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The Case for Unlicensed Spectrum

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I. Introduction

1. The introduction in the past few years of mobile devices such as the iPhone, iPad and Android phones has led to vast increases in the use of wireless data communications, and most forecasters anticipate that this trend will continue. This development raises challenging spectrum policy questions, including how much spectrum to allocate to these new uses, whether and how to re-allocate spectrum from other private and public uses, and what the budgetary impacts of alternative decisions might be. The answers to these questions also interact in fundamental ways with questions about whether and why spectrum bandwidth should be managed differently than any other economic resource.

2. In the US, the most common approach to managing radio spectrum for commercial non-governmental use has been to assign licenses that give the licensee exclusive rights to a particular band of spectrum for a set period of time. The development of spectrum license auctions in the 1990s helped to pave the way for the growth of the mobile phone industry while generating billions in auction revenues for national governments. Yet some of the most valuable and important innovations in wireless communication, in particular the development of Wi-Fi, have taken place on bands of spectrum for which no exclusive licenses were issued. In this paper, we follow common practice in calling such bands and their uses and users "unlicensed" (even though non-exclusive licenses may sometimes be used in its management).[1]

3. Why has unlicensed spectrum been such an effective catalyst for innovation? Should the United States and other countries leave additional spectrum unlicensed, expecting to encourage still more innovation? Or is it better to grant exclusive licenses for all new spectrum bandwidth to capture the stewardship benefits of private control? Is it costly, in terms of auction revenues, to set aside spectrum for unlicensed uses?[2]

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[1] Mark M. Bykowsky, William W. Sharkey and Mark A. Olson, "A Market-based Approach to Establishing Licensing Rules: Licensed Versus Unlicensed Use of Spectrum," Federal Communications Commission / Office of Strategic Planning and Policy Analysis Working Paper No. 43 (2008).

[2] Kenneth R. Carter, "Policy Lessons From Personal Communications Services: Licensed Vs. Unlicensed

4. In this report, we frame the problem of managing spectrum as one about the allocation and governance of an economic resource. While selling exclusive licenses to radio spectrum has been a valuable tool for eliminating conflicting uses and encouraging related investments, it has also contributed to concentrated market structures in wireless telephony and created barriers to entry and innovation. Leaving portions of the radio spectrum unlicensed has created multiple benefits, including encouraging the development of complementary technologies that enhance the effectiveness of devices that use licensed spectrum, triggering the development of alternative technologies that compete with licensed uses, and promoting innovative business models and technologies that have brought unexpected benefits.

5. There is considerable evidence that unlicensed spectrum has huge economic value. Recent past estimates, which already look too conservative, place the value created by current applications of unlicensed spectrum at $16-37 billion dollars a year in the United States alone.[3] However, the primary benefits of unlicensed spectrum may well come from innovations that cannot yet be foreseen. The reason, as we discuss below, is that unlicensed spectrum is an enabling resource. It provides a platform for innovation upon which innovators may face lower barriers to bringing wireless products to market, because they are freed from the need to negotiate with exclusive license holders. Indeed, allocating a mix of licensed and unlicensed spectrum is attractive precisely because the two approaches have diverse advantages in terms of triggering investment and innovation.[4]

6. It is sometimes argued that a drawback of leaving bands of spectrum unlicensed is that governments might have to sacrifice the revenue that they could obtain by auctioning spectrum licenses. But it is not at all certain that leaving some spectrum unlicensed would reduce revenue; it might even increase it. The reason is that leaving some spectrum

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Spectrum Access," *CommLaw Conspectus* 93 (2006).

[3] Richard Thanki, "The Economic Value Generated by Current and Future Allocations of Unlicensed Spectrum," Final Report, Perspective Associates (2009): 4.

[4] Kenneth R. Carter, "3G or not 3G: The WiFi Walled Garden," in *Mobile Media: Content and Services for Wireless Communications*, ed. Eli. M. Noam et al. (Psychology Press 2006).

unlicensed reduces the supply of licensed spectrum and, as described later, encourages the development of complementary, demand-enhancing services that raise the economic value of the licensed spectrum networks.[5] These effects are likely to add significantly to government revenue and could result in higher auction revenue than if all new bandwidth were sold under exclusive licenses. And, even if leaving bands unlicensed were to imply some sacrifice of revenues, that could still be justified if the economic benefit enjoyed by consumers were sufficiently large. Indeed, the types of auctions used to allocate spectrum for licensed use favor putting additional spectrum into the hands of operators with considerable market power, and do not necessarily lead to the lowest consumer prices.

7. One recent proposal is that auctions might serve as an effective mechanism to determine the allocation of licensed vs. unlicensed spectrum.[6] The idea is that potential beneficiaries of unlicensed spectrum would submit bids, which then would be aggregated and compete with bids for licensed spectrum. The proposal is akin to asking users of public parks to bid against developers to decide how land is to be allocated. What makes such ideas untenable is that too many of the beneficiaries – future innovators and consumers in the case of unlicensed spectrum – are difficult or impossible to identify at the time of the auction. As in the case of public parks, ignorance about who the future individual users will be or what their values will be cannot justify overlooking those users and values, as would surely happen in such an auction.

8. The remainder of this report proceeds as follows. Section II discusses the history of spectrum management and unlicensed spectrum uses, particularly the development of Wi-Fi. Section III provides a conceptual framework, based in economic theory, for assessing different approaches to spectrum allocation, and uses that to evaluate the relative merits and roles of property rights versus a regulated commons approach to

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[5] According to our interviews with phone company executives, the growth of demand in mobile data services is driven in part by consumers' desire to extend the wireless services they have at home and in the office to be available at remote locations as well. This happens in much the same way that users of wired telephone services became the first demanders of mobile phone services. And, the ability of licensed networks to offload traffic onto unlicensed spectrum enhances those networks' capacity to provide high quality, nearly ubiquitous coverage.

[6] Bykowsky, Sharkey and Olson, "Licensed vs. Unlicensed Use of Spectrum," 2.

governing the uses of radio spectrum. Section IV describes the economic value of unlicensed spectrum, both in terms of its current uses and as a platform for future innovations. Section V discusses the policy implications of our analysis, and how one might approach the problem of deciding what spectrum to leave unlicensed and how to regulate its uses. Section VI concludes.

II. History and Uses of Unlicensed Spectrum

Radio Spectrum and Spectrum Management

9. *Radio spectrum* is the range of electromagnetic frequencies from approximately 30 kHz to 300 GHz that can be used for radio communications.[7] In addition to supporting military and public safety applications, it is used in a wide variety of other ways. These include broadcast television and radio; navigation and aviation communications, radar, and GPS devices; computer and networking applications (e.g. Wi-Fi and Bluetooth); mobile phones; and other wireless consumer electronics such as wireless heart rate monitors, microwave ovens, baby monitors, two-way radios, and garage door openers.

10. Similar applications are typically allocated in *bands*, which are sections of the spectrum designated for specific services. For example, the band from 4.053MHz to 4.438 is used for maritime mobile communications, the band between 512MHz and 608MHz is used for television channels 21-36, and the band from 1628.5MHz to 1660MHz is used for mobile satellites. Some of these bands are further subdivided into smaller blocks that are assigned to particular licensees (in these examples, broadcasters and mobile telephone network operators).

11. In most countries, radio spectrum is regulated and managed by the government, which decides how to allocate bands to different applications. In the United States, spectrum management dates to the Radio Act of 1912. The Act allowed private radio operators to operate in specific frequency bands if they obtained a license from the Commerce Department. A subsequent federal court ruling, however, held that the

[7] U.S. Department of Justice: Office of Justice Programs, "Radio Spectrum," *IN Short: Toward Criminal Justice Solutions*, National Institute of Justice (2006).

Secretary of Commerce had no legal basis to restrict the number of radio licenses, leading to episodes in which broadcasters purposefully increased power to drown out each others' signals. [8] Congress then passed the Radio Act of 1927, which assigned most responsibility for regulating radio spectrum to a new Federal Radio Commission, and in 1934 the Communications Act, which established the Federal Communications Commission (FCC).

12. Currently the FCC, an independent regulatory agency, administers spectrum designated for non-federal use (state, local government, commercial, and private), while the National Telecommunications and Information Administration, in the Department of Commerce, administers spectrum designated for federal use (e.g., by the Army, the FBI, and the Federal Aviation Administration).

Licensed and Unlicensed Spectrum

13. Spectrum used by private entities can be regulated in a number of ways. Following a common, if informal, practice, we use the term *licensed spectrum* to refer to frequency bands that can be used *exclusively* by licensed operators for a set time period. A license typically defines the frequency ranges and geographic locations in which the spectrum can be utilized, the maximum power level to be transmitted, and other provisions. Licensees can expect to be protected from interference that would disrupt the normal operation within their licensed service areas. TV broadcasting, commercial broadcast radio, and cellular voice and data services are examples of applications that utilize licensed spectrum.

14. Until 1982, the FCC held administrative hearings to allocate cellular licenses. Prospective users would send applications to the FCC, and the FCC would attempt to identify which applicant would offer the greatest public benefit. In 1982, with a growing backlog of license applications, Congress authorized a lottery system, but this proved to an inefficient allocation mechanism. In 1993 Congress authorized the use of auctions, and

[8] Barry Keating, "Economic dimensions of telecommunications access," *International Journal of Social Economics* 28 (2001): 885-6.

the first US spectrum auctions took place in 1994.[9] The FCC auctions are credited with enabling new wireless entrants to establish national presence by lowering the transaction costs of obtaining sufficient spectrum. The quality and quantity of cellular services has increased rapidly since that time. Through the end of 2008, spectrum auctions also had raised $52 billion in revenue for the US government. Auctions are now the primary means of allocating radio spectrum in much of the world.[10]

15. We use the term *unlicensed spectrum* to refer to the frequency bands for which no exclusive licenses are granted and on which unregistered users potentially may operate wireless devices without specific user or device authorizations.[11] Users of these bands do not enjoy exclusivity and can be subject to interference from other users, although regulators typically restrict the transmission power in these bands to limit interference.[12] The use of devices on unlicensed spectrum was authorized first by the FCC in 1938, at which point devices were approved on a case-by-case regulatory process. The initial qualifying devices included wireless record players, carrier current communication systems (transmission of radio signals over power lines), and remote control operated devices. Over time, provisions were made to permit the operation of wireless microphones, garage door openers, various remote controls, telemetry systems, field disturbance sensors (used, for example, in antitheft systems), auditory assistance devices, security alarms, cordless telephones and other devices.[13]

[9] Auctions as a means of allocating radio spectrum were first espoused by Ronald Coase in his seminal 1959 paper, *The Federal Communications Commission*, but his proposals were not well received at the FCC and would not take place for over 30 years after the publication of his paper. See John McMillan, "*Why Auction the Spectrum?"* (1994), for the arguments in favor of an auction process.

[10] Thomas W. Hazlett, David Porter and Vernon L. Smith, "Radio Spectrum and the Disruptive Clarity of Ronald Coase," George Mason Law & Economics Research Paper No. 10-18 (2010): 1.

[11] Kenneth R. Carter, Ahmed Lahjouji and Neal McNeil, "Unlicensed and Unshackled: A Joint OSP-OET White Paper on Unlicensed Devices and Their Regulatory Issues," Federal Communications Commission / Office of Strategic Planning and Policy Analysis Working Paper No. 39 (2003): 4.

[12] Different countries have different rules regarding the use of unlicensed spectrum – for example, in the UK the power restrictions for the 2.14GHz frequency is about 10% lower than in the US.

[13] Carter, Lahjouji and McNeil, "Unlicensed and Unshackled," 4.

16. In 1985, the FCC eliminated the process of regulatory case-by-case approval and instead set forth technical criteria to which new unlicensed devices needed to adhere.[14] The FCC also opened up new spectrum for unlicensed use at 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz. The release of the new unlicensed bands facilitated the introduction of Bluetooth and Wi-Fi devices that have become ubiquitous.[15] These technologies use spread spectrum techniques, originally developed by the military, which provide high immunity to interference noise compared to conventional techniques and allow more devices to operate in a given frequency band, thus promoting more efficient spectrum use. Spread spectrum techniques contrast with the older approach of assigning a single, well-defined frequency to each sender-receiver pair.[16]

17. Over the last twenty-five years, the FCC has made further bands available for unlicensed use. The 59-64 GHz band, for instance, which facilitates high bandwidth wireless communications between electronic devices over short distances, was made available in 1995.[17] In the U.S., as of the end of 2008, approximately 955 MHz are allocated to unlicensed uses below 6GHz.[18] Some of the most commonly-used unlicensed bands are at 900MHz, 2.4GHz, 5.2/5.3/5.8GHz, 24GHz, and above 60GHz.

18. Much of the debate regarding further allocation of unlicensed spectrum focuses on frequencies below 1000 MHz. Radio waves at these frequencies travel further and penetrate walls more easily for a given power level than those at higher frequencies. These characteristics make many of these frequencies especially useful in both licensed and unlicensed applications, from 4G mobile services to long-range Wi-Fi.

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[14] Thomas W. Hazlett and Evan T. Leo, "The Case for Liberal Spectrum Licenses: A Technical and Economic Perspective," George Mason University Law and Economics Research Paper Series 10-19 (2010): 6.

[15] Until the 1990s, cordless phones were the highest-selling unlicensed devices. In 1997, cordless phone sales surpassed the sales of corded phones for the first time. By 2002, the penetration of cordless phones exceeded 80% of households. [Michael Marcus, et al., "Report of the Unlicensed Devices and Experimental Licenses Working Group," Federal Communications Commission Spectrum Policy Task Force (2002): 6].

[16] *Economist Technology Quarterly*, "A brief history of Wi-Fi", June 10, 2004.

[17] Carter, Lahjouji and McNeil, "Unlicensed and Unshackled," 8.

[18] Hazlett and Leo, "The Case for Liberal Spectrum Licenses," 7.

Technologies and Standards for Unlicensed Spectrum Use

19. The use of unlicensed spectrum in different bands relies on transmission standards to which devices conform. Some examples of these standards as well as the products they enable are described below.

20. Wireless LANs and Wi-Fi. A Wireless Local Area Network (WLAN) is a network that connects two or more electronic devices in a limited area using radio spectrum. Users of WLAN enjoy the ability to move around within the coverage area while being connected to the network. Unlicensed devices can be certified as "Wi-Fi" devices by the Wi-Fi Alliance if they conform to "IEEE 802.11," which is a set of standards for implementing WLAN computer communications in the 2.4, 3.6, and 5GHz frequency bands. This certification assures compatibility and interoperability between different wireless devices. Wi-Fi-enabled devices include computers, mobile phones, electronic tablets, and MP3 players.

21. WPANs and Bluetooth. Wireless Personal Area Networks (WPANs) are computer networks designed for communication between electronic devices within close proximity of each other. The most widely adopted form of WPAN is *Bluetooth*, a technology standard that is implemented in a wide variety of applications such as mobile phone headsets, PC networking, PC peripherals such as mice, keyboards and printers, medical equipment, traffic control devices, barcode scanners, and credit card payment machines.[19] ZigBee and WirelessHART are two other forms of WPANs. Devices using these standards can transmit up to a distance of 75 meters at a maximum transfer rate of 250 kbps. Applications include smart energy control systems in homes, smart utility meters, wireless monitoring devices in healthcare, and remote controls.[20]

22. WirelessHD and WiGig. WirelessHD and WiGig use the 60 GHz unlicensed band to achieve multi-gigabit data transfer over the range of a few meters. Devices using this spectrum need to have a clear line of sight between each other as radio waves at this

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[19] Bob Heile, "Wireless PANs tie data into home," *Electronic Engineering Times*, February 14, 2000, 3.

[20] Peter Cleaveland, "Sorting Out Wireless Standards for Smart Valves and Actuators," *Valve Magazine*, January 5, 2010, 3.

frequency have difficulties in penetrating walls and other objects. Applications of these technologies include home entertainment, data networking, and wireless docking.[21]

23. RFID. Radio frequency identification (RFID) is the use of a small chip or tag that is attached to products, animals and vehicles or embedded in cards for the purposes of identification or tracking. Applications of RFID include supply chain management, asset tracking, medical applications, sports event timing, tracking of livestock, contactless credit card payments, and payments for highway tolls and transit fares. RFID devices use unlicensed bands at frequencies below 100 MHz.[22]

The Story of Wi-Fi

24. The story of Wi-Fi, a WLAN technology standard that ensures connectivity and compatibility between devices, is the most important example to date of the enormous benefits unleashed by unlicensed spectrum. Just as cellular networks allow the same frequencies to be reused in different geographic cells, Wi-Fi technology allows multiple low-power devices to make intensive use of spectrum by reusing spectrum many times, but compared to cellular networks, its much smaller transmission radius allows much more reuse.

25. The Wi-Fi story also illustrates the potential benefits to using spectrum to create a technology platform that encourages decentralized innovation in devices and business models. Wi-Fi has its origins in the 1985 decision by the FCC to open up the 900MHz, 2.4 GHz and 5.8 GHz frequency bands for unlicensed use for communications purposes. Then widely regarded as “garbage bands”, these bands previously had limited uses for unlicensed devices such as microwave ovens. The Wi-Fi standard took advantage of spread spectrum technology, which – as described above – permits more devices to operate on a given frequency band while minimizing interference.

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[21] *BusinessWire*, “SiBEAM Showcases Growing Ecosystem of 60GHz-Based WirelessHD Products and Reveals Next Generation Solutions at CES 2011,” January 6, 2011.

[22] Simon Holloway, “RFID: An Introduction,” MSDN White Paper (2006): 18-19.

26. Early WLANs used proprietary equipment and technologies, which implied that equipment from one vendor could not communicate with equipment from other vendors. In the late 1980s, vendors collaborated with the Institute of Electrical and Electronics Engineers (IEEE) in an attempt to establish a common standard. The basic specifications of the 802.11 standard were agreed upon in 1997. The original standard specified a data transfer rate of two megabits per second, using either of two spread-spectrum technologies. More recent standards such as 802.11g and 802.11n, which improve on 802.11a and 802.11b, provide faster data transfer speeds and more resistance to interference.[23]

27. Apple introduced the first Wi-Fi capable laptop in July 1999. Within a few years, nearly all laptop computers were sold with built-in Wi-Fi capability and Wi-Fi access points appeared across college campuses, coffee shops, airports, and private homes as a means of connecting computers to the internet and to other computers and devices. Commercial vendors also sell access to the internet by offering Wi-Fi hotspots. AT&T alone has over 20,000 hotspots in the United Sates and 80,000 worldwide,[24] and had over 220 million connections to these hotspots in the first three quarters of 2010.[25]

28. Today, Wi-Fi-certified devices include personal computers, printers, video game consoles, streaming devices, security cameras, medical devices, MP3 players, digital cameras, smartphones, and tablets. Worldwide, about 200 million households use Wi-Fi networks and there are about 750,000 Wi-Fi hotspots. About 800 million new Wi-Fi devices are sold every year.[26] Currently, more than 58 percent of Wi-Fi devices are

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[23] Kevin J. Negus and Al Petrick, "History of Wireless Local Area Networks (WLANs) in the Unlicensed Bands," (paper presented at the George Mason University Law School Conference, Information Economy Project, Arlington, VA, April 4, 2008): 1-2.

[24] In 2008, AT&T acquired Wayport, a company that provided Wi-Fi hot spots in locations like McDonald's, for $275 million in cash. ["AT&T Advances Wi-Fi Strategy with Completion of Wayport Acquisition," AT&T Press Release, December 12, 2008].

[25] "Third-Quarter Wi-Fi Connections on AT&T Network Exceed Total Connections for 2009," AT&T Press Release, October 22, 2010.

[26] "The Future of Hotspots: Making Wi-Fi as Secure and Easy to Use as Cellular", Cisco White Paper (2011).

mobile devices, exceeding the number of traditional computers.[27] The number of smartphones in use alone has exceeded 500 million in 2010.[28] Cisco projects that by 2015, almost half of IP traffic will be carried over Wi-Fi networks.[29]

29. The range of Wi-Fi applications continues to expand. One area that has already experienced considerable innovation is the integration of Wi-Fi networks with cellular networks. As voice and data services become more popular and demand greater amounts of bandwidth, cellular networks are increasingly strained. When traffic can be shifted ("offloaded") from cellular networks using licensed spectrum onto Wi-Fi networks, that takes advantage of the Wi-Fi's smaller cell radius to reduce congestion and use limited spectrum more intensively. Already a number of mobile carriers allow customers to make calls using Wi-Fi networks. New technologies aspire to allow smooth hand-offs between cellular and Wi-Fi networks, with smartphones switching to available Wi-Fi networks whenever practical.[30] Other future Wi-Fi innovations include in-home video and Wi-Fi Direct, which is a new technology that supports the connection of mobile devices (such as mobile phones, cameras, and gaming devices) to each other without joining a traditional home or office network.

III. The Economic Governance of Radio Spectrum

Common Pool Resources and Property Rights

30. In its early history, radio spectrum was an example of what economists refer to a *common-pool resource*.[31] A typical concern with common pool resources is the potential

[27] "Meraki Study Shows Mobile Platforms Overtake Desktop Platforms, Marked Rise of Android," last modified June 22, 2011, http://meraki.com/press-releases/2011/06/22/meraki-reveals-ipads-use-400-more-wi-fi-data-than-the-average-mobile-device/.

[28] "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015"; Cisco White Paper (2011): Table 2.

[29] "Cisco Visual Networking Index," 11.

[30] Elizabeth Woyke, "Automatic Wi-Fi Offloading Coming to U.S. Carriers," *Forbes Magazine*, April 22, 2011.

[31] In economic theory, a *common pool resource* is a resource that is non-excludable (meaning it is costly to prevent people from using it) and rivalrous (meaning that individual use can deplete the resource or interfere with its use by others).

for congestion or overuse. The concern arises because individuals may not account fully for the fact that their use impinges on others. Garrett Hardin famously called this problem the *tragedy of the commons*. He used the example of cattle over-grazing on common pastureland to demonstrate the problem.[32] In the case of radio spectrum, the danger is interference from conflicting signals, and the problems of the 1930s with radio interference are an example of congestion externalities.

31. The potential for congestion or overuse calls for a governance system to manage resource use. For many resources, the system that is adopted is some form of private property rights. For radio spectrum, licensing plays an analogous role. Just as private property rights in land helped to resolve the tragedy of the commons for some tracts of land, long-term licenses, by providing exclusive use and protections against incursions, can mitigate the problem for some spectrum bands. When property rights are assigned for any resource, the owner of the resource has an incentive to maximize its value and can make investments without fear that its investment will be appropriated by others. In the case of radio spectrum, a licensee obtains the ability to sell services that use the band and exclude others from using its spectrum, limiting interference. These prerogatives allow the licensee to manage congestion and provide it with an incentive to make complementary investments in building out a network. Moreover, through the sale of the license, the government is able to share in the revenue that is created.

32. Despite these merits, property rights and the analogous system of radio spectrum licenses can have several major drawbacks. One disadvantage is that the system for allocating property rights may be imperfect. The auctions currently used by the U.S. and other countries to allocate spectrum licenses have been successful in many ways, but they also have led in most countries to a highly concentrated market structure in mobile communications. This outcome is hardly surprising. A basic premise in the auction is to allocate spectrum in a way that creates value *from the perspective of the bidders*. Consequently, licenses tend to be won by the firms that expect to use them most profitably and not necessarily by firms that might create competitive pressure that lowers

[32] Garrett Hardin, "The Tragedy of the Commons," *Science* 162 (3859) (1968): 1243–1248.

prices. Put another way, auction theory tells us that the type of auction mechanisms used to allocate spectrum, if they work well, will tend to maximize industry profits, and one expects industry profits to be higher with more concentration.[33]

33. Another drawback to property rights is that they can stifle third-party innovation: third-party innovators face a threat of *hold-up*. A company that comes up with a new mobile device or business model needs to convince the owner of the spectrum to let it develop its idea, and it may have to share a large fraction of the value that is created with the spectrum owner. If the new development threatens the owner's existing business, it is particularly unlikely to be allowed. And, if the innovation requires the assent and coordination of multiple spectrum owners, it is even more difficult to get the owners all to agree. The potential for this type of coordination failure is sometimes referred to as the *tragedy of the anticommons*.[34] It has become a familiar problem in intellectual property, arising when product developers must license such a large number of patents that the process of innovation becomes cumbersome, unwieldy and inefficient.

34. We emphasize that the innovation problem is particularly weighty when, for historical or other reasons, important innovations are most likely to be driven by diverse parties, some of whom are not necessarily the current owners of the spectrum. In the contrary circumstance, where innovation to enhance a particular asset hinges on making large investments in laboratories and other resources, ownership can enhance incentives by encouraging and protecting large investments. For radio spectrum, history suggests a mixed innovation and investment story, with licensed spectrum having been valuable to encourage the necessary network infrastructure for wireless mobile handsets and unlicensed spectrum encouraging a long series of novel, valuable, and unanticipated uses.

35. A third concern with allocating property rights over spectrum is that once licenses have been allocated, reallocation tends to be a slow and difficult process. For example, even within cellular communication bands, there has been historically a very limited

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[33] Hazlett, Porter and Smith, "Radio Spectrum".

[34] Michael Heller, "Tragedy of the Anticommons: Property in the Transition from Marx to Markets," *Harvard Law Review*, 111 (3) (1998): 621-687

market for spectrum trading. In the United States, the creation of nation-wide networks from the initially fragmented license allocations took many years and major corporate acquisitions and consolidations to accomplish. There is no significant real-time spectrum market for spectrum trading, despite the potential economies in reducing congestion that such a market promises.

An Alternative: The Managed Commons

36. An alternative to assigning exclusive rights to particular small bands is to establish rules or regulations governing the utilization of bands as a common pool resource. In the case of radio spectrum, restrictions on transmission power are an example of a regulatory approach. For example, Wi-Fi operates at very low power relative to cellular networks. This has a downside because Wi-Fi signals do not travel as far, but also reduces and in many cases eliminates problems of interference, thereby addressing the potential for congestion.

37. The Nobel laureate Elinor Ostrom has written extensively on the diversity of governance systems for managing common pool resources. Her work identifies several key principles: the creation of clear rules that respond to local conditions; collective decision-making that allows the participation of most community members; effective monitoring, enforcement, and conflict-resolution mechanisms; and coordination between organizations that manage common-pool resources. [35] As she emphasizes, these principles do not necessarily imply the creation of exclusive property rights; in many cases, alternative systems can work better. [36]

38. As the Wi-Fi example suggests, the regulation of unlicensed spectrum can be viewed as a successful example of a *managed commons* approach. Traditionally, governments have regulated the use of unlicensed spectrum by establishing clear standards as well as pre-approving unlicensed devices. From an economic perspective,

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[35] Esther Mwangi and Elinor Ostrom, "Top-Down Solutions: Looking Up from East Africa's Rangelands," *Environment: Science and Policy for Sustainable Development* 51 (1) (2009): 34-44.

[36] Elinor Ostrom, *Governing the commons: the evolution of institutions for collective action* (Cambridge University Press, 1990).

this regulatory approach has a number of benefits that allow unlicensed spectrum to be part of a platform for innovation and a source of services that are complementary to those created by licensed spectrum.

39. First, the availability of unlicensed spectrum can make the cost of setting up and deploying systems for local wireless transmission extremely low. There are no licensing fees to pay, no approvals to obtain, and no need for radio frequency planning.[37] A lack of entry barriers encourages companies to develop new products and business models, leading to innovation and competition. In the case of Wi-Fi, manufacturers can develop products and market them directly to consumers, without having to work with a limited number of licensees that control cellular networks. This has facilitated the rapid introduction of Wi-Fi capabilities into new products: laptops, book readers, tablet computers, home security systems, smartphones, and many more.

40. Free access to unlicensed spectrum also encourages a more competitive market structure in the provision of wireless services, in contrast to the situation on licensed bands. Services that operate on unlicensed spectrum increasingly compete with services offered by operators that rely on licensed spectrum. For example, voice calls on Wi-Fi networks – in applications such as Skype – competes with calls on traditional cellular networks that use licensed spectrum. With a Skype-enabled phone, a receiver can move from place-to-place and, so long as his device is connected to a Wi-Fi network, can make calls without using the 3G networks. This is an example of how unlicensed spectrum may protect consumers from excessive market power possessed by spectrum owners.

41. Unlicensed spectrum facilitates the adoption and spread of new technologies. The increased pace of innovation allowed by unlicensed spectrum is demonstrated by the early appearance of technologies in WLAN relative to their introduction in cellular networks. Such technologies include digital signal encoding, spread spectrum techniques, multiple input and multiple output (MIMO), and orthogonal frequency-division

[37] Daniel Carpini, "Why Unlicensed Radio Spectrum Is The Answer To Our Wireless Needs," *Business Insider*, May 13, 2011.

multiplexing (OFDM).[38] The FCC permitted spread spectrum techniques in unlicensed bands for the first time in 1985, laying the foundations for Wi-Fi, Bluetooth, and many other standards, and already the first WLAN products were appearing in the late 1980s.[39] In contrast, the two key applications of spread spectrum techniques on licensed spectrum, namely code division multiple access (CDMA) and time division multiple access (TDMA), were not introduced in cellular networks until the mid-1990s.[40]

IV. Economic Benefits of Unlicensed Spectrum

Value of Current Applications of Unlicensed Spectrum

42. Precisely because applications of unlicensed spectrum are so numerous, it is difficult to place a reliable economic value on their use. Nevertheless a variety of approaches all point toward economic benefits at least in the tens of billions of dollars a year. In this section we discuss some of the most significant benefits of current uses of unlicensed spectrum and estimates of their economic value.

43. A useful baseline is a 2009 study sponsored by Microsoft that employed a variety of methods to forecast the economic value attributable to three specific applications of unlicensed spectrum – home Wi-Fi, hospital Wi-Fi, and clothing RFID tags – over the 2009-2024 period.[41] The study estimated the value of home Wi-Fi alone at between $4.3 and $12.6 billion per year, and the value of all three applications together at $16-37 billion per year. However, as pointed out by the authors, these numbers are probably far too conservative and can at most be regarded as a lower bound on the value of Wi-Fi at home.

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[38] MIMO is a technique where signals are sent and received by multiple antennas, improving speed, coverage and reliability. OFDM is a technique that allows multiple signals to be transmitted at lower power using multiple carriers, achieving high bandwidth by having many carriers while keeping the signal rate low on any given carrier. [Helmut Bölcskei and Eth Zurich, "MIMO-OFDM Wireless Systems: Basics, Perspectives, and Challenges," *Wireless Communications, IEEE* 13 (4) (2006): 31-37].

[39] Negus and Petrick, "History of WLANs in the Unlicensed Bands."

[40] Thomas W. Hazlett, "Optimal Abolition of FCC Spectrum Allocation," *Journal of Economic Perspectives* 22 (1) (2008): 122.

[41] Thanki, "Economic Value Generated by Unlicensed Spectrum".

44. Apple released the first version of the iPad in April of 2010 (just after the release of the Microsoft study), and as of the third quarter of 2011, had sold over 25 million iPads over the last year. It is difficult to say how much of the value of this market should be attributed to Wi-Fi, but consider the following. An iPad with Wi-Fi capability but no 3G capability, and with 32GB of storage, retails for $599. Analysts have put its production cost at just under half this amount.[42] That translates into a producer surplus on each sale of roughly $300, and a plausible first guess is that consumer surplus is the same magnitude. If so, the value created with each iPad sale is around $600, for a total of over $15 billion over the last year.[43] How much of this value can we attribute to the presence of Wi-Fi? It seems hard to believe that a product for which 3G access is not standard, but only an option, would have been nearly as successful or widespread, and perhaps it might not have succeeded at all, if users were forced to rely on a combination of cellular and wireline access to data and services.

45. The iPad also illustrates how Wi-Fi can complement licensed data services. In one typical pattern, an iPad owner uses Wi-Fi when it is available, but switches to 3G mobile to operate outside of Wi-Fi hotspots. The Wi-Fi capability creates the basic demand for iPad services for these users, with additional mobile data service provided using licensed spectrum. In this example, the availability of unlicensed spectrum applications helps create more consumer demand for licensed spectrum services.

46. Other examples of the complementarity between Wi-Fi and licensed spectrum come from marketing developments in various countries. In the UK, British Telecom's BTFon service uses dual-network routers installed in the homes or business premises over 3 million wired internet customers.[44] Each router supports two networks. One network is private for the customer; the second is open to BT's other wireless customers. BT uses the Wi-Fi network to offload data traffic from its wireless customers, which

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[42] In particular, at $258.85. [Andrew Rassweiler, "Mid-Range iPad to Generate Maximum Profits for Apple, iSuppli Estimates," iSuppli Press Release, February 10, 2010].

[43] These figures represent worldwide sales. We assume that the economic value of all iPad versions are similar to the economic value of the 32 GB Wi-Fi-only version.

[44] "FON Customers Questions," last modified October 3, 2011, http://www.btfon.com/support/faqs.

would otherwise suck capacity from its licensed network. A similar system is used in France, where, for example, SFR has installed 1.3 million dual-network routers, which provide a private network for the consumer and a guest network for SFR's other customers.[45]

47. The Microsoft study mentioned above does not consider explicitly another major application of Wi-Fi, which is its use by mobile phone users. Today, most smartphones are equipped with Wi-Fi capabilities that enable users to transfer data using broadband internet instead of 3G. One benefit of the use of Wi-Fi on mobile phones is that it allows data transfers at much higher speeds. Another benefit is the ability to transfer data when the 3G network is unavailable. And, offloading data traffic to Wi-Fi reduces the congestion on 3G networks. Today, we estimate that about a third of all mobile data traffic is transferred through Wi-Fi.[46]

48. Again, it is difficult to place an exact number on the value created by having Wi-Fi connectivity on mobile phones. One way to get a rough estimate is to assume that users attach the same value to each bit of data, whether it is transferred on the 3G network or through Wi-Fi. A ballpark estimate for the value created by 3G data transmission might be the data-related revenue of mobile carriers; in 2010, this exceeded \$50B. If mobile phone users use Wi-Fi to transfer roughly half this amount of data, it suggests an annual economic value being created in excess of \$25B.

49. An alternative way to think about the value of Wi-Fi in mobile phones is to quantify the benefits of higher speed (an advantage of Wi-Fi over 3G in mobile devices). Rosston, Savage and Waldman (2010) estimate that consumers would be willing to pay on average \$45-\$48 a month to upgrade their home internet connection from "slow" to "fast" or "very fast", while Dutz, Orszag and Willig (2009) estimate that consumers

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[45] "SFR Femto : pour une couverture 3G optimale à domicile", last modified October 3, 2011, http://www.sfr.fr/vos-services/equipements/innovations/sfr-home-3g/comment-ca-marche/

[46] Cisco calculates the fraction of data transferred through Wi-Fi at home to be roughly 50%, and the combined home + workplace data usage to be 65% of all uses. Assuming that a customer uses Wi-Fi for 50% of her home/workplace use and for 0% of her on-the-move use, the total faction of data transferred through Wi-Fi is about a third.

would be willing to pay on average $24 and $31 monthly to switch from dial-up to 5Mbps and 50Mbps internet connections, respectively. Both studies suggest that users place high value on faster internet speed. If we were to assume a value on higher speed for mobile internet of $30 a month per consumer, and scale this value by a third to reflect the share of data transmitted by Wi-Fi, this would suggest a consumer value of $10 a month for the Wi-Fi functionality of her smartphone. With over 100 million smartphones currently active in the U.S., the economic value of the speed aspect of Wi-Fi alone in mobile phones exceeds $12B a year.

50. While one should be cautious in placing too much faith in any single estimate, the various approaches we have discussed all indicate that Wi-Fi applications on new smartphone and tablet devices developed subsequent to the Microsoft study each yield economic benefits on the order of tens of billions of dollars a year. Moreover, we have not even tried to account for the likely rapid growth of both smartphones and tablets, and data use of these devices, or for the mobile use of laptops or netbooks, or for the convenience benefits of Wi-Fi in allowing home networks to be set up easily and without cumbersome wiring, or in enabling users to connect to the internet in circumstances that would not allow them to be connected otherwise (e.g., in airports and cafes).

Future Applications of Unlicensed Spectrum and Its Value as an Enabling Resource

51. The substantial benefits associated with unlicensed spectrum today, in particular the large value attributable to ubiquitous technologies such as Wi-Fi and Bluetooth, suggest strongly that additional unlicensed spectrum would continue to contribute to social welfare. In this section we discuss a few of the future applications that might emerge if additional unlicensed spectrum were made available. We then return to our basic theme that unlicensed spectrum is an enabling resource that provides a means for dispersed innovators to create a variety of unanticipated products and services. While this benefit may be large and perhaps the most important, it is naturally difficult to quantify or predict with precision.

52. Some possible uses of new unlicensed spectrum already can be identified. One application is “Super Wi-Fi”, which is expected to increase the range of Wi-Fi by a factor

of two to three as well as allow Wi-Fi to go over hills and through walls.[47] Super Wi-Fi achieves these benefits using white spaces – the unused bands of spectrum between used channels – in the lower frequency television bands between 54 MHz and 698 MHz.[48] In order to prevent conflicts and interference, the 802.22 standard incorporates technologies such as spectrum sensing, dynamic spectrum access, and geolocation techniques.[49] One application of Super Wi-Fi is providing the "last-mile" connection in rural broadband deployment.[50] Instead of running wires to each individual home, a single fiber optic cable could be laid in close proximity to rural settlements, with Super Wi-Fi antennas broadcasting the signal to individual homes in the area.

53. These same white spaces potentially can be used for a variety of other new technologies. One example is improved home wireless networking that would allow for one-way and two-way video communications for applications such as security, monitoring, and entertainment.[51] Another potential application is Advanced Meter Infrastructure (AMI). AMI systems utilize communication media to trace energy usage through smart meters. Applications of AMI include automated meter reading, outage management, and electricity theft detection. In particular, the use of white spaces can allow utility companies to monitor and access smart meters remotely. [52]

54. Municipal Wireless Networks ("*Muni-Fi*") are another potential application that could emerge with additional unlicensed spectrum. Muni-Fi provides internet access to members and visitors of a community and facilitates improved city operations,

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[47] John D. Sutter, "FCC heralds a new era of 'super Wi-Fi'," *CNN*, September 15, 2010.

[48] Andrew Burger, "IEEE Completes 62-Mile, 'Super Wi-Fi' Wireless Broadband Standard," *Clean Technica*, August 7, 2011.

[49] Carl R. Stevenson, et al., "IEEE 802.22: The first cognitive radio wireless regional area network standard," *Communications Magazine IEEE* 47 (1) (2009): 131.

[50] "Last mile" is the final leg of delivering connectivity from a communications provider to a customer's premises.

[51] "US TV White Spaces: Usage & Availability Analysis," Spectrum Bridge White Spaces Report, 2Q 2010: 4.

[52] Omid Fatemieh, Ranveer Chandra and Carl Gunter, "Low Cost and Secure Smart Meter Communications using the TV White Spaces," (paper presented at IEEE International Symposium on Resilient Control Systems (ISRCS '10), August 2010).

increased economic growth, and innovation.[53] There are already some examples of this. As of June 2010 there were approximately 110 municipalities with citywide Wi-Fi access for the general public, 56 cities with citywide or near citywide coverage for government use, and 84 cities with Wi-Fi hot-zones located in parks and downtown areas.[54]

55. Muni-Fi networks can take the form of municipality-driven networks, provider-driven networks, and user-driven networks. The objective of municipality-driven networks is to provide wireless access to city staff, citizens, or tourists in specific areas. An example of such a network is Paris Wi-Fi, which provides free internet access in many parks and municipal libraries, museums, and other public places. Provider-driven networks are sometimes financed by private companies; one example is Wireless Philadelphia, which was (but is no longer) financially backed by Earthlink, thereby allowing Earthlink to control the network and the services that it provides. Google has financed city-wide Wi-Fi in Mountain View, CA. In contrast, user-driven networks rely on members of the community to provide wireless access to other members, together supporting a community-wide network.[55] There are also combinations of these models. Muni-Fi networks may be free, supported by advertising, or provided for a monthly charge.

56. Muni Wi-Fi has proved difficult to implement, in part because of current limitations in the quality and quantity of unlicensed spectrum. First, unlicensed spectrum is shared between many users and devices, and therefore may suffer from congestion and interference. Second, signals traveling on unlicensed spectrum face difficulties traveling through trees and walls or over hills, making it difficult for Muni-Fi to be available in all parts of a community. Finally, Muni-Fi requires a dense installation of transmitters due to

[53] Tobias Heer, et al., "Collaborative Municipal Wi-Fi Networks – Challenges and Opportunities," (paper presented at the 8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops), March 29, 2010).

[54] Esme Vos, "Updated list of US cities and counties with large scale WiFi networks," last modified June 7, 2010, http://www.muniwireless.com/2010/06/07/updated-list-of-cities-and-counties-with-wifi/

[55] Heer, et al., "Collaborative Municipal Wi-Fi Networks": 588-593.

the limited power of any transmitter that operates on unlicensed spectrum bands.[56]

57. Some of the problems associated with Muni-Fi could be alleviated if it could utilize the lower end of the spectrum. Because signals travelling on lower-frequency bands can travel longer and penetrate objects more easily, Muni-Fi utilizing such bands can cover wider service areas at considerably lower costs.[57]

58. The examples we have given, such as Super Wi-Fi and Muni-Fi, already can be foreseen. Yet as the iPad example illustrates, innovation can be sudden, and the full extent of future innovation is very hard to predict. Certainly, it would have been very difficult to foresee in 1985, when the FCC released additional unlicensed spectrum, the new technologies and applications that would be created within a relatively short period of time.

59. Nevertheless, even when innovations are hard to predict, one often can identify resources that facilitate innovation. It would have been hard to conceive iPhone apps before the iPhone, or the many uses of the internet before the internet, or the value of web browsers before the development of search engines and commercial websites, etc. Each was an enabling technology that created vast opportunities for innovation. Unlicensed spectrum has shown itself to be a similar type of building block without which such technologies as Wi-Fi and Bluetooth may have not been developed, and without which the markets for devices and apps would be severely limited.

More Unlicensed Spectrum Need Not Imply Lower Revenues

60. Between 1994 and 2008, the sale of spectrum licenses by the FCC produced $52 billion in revenue. This suggests a concern that creating additional unlicensed spectrum might reduce government revenues by lowering the amount of licensed spectrum available at auction. However, the reverse can also happen: additional unlicensed spectrum could increase revenue in several ways.

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[56] Christopher Mims, "Where's All the Free Wi-Fi We Were Promised?" *MIT Technology Review*, October 5, 2010.

[57] Mims, "Where's All the Free Wi-Fi We Were Promised?"

61. First, a reduction in the supply of licensed spectrum is highly likely to increase its per-unit price. If the aggregate demand for licensed spectrum is relatively inelastic (with an elasticity between 0 and -1), a reduction in the available spectrum would, by itself, actually increase the revenue that can be expected from a given auction.

62. We are not aware of convincing estimates of the aggregate demand for licensed spectrum. Bulow, Levin and Milgrom (2009), however, have pointed out that in large spectrum auctions, the overall auction revenue tends to reflect the aggregate budgets of the participants. To the extent that telecommunications firms allocate budgets for spectrum purchases that are relatively insensitive to changes in the available spectrum, and tend to spend their budget at auction, changes in the available spectrum will have only modest effects, if any, on government revenue.

63. A second point is that complementarity between licensed and unlicensed spectrum can lead to a situation where unlicensed spectrum applications increase the demand for licensed spectrum applications and lead to higher license prices. One example is consumer wireless broadband services. The ability of smartphones and tablets to connect to Wi-Fi networks increases the value of these products to consumers, which, in turn, can increase the sales of mobile data services and therefore the revenues obtained from selling licensed spectrum.[58]

64. To make an analogy, suppose that a city is planning to construct a new neighborhood and considers allocating space for a park. Would building a park instead of extra houses necessarily reduce revenues? On one hand, the city foregoes the revenues that could be obtained by selling these extra houses on the market. On the other hand, the lower availability of houses is expected to increase the price of each house, potentially reversing the impact of lower supply. The effect of lower supply of houses on the city revenues would depend on the elasticity of demand for houses. Additionally, proximity to

[58] Of course, additional unlicensed spectrum might also create competition for services offered by licensed spectrum, reducing the profits of licensees. This could have an adverse effect on auction prices, although consumers likely would benefit directly from the increase in competition.

a park would raise the value of each house in the neighborhood, increasing the city's revenues.

V. Policy Implications

Allocating Spectrum Bands for Unlicensed Uses

65. Not all spectrum bands have the same properties. Specifically, spectrum between 10 and 1,000 MHz has great potential for longer-range, more reliable, and ultra low-power unlicensed applications requiring high data rates. In order to facilitate innovation in new services, to encourage competition from services using unlicensed spectrum for ones using licensed spectrum, and to grow complementary services using unlicensed spectrum to match those using licensed spectrum, the quality and capacity of unlicensed spectrum should grow apace.

66. The availability of unlicensed spectrum must be sufficiently reliable to encourage innovators to invest in new technologies. If spectrum (or specific bands) is only sporadically available, the incentive of innovators to invest in research and development of new technologies and of manufacturers to build equipment that exploits those bands would be greatly diminished.

67. It has recently been proposed that auctions, rather than an administrative process, can serve as an effective mechanism to determine the allocation of licensed vs. unlicensed spectrum.[59] The basic idea is that potential beneficiaries of unlicensed spectrum would submit bids for unlicensed spectrum. The bids for unlicensed spectrum would be aggregated and compete with individual bids of market participants that compete for licensed spectrum. To prevent free-riding by the beneficiaries of unlicensed spectrum, a recent FCC working paper has proposed that a Vickrey-Clarke-Groves

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I. [59] Matthew Lasar, "Congress goes after unlicensed wireless 'free riders' (like Google and Microsoft)," *Ars Technica: Law & Disorder*, July 14, 2008.

mechanism be used to aggregate bids and determine the allocation of spectrum and corresponding payments by auction participants.[60]

68. While allowing market forces to determine the allocation between licensed and unlicensed spectrum might superficially appear to be an attractive option, it is not a practical alternative. Auction markets work best when one can identify the relevant bidders in advance, bring them to the auction, inform them about what is for sale, and motivate them to bid. As we have indicated, there is a diverse and evolving group of devices that use and benefit from unlicensed spectrum: computers, mobile phones, tablets, wireless heart rate monitors, microwave ovens, baby monitors, two-way radios, garage door openers, security systems, etc. The beneficiaries of unlicensed spectrum are the manufacturers of all these devices (as well as the millions of consumers that use them). Even the group of existing beneficiaries is too large and diverse to be identified, informed and motivated to bid, particularly when individual beneficiaries cannot expect their bids to have any effect on the outcome. And, without knowing how many other users there might be or how much interference might arise, they would be unable to make realistic estimates of the value.

69. Moreover, the importance of innovation to capture the full benefit of unlicensed spectrum would make it even more implausible that beneficiaries of unlicensed spectrum could be assembled. For potential innovators who may use unlicensed spectrum, the main problems are that they are numerous and their identities are unknown; their participation is costly, making it hard to bring them to the auction; and the very nature of innovation makes their information about their future benefits unreliable. In contrast, the beneficiaries of exclusive licenses know who they are and can estimate business plans, knowing that their spectrum is protected from interference by other users.

70. These factors make the idea of an auction pitting licensed versus unlicensed uses untenable. Any such auction would be decisively biased against unlicensed uses,

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[60] Bykowsky, Sharkey and Olson, “Licensed vs. Unlicensed Use of Spectrum.”

even in cases where the unlicensed uses would be far more valuable than the licensed ones.

71. The weaknesses of the proposed auction mechanism can be demonstrated through the public park example discussed earlier. Suppose that a city decides to use an auction mechanism to determine the amount of park space to be included in the new neighborhood, and conducts one auction in which (1) potential residents bid for houses, and (2) potential beneficiaries of the park bid to reserve some public park space. Such a mechanism is unlikely to lead to an efficient outcome for a number of reasons. First, it could be hard to collect from all the future neighborhood residents bids that reflect their valuations of the park. The identities of these residents may be unknown at the time of the auction and their future benefits from the park are likely to be uncertain. Second, it would be impossible to assemble bids from park visitors, who would not be neighborhood residents but would still benefit from the existence of the park. And finally, there may be substantial uncertainties regarding the future uses and benefits stemming from the park: for example, perhaps at some point in time the park would start hosting a popular festival or give rise to some other innovative activities. Potential bidders are unlikely to have accurate information about their future valuations of the park given that the nature of such benefits is still unknown at the time of the auction. For all these reasons, the aggregate bids for park space are expected to greatly underestimate its actual value.

Management of Unlicensed Spectrum

72. The economic case for unlicensed spectrum rests in large part on there being dispersed innovation by third party innovators, but then how is the spectrum common pool to be managed? Of course, one requirement is that the pool must be large enough to allow multiple uses, including new ones, and the spectrum must be of suitable quality to support services that complement and compete with licensed wireless services.

73. Given the size of the allocation, efficient common governance of a pool resource requires adopting restrictions on or etiquettes for its use. If the air’s capacity to accept pollution is managed as a common pool resource, then power plants may be

allowed to emit, but only with suitable emission control equipment. If fisheries are managed that way, then fishermen may be limited in the mesh size of their nets and the proximity of their boats to others in the fishery. On public tennis courts, users may be limited to one-hour sign-ups, and park users may be forbidden to play music that is too loud. Similarly, the devices that use unlicensed spectrum are subjected to restrictions on their power, their use of bandwidth, and etiquette or protocols that reduce interference with other devices. As Ostrom has emphasized, to be most effective, these regulations should be developed with the participation of those who are most affected. For that function, industry standards bodies perform a function similar to the communities in Ostrom's studies.

74. Because unlicensed devices are low-powered, another factor that contributes to efficient use is the local user, who helps to regulate the interaction of devices by turning off (or refusing to buy) devices that interfere too much with others. Together with the standards and protocols described above, the common pool regulation alternative is an effective way to promote non-interference, allowing the bands to be used efficiently. And, as already argued, free use of the band is key to encouraging third-party innovation.

75. A variety of new technologies have enhanced unlicensed devices' ability to use spectrum effectively, and the development of these technologies suggests, in itself, pent-up demand for additional and higher quality unlicensed spectrum. *Dynamic white space allocation* refers to techniques that allow for more efficient use of quality low-frequency spectrum. TV broadcasters typically use low frequency spectrum (between 54 and 698 MHz).[61] TV transmitters typically broadcast at hundreds of kilowatts of power, and therefore neighboring stations use different frequencies to avoid interference. The vacant channels in the television bands between the frequencies used by incumbent stations are called white spaces. These white spaces can be used for longer range unlicensed communications that could also provide cheap "last-mile" infrastructure.

[61] "US TV White Spaces," Spectrum Bridge Report.

76. New "Cognitive Radio" (CR) capabilities better manage interference and help use available spectrum more efficiently. CR technologies utilize a radio frequency (RF) sensor to detect unused spectrum that is available and capable of communications. CR understands the properties inherent to the user such as battery life, signal interface, and attenuation, which are then used in a set of decision-making algorithms to provide the best capabilities for each user.

77. Cognitive radios can also change frequencies dynamically to maintain reliable communications.[62] As a result, CR helps improve the efficiency of spectrum usage. CR technologies can also be used to ensure that new unlicensed users do not interfere with TV signals: when databases of incumbent licensees are available for a given location, devices can be instructed to avoid those frequency bands.[63] Spectrum etiquette (or legally binding) rules, such as avoiding occupying a channel when there is no data being transmitted or avoiding channels where there is already a certain amount of traffic on that channel, also help to manage interference.[64]

VI. Conclusion

78. In our introduction, we asked a series of questions. For the first – why have the unlicensed portions of the spectrum been such an effective catalyst for innovation? – our answer is that unlicensed spectrum is an enabling resource that, like other enabling resources and technologies, encourages innovation by many parties. Licensing or ownership that limits access to such resources discourages innovation by giving too much power to the licensee or owner.

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[62] Stephen J. Shellhammer, Ahmed K. Sadek and Wenyi Zhang , "Technical Challenges for Cognitive Radio in the TV White Space Spectrum," (paper presented at the Information Theory and Applications Workshop, February 8-13, 2009): 323-333.

[63] António Morgado and Nuno Borges Carvalho, "White Spaces Communications in Europe," Working Paper, Universidade de Aveiro, Aveiro, Portugal (2011).

[64] Nie Nie and Cristina Comaniciu, "Adaptive Channel Allocation Spectrum Etiquette for Cognitive Radio Networks," (paper presented at the First IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks, November 8-11, 2005): 269-278.

79. Our second question was: Should the United States and other countries leave additional spectrum unlicensed, expecting to encourage still more innovation? Or is it better to license all new spectrum bandwidth to capture the stewardship benefits of private control? We have argued that there are valuable roles for both licensed and unlicensed spectrum in overall spectrum policy. Licensed spectrum supports many uses, including mobile telephones and the associated 3G and 4G mobile wireless technologies, as well as broadcast radio and television, satellite services, and many more. These uses require large infrastructure investments, from broadcast towers to satellites to cell sites and equipment, and exclusive licenses provides the protection needed to encourage those investments. But just as economic analysis predicts, allocating spectrum for unlicensed use has been more effective in encouraging the development of a host of innovative uses by a host of independent parties. Wi-Fi, in particular, played an essential role in the development of modern mobile phones and tablet computers, which have driven the initial explosive growth in demand for wireless data communications. Unlicensed spectrum supports low-powered uses that allow greater reuse and sharing of the spectrum and encourage third-party innovation. And, of course, it spurs investment in complementary technologies. For example, Wi-Fi encourages the building of high-speed connections to homes and businesses where it is used.

80. The continued development of unlicensed technologies is likely both to increase the value of licensed spectrum by providing complementary services and to provide a platform for competing services. These effects provide ample reason for policy makers to expand the quality and quantity of unlicensed spectrum alongside that of licensed spectrum.

81. Our last question was: Is it costly, in terms of auction revenues, to set aside some spectrum for unlicensed uses? The surprise for many will be that economic theory provides no clear answer, but we believe that the most likely answer is no. Reserving some spectrum to be unlicensed reduces the quantity available to be sold, which both raises prices and reduces quantities. So, even if unlicensed spectrum had no demand-enhancing effects, the revenue effect of reserving some spectrum for unlicensed could be

ambiguous. The demand-enhancing effects of unlicensed spectrum, however, have been and likely will continue to be quite large. There is a strong argument that the exploding demand for mobile data was seeded by Wi-Fi devices, and that products like tablet computers, which create huge extra demand for mobile data, could not have been introduced successfully without their Wi-Fi capabilities. If new unlicensed uses have even a fraction of this impact, then the enabling resource of unlicensed spectrum will have a hugely positive impact on the value of licensed spectrum, leading to increased auction revenues.

82. As the demand for licensed spectrum grows, it is a fair guess that the demand for equally good unlicensed spectrum will grow apace. Wise policy should allow and celebrate that sort of growth.