitted, and has an ongoing consultation requesting input on operation of databases that would control access by devices utilizing geolocation capabilities. (Ofcom 2009, Ofcom 2010).

A number of prototype systems (Ghosh 2008, Bahl 2009) and network standards have been developed (Cordeiro 2006) showing that TVWS technology is practical. The critical conclusion of these studies is that geo-fencing and spectrum-sensing technologies can allow the TVWS to be shared by multiple users, much as the

existing unlicensed spectrum can be shared, without adversely affecting licensed users of spectrum.

Other research has quantified the benefits of using TVWS spectrum. A recent, comprehensive study (Harrison 2010) uses databases of existing TV stations, propagation models, and census information to determine how much TVWS spectrum is available across the United States by land area and by population. The measurement of spectrum by land area is important for machine-to-machine communication—the Internet of Things. Measurements were derived for both short-range networks, assuming a network range of 1 kilometer, and long-range networks with a 10-kilometer range. Networks with a shorter range provide more total wireless network bandwidth, but longer-range networks are more practical for rural broadband.

Figure 4 shows the available spectrum (in MHz) as well as the average data rate per person for long-range 10-kilometer networks. The amount of available spectrum (and per-capita data rates) is greatest in rural areas with few TV stations. The data rate appears low, but the calculations are based on the assumption that all the people in a given area are using the network at once, which rarely occurs. The resulting bandwidth is sufficient for high-speed wireless networking in many rural areas.



Available Spectrum (in MHz) Bandwidth (in Kb/s/person)

Figure 4. U.S. projected spectrum and data rate availability (Harrison 2010).

One benefit of the FCC's TVWS regulations (and regulations proposed in some other countries) is that the same spectrum bands can be used for high-power long-distance networks in rural areas (as shown in Figure 4) *and* for lower-power short-range networks in more urban environments. In fact, Harrison's analysis indicates that urban and suburban users may benefit from TVWS more than rural users.

Harrison's study has been corroborated by studies from commercial spectrum management companies (Spectrum Bridge 2010). A limited number of studies have looked at other countries; Nekovee (2009) has published one such survey for the UK showing an average of ~150Mhz of spectrum available for short-range devices. Leng (2010) describes studies from Singapore and Australia, but with less detail than the Harrison and Nekovee studies.

Dynamic spectrum access technologies and the spectrum regulation mechanisms they allow, have broader applications than just the TVWS. The same techniques should be applied to other spectrum bands, such as the 3.65 GHz band that has geographical restrictions in the United States. In other words, it is possible to automate the licensing of spectrum—such as by licensing the 3.65GHz band using a time-of-use model (that provides access to spectrum when needed) rather than the time-of-application approach currently used (that provides access to spectrum for the duration of the license). Although the TVWS has sparked the most interest in the area of dynamic spectrum management, studies are under way to examine how dynamic spectrum access technologies can be used in the 410-420 MHz U.S. federal band (Strickling 2009). A similar approach is being used to simultaneously allow better use of the 5 GHz UNII spectrum and reduce interference with weather RADAR (Knapp 2010).

How Spectrum Is Used

More intense use of finite spectrum resources is forcing policymakers and network operators to pursue use of unused or underutilized spectrum bands and new, innovative approaches to spectrum allocation. Historically, consumer use of spectrum was largely limited to radio and TV; companies and government agencies used spectrum mostly for navigation and mobile communication. Business, consumer, and governmental use of spectrum has ballooned in recent years, primarily through a combination of licensed (cellular, satellite TV, fixed wireless) and unlicensed (Wi-Fi, Bluetooth) services.

Cellular networks will probably not be able to sustain the burgeoning applications that are appearing. Many services, such as taxi dispatching, now use cellular infrastructure instead of land mobile radios because it provides more functionality (such as location tracking and credit card processing). The increasing availability of wireless services has also enabled new uses such as wireless video surveillance cameras. These uses are loading the existing resources. In a 2009 survey (PCWorld 2009), cellular data networks were found to have widely varying data rates and reliability.

Increasingly, wireless networks are used for Internet access. Individual services, such as cellular, unlicensed Wi-Fi, and fixed wireless services, are largely substitutable or are used to augment one another. Additional spectrum bands, such as the 3.65 GHz band for fixed wireless, the 4.9 GHz public safety band, and the 2.5 GHz Educational Broadcast Services band, are increasingly used for automating many services, such as automated meter reading, video surveillance, and infrastructure networks connecting hospitals or other facilities to the Internet.

It is usually difficult for a single system (e.g., video surveillance) to take advantage of all of the wireless services or available spectrum at any one location, both because of the radio technologies involved and because of the rules governing spectrum use. This leads to many single-application uses of spectrum. For example, in the U.S., the Utilities Telecom Council unsuccessfully proposed devoting 30 MHz of the TVWS

spectrum to smart-grid networks, arguing that commercial wireless networks cannot withstand disasters. However, restricting that spectrum band to a single industry makes it unavailable for other uses. While multi-party disaster-tolerant networks are needed, many of the proposed applications, such as day-to-day meter reading or communication, could share spectrum resources by using one of many available Internet networks such as local Wi-Fi or cellular connections.

Home users are also increasing their use of wireless networks. Wi-Fi and Bluetooth are now ubiquitous technologies. A rich market has developed in wireless audio systems, Internet radios and alarm clocks, wireless gaming consoles, and the like. These new products are straining the available wireless network resources. A number of products are coming on the market to connect TV displays to video sources. Some of these have relied on heretofore "exotic" spectrum such as the unlicensed 60GHz band[10] or use the entire 160 MHz of the 5 GHz band, as proposed in the 802.11ac standard. At the same time, machine-to-machine communication, including energy monitoring, lighting and environmental controls, and entertainment devices, is rapidly increasing. This will drive demand for both high-bandwidth and high-propagation wireless networks.

Meeting Increased Wireless Network Demand

How much additional spectrum is needed for emerging applications? It depends on how the networks using that spectrum are designed.

In general, large chunks of contiguous spectrum are preferred. Wireless networks have a capacity defined by the Shannon-Hartley Theorem, which can be measured in bits per second. That theorem says that $Capacity = Bandwidth * \log_2(1 + Signal/Noise)$. In this equation, "Signal" is the information to be communicated, and "Noise" is all other information that uses the same bandwidth (possibly including someone else's signal). Signals from radios decay or attenuate because the signal

[10] The 60 GHz spectrum is commercially viable only because of recent advances that allow inexpensive 60 GHz radios to be built. For in-home networks, power limitations make these signals difficult to propagate through walls; they can also be used for higher-power outdoor directional links.

spreads out through space. To be decoded, a signal must be sufficiently "louder" than the noise at the receiver. The capacity equation shows that to double the data rate, one must either double the bandwidth used (e.g., using 20 MHz rather than 10 MHz) or increase the transmission power by a factor of 4 (because of the logarithm). However, increasing the transmission power causes additional noise for other nearby receivers.

Wireless transmissions decay rapidly with distance and reflection from objects such as buildings and materials such as metal. As a signal decays, it becomes harder to receive an error-free message. This makes it difficult to categorically state what transmission rate can be achieved at a given location. Radio engineers address these problems by using more efficient modulations for stations close to the access point and less efficient but more noise-tolerant modulations for more distant stations.

Typically, the range for the best modulation is very limited. For example, the throughputs shown in Figure 5 are taken from a paper (Tran 2008) that describes a field trial of Mobile WiMAX.[11] The vertical axis shows the throughput (in Mb/s) vs. distance from the access point, which uses a well-designed network in the licensed 2GHz band with high power and efficient antennas. As the receiver moves farther from the transmitter, the signal decreases and noise increases. This reduced signal-to-noise ratio (SNR) makes it difficult to receive a message correctly.

[11] This diagram shows the results of a *model* of the transmission distance. Tran demonstrates that the model reflects measured data. The model data is likely to overstate the performance for any specific location because it doesn't include the obstructions at those locations.

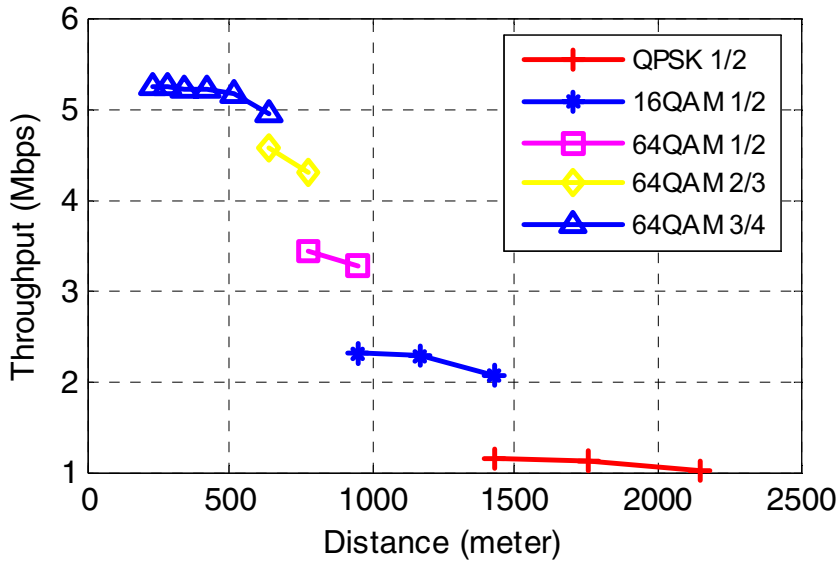


Figure 5. Example throughputs for different signal modulations and distances.

To compensate, the transmitter dynamically selects a less efficient modulation technique when errors are detected. The 64QAM ¾ modulation is the most effective, delivering ~5.2Mb/s in this example, but only for stations up to ~600 meters from the transmitter. After that, reception quality quickly degrades, reducing the bandwidth at 1400 meters and beyond to ~1.1Mb/s using the QPSK ½ modulation. Because of the reduced signal, only ~8% of the area reached by the WiMAX signal in this example can actually use the highest (fastest) modulation. Fully 44% of the area receiving the signal is forced to use the lowest (slowest) modulation.

An alternative way to achieve the same 5.2 Mb/s data rate would be to increase the bandwidth used by a factor of five while reducing the transmission power by a factor of 10. Not only would this achieve the same throughput, but it would generate less noise for other users of that spectrum, allowing wireless networks to be more closely spaced, which is essential to increasing the total wireless capacity.

Almost all modern networks use multiple modulations to improve total network efficiency. However, if even one station falls back to a lower modulation, it can affect the performance of all stations. For example, let's say that 10 stations are using a single access point to continuously receive messages of the same size. One station

uses a slow modulation, taking 10 times longer to transmit the same-sized message as the other 9 stations. If the stations take "fair turns," the station using the slow modulation will take as much time to receive a message as all the other stations combined. If such a fair schedule is used, the stations that are able to use a faster modulation will effectively run at the rate of the slowest station (Giles 2003).

Using the Right Network at the Right Time

Because bandwidth allocations are commonly fixed and it is not always possible to increase the amount of available spectrum, many wireless networks use increased transmission power to achieve higher data rates. As depicted in Figure 6, this allows a single cell to handle many users, albeit with varying degrees of efficiency and throughput, as indicated by the rings denoting different levels of performance.

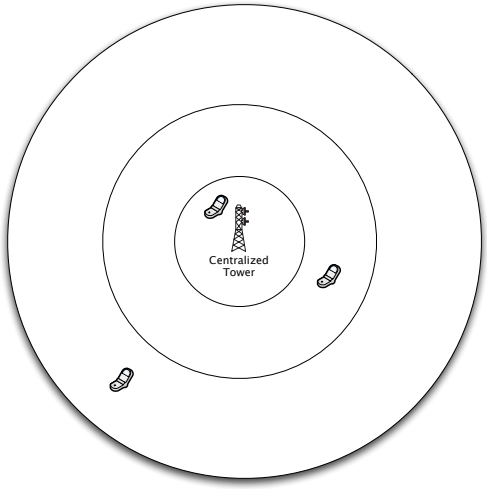


Figure 6. Single large cell.

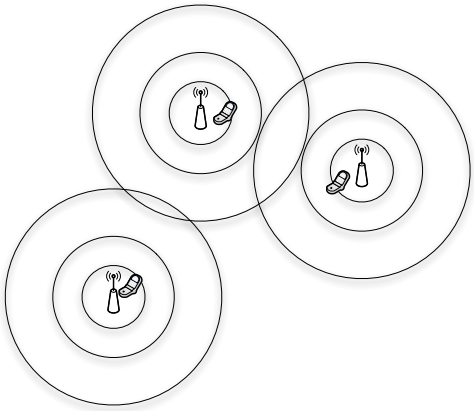


Figure 7. Multiple smaller cells.

An alternative is to use multiple smaller cells, lower-power microcells, femtocells, or distributed antennas (Chandrasekhar 2008), as depicted in Figure 7. (Femtocells are essentially small cellular radios that cover a single house or business and usually use the homeowner's wired Internet connection.) Each of these methods breaks a single large cell into a number of small cells. The primary difference between microcells, femtocells, and the like is the degree of planning and infrastructure

needed to deploy the multiple smaller radios. To avoid interference, a channel may be divided into subchannels that are used for adjacent cells. For example, cellular networks typically use patterns of different channels to avoid interference, reducing the spectrum (and peak data rate) available for any one channel.[12]

Figure 7 shows a situation where each receiver is able to use the high-rate modulations of the radio. As indicated earlier in Figure 5, there may be a 5-to-1 difference in performance among the different radio modulations. That difference, coupled with the fact that each smaller cell serves fewer users, can lead to large improvements in network performance. Another alternative to reducing interference is to share the channel over time (much like police radios do), but this requires cooperation or etiquettes among the network users. This is the mechanism used in most unlicensed devices, such as Wi-Fi and Bluetooth.

A combination of localized, in-building networks and wide-area networks leads to more total available bandwidth. Localized, low-power networks allow spectrum to be reused, allowing more total wireless bandwidth, while wide-area networks allow mobile devices to be used over a much wider area (Zander 2004). This is why cellular companies have focused on femtocells (Chandrasekhar 2008) and unlicensed mobile access[13] (UMA) as ways to increase the data rates available to their mobile devices. Some cellular companies, including T-Mobile in the U.S., allow phone calls to be placed using existing Wi-Fi networks.

A study by an industry group called the Femtocell Forum (Femtoforum 2010) stated:

> With interference mitigation techniques implemented, simulations show that femtocell deployments can enable very high capacity networks by providing between a 10 and 100 times increase in capacity with minimal deadzone

[12] The technical term for the number of channels is the *reuse factor*. The CDMA technology does not employ frequency reuse or channels, but the more common GSM frequency division does.

[13] UMA systems use unlicensed networks such as Wi-Fi for the same purpose as femtocells—connecting phones and other wireless devices to the Internet. A good description of UMA systems is available at http://www.smart-wi-fi.com.

impact and acceptable noise rise. Femtocells can also create a much better user experience by enabling substantially higher data rates than can be obtained with a macro network and net throughputs that will be ultimately limited by backhaul in most cases (over 20 Mbps in 5 MHz).

These findings are encouraging because femtocells were found to increase capacity even when using the same spectrum as local "macrocells." Although femtocell adoption has been slow, the market research firm iSuppli projects that worldwide shipments of femtocells will increase from 571,000 units in 2009 to 39.6 million units in 2013. Existing femtocells have primarily been targeted at consumers, but future growth is expected from deployment in commercial environments. In addition to enabling better spectrum reuse, which allows more high-speed data connections in existing spectrum bands, femtocells also reduce the cost of "backhaul" because each cell serves a limited number of users with an existing wired network that is often provided by a consumer or business.

A combination of localized, in-building networks and wide-area networks leads to more total available bandwidth.

Migrating users to local networks and away from wide-area networks generally improves the network performance of all users; however, an increased number of local networks (whether using femtocells or schemes such as UMA) may require extra spectrum, and greater density of those local networks may lead to interference, indicated by the overlapping rings in Figure 7 that show different performance levels. That interference is already the primary source of performance variability in home networks (Maier 2009). Interference can be reduced by increasing the available spectrum, coordinating the configuration of the independent networks (Akella 2005), using the right transmission power (FemtoForum2010), and using the right spectrum bands.

Using the Right Spectrum Bands

Depending on the density of transmitters or cells, there comes a point where increasing the power or the density of cells to improve the capacity of one network decreases the capacity of a neighboring network that uses the same spectrum band. The best power level or cell density depends both on the propagation characteristics of the spectrum band and the power used, as well as the density of users for that channel. For example, Kawade (2010) analyzed the available throughput of TVWS home networks using models of population density and building materials common to the United Kingdom.

Figure 8 is reproduced from that paper. Kawade sought to determine how the propagation of different spectrum bands affects wireless network performance for home users.

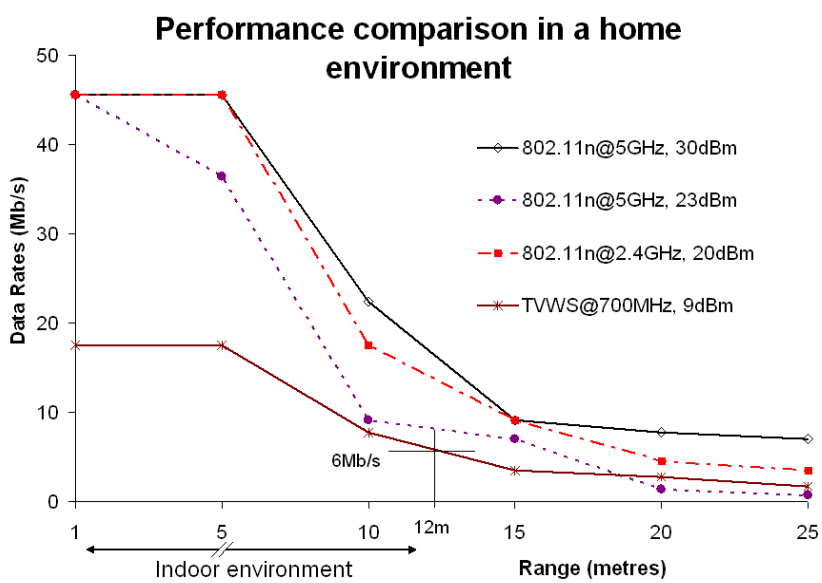


Figure 8. Propagation vs. spectrum range (Kawade 2010).

The analysis assumes that only a single 6 MHz channel of the TVWS spectrum can be used at once, versus the 20 MHz channels of the 2.4 GHz and 5 GHz spectrum. This limits the total available data rates of the TVWS to 18 Mb/s, while the other networks can achieve 48 Mb/s.

The Kawade study focuses more on the propagation differences than on the peak available bandwidth near the transmitter. Figure 8 shows the data rate for the different spectrum ranges at different power levels—the 700 MHz network achieves the same bandwidth as the 2.4GHz and 5GHz networks at longer ranges, even though it uses 25 times less power than networks at other frequencies and uses a third of the bandwidth of those networks. This shows that TVWS spectrum can enable new applications or make it easier to deploy a network in a house or business.

However, longer range is not always better—in environments with many different networks, such as cities, long-range networks are more likely to interfere with one another. Although the 5 GHz signal requires more power to cover the same area, it attenuates quickly enough that interference with neighbors is less likely. This shows that a mix of spectrum allocations or power levels for local networks is more useful than any one single band if the networks can effectively choose among the different bands.

Making Use of All Available Spectrum

Increasingly, consumer products are already using a combination of radios to meet networking demands—many computers and wireless routers use both the 2.4 GHz and 5 GHz bands. Although having multiple radios increases costs, the radios that operate in those bands are comparatively simple because a single network can use the full band. Indeed, the IEEE 802.11ac extension to Wi-Fi is designed to use 80-160 MHz, but there are no "holes" in that bandwidth. Those simple radios also can only operate in restricted ranges—one radio can operate in 2.4 GHz and one can operate in 5 GHz. By comparison, even in areas with no competing TV stations, the TV White Spaces contain gaps (as shown earlier in Figure 3). Using more than one channel of this spectrum requires multiple radios, novel radio architectures, or "band packing," wherein existing users are relocated to a contiguous part of the spectrum.

Exploiting additional spectrum bands (such as the 500-700 MHz TVWS, 900 MHz ISM band, or 3.65 GHz lightly licensed band) requires either additional radios or new radio designs. Fortunately, technology is rapidly advancing to address both of these issues. One example is a wideband radio (Hasan 2010) that can operate at anywhere from 100 MHz to 2.5 GHz. Our research group is also working on a wideband radio that can operate four distinct radios, each tunable from 100 MHz to 7 GHz (Grunwald 2010). Similar handheld radios have been developed by the U.S. Defense Advanced Research Projects Agency (DARPA). The benefit of these radio designs is that each radio can use any spectrum in those ranges. McCloskey (2010) is taking another approach based on a radio design that can use the entire 186 MHz of the TVWS bandwidth at once, allowing a very high-speed wireless network.

Increasingly, radios are being designed to use noncontiguous chunks of spectrum. For example, the Wireless@Colorado research group is working to develop noncontiguous OFDM radios (Dutta 2010). Figure 9 shows a measurement of that radio using different spectrum (shown on the horizontal axis) over time (the vertical axis). Red indicates the spectrum being used, and green indicates unused spectrum. The spectrogram shows that the spectrum being used to transmit a message can vary from one microsecond to the next, deftly scheduling around the primary user that is presumably resident in the green sections of the plot. Radio designs such as these allow larger sections of "cluttered" spectrum (such as TVWS) to be used by "notching"—not transmitting in regions used for other purposes (such as TV stations or wireless microphones).

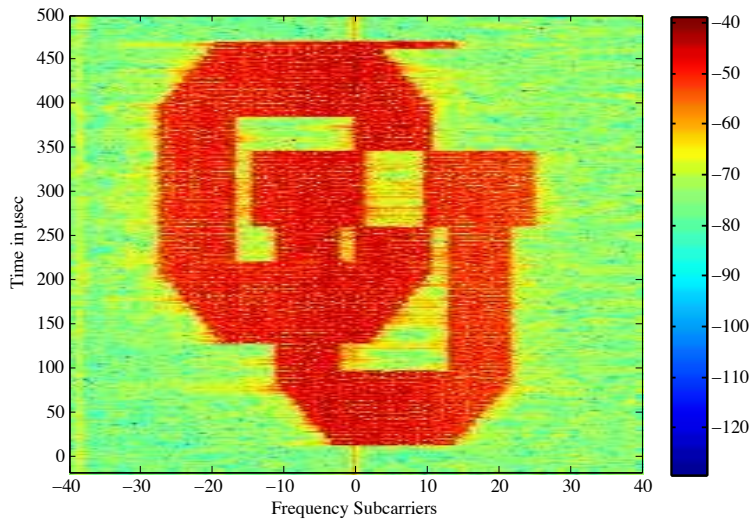


Figure 9. A radio system that uses noncontiguous spectrum.

These radio designs, which combine multiple radios, radios that operate over large swaths of spectrum, and radios that can nimbly avoid interference with incumbent devices or users, will have a large impact on wireless networking. Assuming sufficiently flexible spectrum policies, future radios will be able to support higher-bandwidth networks that adapt to adjacent local networks and reduce interference with other sources by using more spectrum at lower power.

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New Approaches to Spectrum Management

How much spectrum is needed for new wireless applications? What spectrum should be used? The prior discussion highlights some technical properties of spectrum, radios, and system architecture that should be considered in formulating spectrum management policy. The following are several considerations arising from the technical properties described in the previous section:

- A mix of very local (~100 meter connectivity), local (~1 kilometer), and cellular (~10 kilometer) networks is needed to achieve the highest network performance while retaining mobility from wireless data networks.
- Large, contiguous spectrum blocks are better for high-bandwidth wireless networks using existing technology.
- It is useful to have spectrum with high propagation (e.g., TVWS) for wide-area applications and spectrum with poor propagation (e.g., 5 GHz) for localized high-bandwidth networks in dense environments.
- Operating radios using low power and wider spectrum improves the available wireless network bandwidth.

Many spectrum policies are based on national interest. Some are obvious, such as priority communication access for police, fire, first responders, and emergency personnel when needed. Other policy priorities include setting aside specific bands for scientific monitoring or measurement, such as for radio telescopes, which are very sensitive to interference from wireless devices and need to monitor specific frequencies because of the stellar objects they are observing. Additional considerations include fostering the development of nationwide communication systems that promote commercial and societal well being.

In the recently published U.S. National Broadband Plan, the FCC proposed eventually freeing up 500 MHz of spectrum, including 300 MHz of spectrum within the next 5 years. Most of this spectrum, including the proposed unlicensed spectrum, would be available nationwide or at least through large parts of the nation. New mechanisms such as software-defined cognitive radios, wide-spectrum radios, and online spectrum databases can greatly increase the potential for wireless networks to meet specific policy goals. At their core, these technologies work by managing interference and making better use of spectrum. They offer greater flexibility

Greater flexibility can be had by moving beyond traditional spectrum allocation and even beyond the database methods being adopted as part of the TVWS transition.

and the opportunity to move beyond traditional spectrum allocation and even beyond the database methods being adopted in the U.S. (FCC 2010c) and the UK (Ofcom 2010) as part of the TVWS transition.

Spectrum Databases

Online spectrum databases are systems that record the location of transmitters. Coupled with propagation models, they can indicate the location of possible receivers for the transmitted signals. The design of proposed systems in the U.S. (FCC 2010c) and the UK (Ofcom 2010) are similar. Those databases operate at time scales of minutes or hours—much faster than spectrum regulation, but still much slower than is possible when devices are connected to the Internet.

Moreover, existing spectrum databases document transmitters but not receivers. This is appropriate for systems with millions of receivers, such as TVs, but other systems, such as the grandfathered RADAR systems in the 3.65 GHz spectrum, are clearly easier to enumerate and record in a spectrum database. Between these two examples are systems such as satellite downlink stations that use considerable bandwidth at a limited number of locations across the country. For wireless networks that are local (~100m-1km), significant spectrum is likely to be available in some locations.

Spectrum Coordination

Spectrum allocation can also be coordinated through the use of tightly synchronized and highly accurate clocks. If a specific spectrum band is needed in one locale at a specific (predictable or at least scheduled) time, secondary users of that band could migrate to other bands or simply curtail use for short periods of time. For example, existing policies limit use of radio devices in specific bands to allow radio telescopes to explore deep space. If radios using those bands could be controlled through a real-time control system, it would be possible to temporarily quiet specific radios to ensure that radio telescopes or deep-space communication systems could operate without interference. Those radios could be disabled for a fraction of every second

rather than disallowed or excluded from those bands. The earth observation and radio science community has studied such methods to ensure future success of radio observation (Cohen 2010).

New Technologies That Enable New Policies

Because of these rapid technological changes, conversations about whether spectrum should be licensed or unlicensed fall short of the mark. The real question should be how we can make the most use of otherwise underutilized spectrum. Licensed and unlicensed mechanisms are ways of prioritizing specific applications and simplifying conflicts between them over long periods of time. Some spectrum should be unlicensed to ensure that sufficient fallback spectrum exists, but using extensions of the existing database methods would allow that spectrum to be managed much more dynamically.

Using extensions of the existing database methods would allow that spectrum to be managed much more dynamically.

Clearly, not all uses of wireless spectrum can be managed using an Internet-managed infrastructure, and the subject is open to both debate and research activities at universities around the world (NSF 2010). Some devices, such as RADAR navigation, radio telescopes, GPS, satellite uplinks and downlinks, and portable devices for operation in isolated regions, require substantial investments, exploit critical properties of specific spectrum bands, or are not constantly connected to a database or Internet-managed control system. However, devices that seek to use that spectrum can often be controlled in a way that avoids conflicts with those systems.

In addition to using more of the available spectrum, it is also important to understand that Internet-managed data networks can dynamically control their transmission power, allowing spectrum bands to support more efficient modulation and higher spectral efficiency. Recall that Figure 8 shows that an increase in the

transmission power of a device using 5 GHz spectrum from 200 milliwatts to 1 watt (a five-fold increase), results in significant improvement in throughput. Current 802.11 Wi-Fi networks are limited to 100 milliwatts for 2.4GHz and 1 watt for 5GHz in the United States and even less in other countries. Efforts are already under way to reduce interference and allow better use of the 5GHz band through a spectrum database (Knapp 2010); allowing an Internet-managed power increase would increase coverage and efficiency.

What spectrum could be used for new-generation data networks? The answer depends on how much data bandwidth is needed. For some applications, such as environmental monitoring, it is more important to have a small amount of low-frequency spectrum rather than more high-frequency spectrum because of the reduced power and enhanced propagation possible at lower frequencies. These applications, such as water monitoring or stream gauging, already make use of some federal spectrum (such as at 412.5MHz). Through a coordinated Internet-managed and spectrum-sensing strategy, these very short, very infrequent intermittent narrow-band applications could make use of spectrum adjacent to the TVWS that is currently used by amateur radio users and licensed private land mobile spectrum such as that found in the 30 MHz range as well as in the TVWS.

Finding larger blocks of spectrum for campus networks or enhanced home networks that may cover 1-4 kilometer ranges is more complex because those applications typically require more bandwidth. Figure 10 summarizes U.S. spectrum occupancy measurements made in a study funded by the National Science Foundation (McHenry 2004). Similar studies were conducted earlier (Sanders 1995), later (Shared Spectrum 2010, Strickling 2009), in Europe (Valenta 2010, Wellens 2009), and at other locations worldwide.

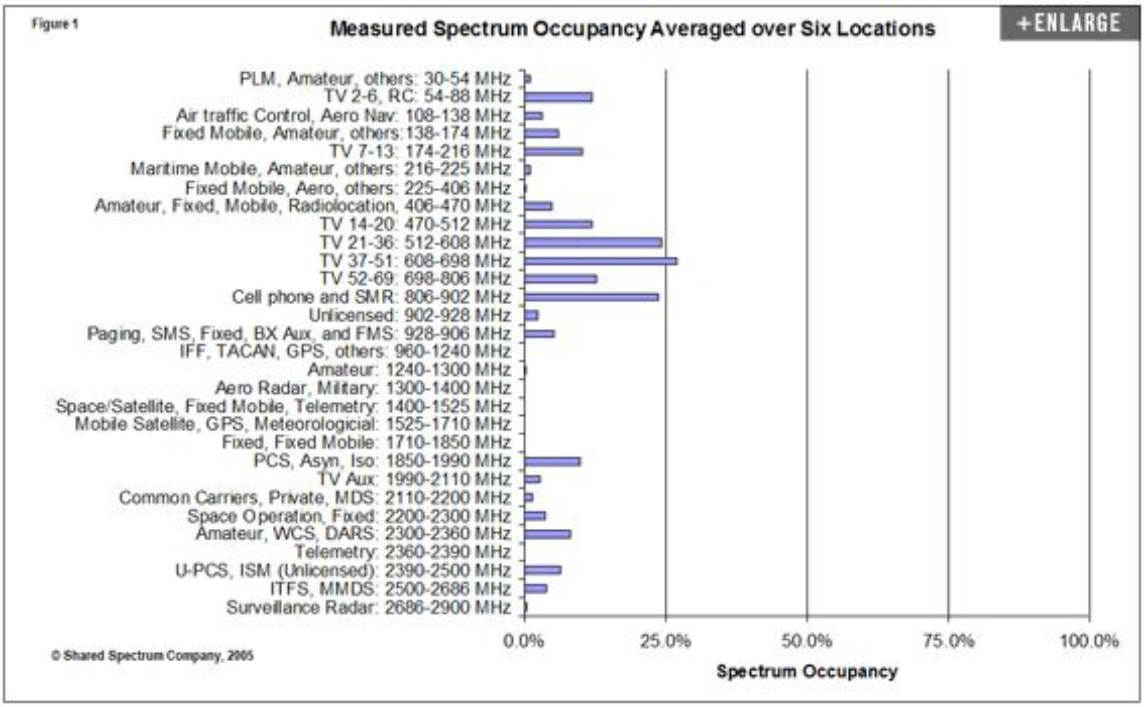

Figure 10. Summary of U.S. spectrum occupancy measurements in the McHenry study (2004).

In McHenry, measurements were taken over multiple days at six locations ranging from rural to metropolitan (New York City). The average occupancy over all of the locations was 5.2%. The maximum occupancy was 13.1% (in New York City), and the minimum occupancy was 1% at the National Radio Astronomy Observatory at Green Bank, W. Virginia. Some uses of spectrum would not be indicated in these measurements because they would be used only in specific locations or perhaps for specific sporadic events. However, that is precisely why those spectrum bands may be usable for other purposes at other times.

Some researchers (Anderson 2008) argue that some spectrum uses have signals that are too faint to be detected using McHenry's methods. Some signals (such as radio astronomy bands or weak power satellite bands) require special treatment because purely measurement-based analysis does not address their uses. However, there is broad consensus that much of the licensed spectrum is not being actively used over long periods of time, and these studies can guide when secondary uses of that spectrum are possible. Repurposing underutilized spectrum benefits traditional

licensed broadband uses because it reduces the number of cell towers that need to be deployed (FCC 2010). It also benefits more localized data networks used by consumers, commercial applications, and the interconnected devices that typically use unlicensed spectrum (Thanki 2009).

Determining whether spectrum should be used for high-power cellular networks or more decentralized networks deployed by consumers, companies, and governments is a difficult question and depends on the evolution of technology over time. Studies have shown that mobile phones are most often used in homes or workplaces, where localized networks based on femtocells, UMA, or other technology can be used. Moving to an approach that uses local networks in conjunction with wide-area networks would allow more efficient use of available spectrum (Zander 2004). A flexible mechanism such as Internet-managed radios would allow policy to evolve over time.

Because of their rapid turnover, networks that use unlicensed spectrum are most likely to adopt novel spectrum management techniques. Unlicensed devices have long led the way in new wireless innovations. Because these devices currently use unlicensed spectrum, the easiest transition would be to identify underutilized spectrum bands that abut current unlicensed allocations; however, these high-speed networks can also benefit from new spectrum both for higher data rates and the ability to trade off different spectrum bands for different tasks and circumstances.

Given the benefits of using wide bands for high-speed networking, the spectrum bands that make sense for Internet-managed wireless networks include:

- The 420-450 MHz band, currently used for a combination of public and governmental land mobile, amateur, and federal applications, as well as private land mobile radio.
- In addition to the recently allocated UHF TVWS spectrum (portions of 54-72, 76-88, 174-216, 470-512, 512-608 MHz), some of the additional spectrum that arises from consolidation of existing TV channels. This will provide more usable and contiguous spectrum, which should be used for a combination of high-speed local, campus-level, and rural access networks that use spectrum

sensing and sharing for consumer, corporate, and carrier networks.

- Portions of the 960-1215 MHz radio navigation and amateur bands, because of their proximity to the 900 MHz ISM band and TVWS.
- Controlled use of the 2360-2400 and the 2500-2655 MHz bands, because of their proximity to the existing 2400 MHz ISM band.
- Controlled use of the 2900-3100 MHz and 3550-3650 MHz bands, because of their proximity to the lightly licensed 3650-3700 MHz band.

These examples simply illustrate the types and amounts of spectrum needed. Actual allocation decisions would need to consider whether the secondary users could successfully use the spectrum (such as the 3.65 MHz band), the impact on incumbent users, competing interests, and harmony with international spectrum plans. The use of much of that spectrum would normally raise objections from many existing users, but Internet-managed radio networks can accommodate new uses while sharing the spectrum with incumbent users

Network carriers have long argued that only licensed spectrum provides the guaranteed performance needed for real-time voice applications, but some carriers have used consumer Wi-Fi networks for voice traffic. Real-time voice and video would use only a fraction of the bandwidth enabled by new spectrum allocations. Using a combination of Internet-managed policies and spectrum-sharing etiquettes would allow large blocks of spectrum, such as that arising from any TVWS consolidation, to be used in multiple ways to benefit consumers.

Campus-level networks, rural access networks, and remote telemetry applications such as video surveillance all benefit from lower-frequency spectrum such as the TVWS (Bahl 2009). However, given the variable amount of TVWS available, additional spectrum would be needed, and the specific spectrum bands would vary widely in different regions of the world. Various spectrum studies have shown that the 902-928 MHz ISM band is lightly used, largely due to interference from devices such as baby monitors that have poor network etiquette. Having significantly more

spectrum available nearby would increase the utility of that band for campus-scale applications.[14]

The 960-1215 MHz band is used for numerous RADAR and navigation tasks, including one GPS channel. Proposals have been made to repurpose 155 MHz of that band for land mobile radio as the initial uses are superseded by new technologies. Just as the TVWS spectrum has good propagation, the 960-1215 MHz band would have good characteristics both for wide-area networks and for low-power in-building networks. Even if that band were primarily available for land mobile radio systems (which include public service systems as well as systems used to communicate within a warehouse or worksite, for example), simply registering where and when those systems are deploying would allow the band to be used for other applications elsewhere.

The 2360-2400 MHz band directly abuts the existing 2400 MHz ISM band. Likewise, the 2495-2600 MHz Broadband Radio Service (BRS) and Educational Broadband Services (EBS) band abuts the ISM band. That band was originally used for microwave distribution of multimedia by educational institutions and for some fixed wireless applications. Much of the EBS band has been underutilized, and existing users must demonstrate "sufficient academic use" of those bands by May 2011 or risk losing their licenses. WiMAX network providers such as Sprint and Clearwire are actively licensing the 2.5 GHz band, and LTE networks are also planned in that spectrum. Those cellular networks may not use the full band in all locations, particularly in rural environments where commercial high-speed data networks may not be profitable. The ability to use the additional bandwidth at high power would be useful for ranchers, farmers, consumers, and businesses. Having the band abut the well-used ISM band would require only slight modification of existing

[14] Early 802.11 wireless networks used the 902-928 MHz ISM band, but later networks focused on 2.4 GHz and 5 GHz because of the increased bandwidth and decreased interference. However, companies such as xG Communications have recently demonstrated that cognitive radio technologies can use the 902-928 MHz ISM band for an unlicensed wide-area cellular network. For more information, see the October 2010 issues of the *MIT Technology Review* (http://www.technologyreview.com/communications/26581/?p1=A4).

antennas and radio designs, reducing the cost of a network that may be available only in certain locations.

> Instead of managing spectrum, we should focus on managing interference.

Likewise, maritime navigation and military systems make use of the 2900-3100MHz region. These bands could be used for low-power home networks in some locations, much like 3650-3700 MHz band. In October 2010, the U.S. NTIA ordered that the 3550-3650 MHz band be converted from RADAR applications to wireless data. Having a broad section of spectrum from 2900-3700 MHz simplifies antenna and radio system design. The use of any one of these spectrum bands is similar to the use of the 3.65 GHz band mentioned earlier—the spectrum is not available in all locations, power levels may need to be low in other locations, and it may not be available at all times. However, future radio networks can be flexible enough to adapt to the available spectrum at a specific time, place, and power level.

Conclusion

Wireless networks have become essential to businesses, consumers, and governments. They will become increasingly important as the Internet of Things develops, connecting people to all of the devices and information in their environment. The last 20 years have brought amazing technological innovations that have revolutionized how people communicate. Some of that innovation has occurred using licensed or application-specific spectrum allocation, but significant innovation also has happened using a limited amount of unlicensed spectrum. Future innovation will depend on expansion of the total wireless bandwidth available to people and machines and on the ubiquity of high-speed networks.

Due to the physics of radio, meeting the future need for high-speed wireless networks will require an increased number of shorter-range networks to

complement wide-area networks. Providing spectrum for those networks and coordinating their interactions will require automated solutions.

Radio technologies currently under development, including software-defined cognitive radios that can operate across vast sections of spectrum, can meet those needs for both capacity and ubiquity. But making this happen will require rethinking how spectrum resources are managed. Instead of managing spectrum, we should focus on managing interference.

Spectrum regulations take a long time to change. Governments, research labs, and companies should fund prototype systems to assess the feasibility of novel techniques such as Internet-managed spectrum. Most importantly, regulators should consider how technology being developed today will affect spectrum needs and uses in the years to come.

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