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Toward Property Rights in Spectrum
The Difficult Policy Choices Ahead

by Dale Hatfield and Phil Weiser

Executive Summary

The vision laid out by economist Ronald Coase in his 1959 paper on spectrum remains the guiding light for spectrum policy reform. Property-like rights in electromagnetic spectrum and a secondary market for spectrum licenses are well recognized as the best ways to allocate spectrum to its highest and best uses. When spectrum is better allocated, both telecommunications consumers and providers will be far better off.

Numerous commentators have built on Coase's wisdom and charted paths to facilitate markets in spectrum. However, defining rights to use spectrum is far more difficult than ordinarily suggested. Problems such as geographic spillover and adjacent channel spillover make it much more difficult to define rights to spectrum and to determine how to measure when those rights have been transgressed. Unlike the case of real property, which is measured in two or three dimensions, there are as many as seven dimensions by which electromagnetic frequency can be measured, and the best way to measure these dimensions remains unsettled. Many decisions remain, such as whether to use statistical models of radio wave propagation, actual measurement of interference, or some combination of the two to determine the scope of rights in spectrum.

More careful analysis is needed to determine what type of property regime will operate effectively to govern rights in spectrum. A number of questions must be answered for a transition to a property rights regime to be successful.

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Wireless spectrum plays a critical role in national defense, homeland security, and other important services.

Introduction

Imagine a world where government regulation of gasoline, justified by scarcity of supply, dictated that 20 percent of the gasoline in the United States be used for farming, 20 percent for manufacturing, 20 percent for home use, and 20 percent for government, and where another 20 percent was held in reserve for future potential government uses. In this world, prices would regulate the use of gasoline within each sector, but consumers would pay vastly different amounts for, say, farming and residential use.

One response to such a state of affairs would be regulatory "arbitrage," where lawyers would enable firms to profit without taking risks by convincing government regulators that certain uses were not, for example, really residential but actually for farming. Another, more economically sensible response would be to reconsider whether government "command-and-control" restrictions actually served the public—as opposed to certain privileged groups (i.e., those with generous allocations of gas or effective lawyers).

In the world of spectrum policy today, the United States has a system much like that described in the illustration above. Certain groups enjoy generous allocations of spectrum while others are starving for more access to it. Consequently, many telecommunications lawyers earn their living making arguments along the lines noted above.

The origins of the current command-and-control model are more complicated than is often appreciated, but at its core it reflects a New Deal sensibility that government planning can divine an effective allocation of resources. Unfortunately, government has rarely forecast technological developments accurately. This explains why, for example, U.S. broadcasters continue to own "beachfront property"—the most desirable bands of radio spectrum—while innovative wireless communications companies clamor for more. Thirty years ago, when a majority of Americans relied on over-the-air television and few used cellular telephones, this state of affairs might have been defensible. Today, when European wireless companies possess twice as much spectrum as their American counterparts, and television broadcasters reach only around 15 percent of Americans through over-the-air transmissions, the status quo can no longer be defended.

In Congress, the Federal Communications Commission, and academia, there is an emerging consensus that U.S. spectrum policy is deeply flawed, but the way forward is unclear. On the congressional front, a critical opportunity is within reach to expedite the return and redeployment of a set of licenses now being used by the television broadcasters as part of the transition to digital television.[1] Unfortunately, even the return of those licenses would be a fairly modest step toward comprehensive spectrum policy reform.

Spectrum policy is important because the world is becoming increasingly dependent on wireless communications and broadband Internet access. Moreover, wireless spectrum plays a critical role in national defense, homeland security, and other important services such as satellites that aid in weather forecasting. In the case of wireless communications, the importance of more readily available access to spectrum is obvious—the radio spectrum is the sine qua non of all such communications. Spectrum policy influences broadband Internet access too. Today, would-be consumers of broadband can choose between DSL and cable modem service in most parts of the United States. But for those living in rural areas without access to any wired broadband service and those interested in a third or fourth broadband option, spectrum policy reform is critical to enabling wireless broadband providers to emerge as another major source of Internet access.

It is important to make clear at the outset that the concept of "spectrum policy reform" means different things to different people. For some, the critical challenge is merely ending the legacy restrictions that control how spectrum is used. This could be accomplished by either leaving the spectrum as a commons or developing a system of property-like rights to govern the radio spectrum.[2] In either case, government policy would facilitate a transition away from legacy users—like UHF television broadcasters—who are not allowed to sell their licenses for other uses and who are not about to surrender the spectrum they have been granted without a fight (or some reward).

For present purposes, we will not focus on the challenges of transitioning from the old regime to a new one, or even whether the new regime should leave spectrum available as part of a commons. Rather, we are interested in explaining how promoting a property rights regime in spectrum is not nearly as simple as some people suggest. In short, spectrum is not like land. Consequently, spectrum property rights would require a much more complicated legal regime than that used for real property rights. Without an appropriate understanding of radio spectrum and how it differs from real property, we believe that important efforts to establish clearly defined, defensible, and divisible property-like rights will, at best, fail to realize their objective or, at worst, be counterproductive.

This paper proceeds in five parts. First, we set forth the basic background of spectrum policy as it currently exists. Second, we outline the current state of the debate and survey the notable works that attempt to define property rights in spectrum. Third, to underscore the shortcomings of the current proposals, we explain how they fail to appreciate the nature of radio wave propagation and thus do not provide a reliable guide for developing clear and enforceable spectrum property rights. Fourth, we outline an alternative framework that takes account of how the realities of radio waves should inform the design of property-like rights for spectrum. Finally, we set forth our conclusions and recommendations.

Background

For most Americans, the radio spectrum is an elusive concept. For many years, scientists could not believe that "air" could conduct radio waves or electricity—think of Benjamin Franklin's experiments with lightning—and thus assumed that a substance called "the ether" resided in the atmosphere. During the later years of the 1800s, scientists concluded otherwise, discovering some of the essential characteristics of how radio technology works. In honor of one of those scientists, Heinrich Hertz, the defining unit of the radio spectrum—the frequency of radio waves—is measured in Hertz or Hz for short.[3]

In the years after the work of Hertz and others, inventors began to exploit the fact that, by modulating or changing the characteristics of a radio wave of a given frequency, individuals could communicate information over distances without wires or other physical media. In the case of analog cellular services, a frequency range (often called a channel or band) 30,000 Hz (or 30 kHz) wide can provide sufficient bandwidth to establish a reliable communications link.

Significantly, one can use a particular 30 kHZ channel to provide analog cellular service on one day and have the same amount of radio spectrum available for use on the next, meaning that spectrum is infinitely renewable. Nonetheless, spectrum is a scarce resource in that two individuals cannot use the same frequency at the same time and in the same place without canceling out (or at least interfering with) one another's transmissions.

When commentators discuss the radio spectrum, they generally focus on the set of frequencies that are most suitable for commercial use. Because different bands within the radio spectrum have different technical characteristics, some bands are more attractive for particular purposes than others. The most notable uses of spectrum rely on the frequencies between 300 MHz and 3 GHz, because the physical dimensions of the antennas required are reasonable, transmitting and receiving devices are low in cost, and, most fundamentally, the radio waves are less susceptible to being blocked or weakened

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by natural or man-made obstacles such as hilly terrain or tall buildings. To be sure, technological change can minimize such obstacles, and the range of usable spectrum has expanded over time, but when commentators discuss the "radio spectrum," they often have in mind that set of frequencies.

The concept of "spectrum management" generally refers to the broad array of activities associated with the regulation of this somewhat unusual natural resource. In short, the concept includes (1) allocating bands of frequencies for certain purposes (e.g., television broadcasting, terrestrial mobile radio services, or unlicensed spectrum not designated for a particular use), (2) assigning licenses that authorize individuals or firms to use particular bands of spectrum, (3) developing the rules and regulations that govern the use of a channel or group of channels (e.g., maximum transmitter power) within a band in a specified geographic area, and (4) enforcing the associated rules once they are adopted.[4] As noted at the outset, the FCC has traditionally relied on a command-and-control model of regulation that presumed that "wise men" at the helm could best oversee the licenses to use spectrum at different frequencies.

The FCC's traditional system for managing the radio spectrum is a paradigm of economic inefficiency. The system prevents two licensees —say, one authorized to operate a UHF broadcast television station and the other a wireless telecommunications operator—from selling or leasing spectrum rights to one another. Rather, the right to use spectrum is almost exclusively obtained by petitioning the FCC, which uses drawn-out proceedings to mete out spectrum rights, narrowly prescribing how the spectrum may be used by particular licensees.

To a now-famous economist named Ronald Coase, this sort of closely regulated system violated a fundamental insight: In the face of low transaction costs, individuals allowed to bargain and trade with one another will agree how to put resources to their most efficient use. This insight has become known as the "Coase theorem." Today, this theorem shapes much of the law and economics literature, underscoring that the critical role for government is to define and enforce property rights, which then enable the market to work—at least if transaction costs are reasonably manageable.

The FCC's traditional disregard of Coase's insights, which were spelled out eloquently in a now-influential 1959 paper (which anticipated his Nobel Prize–winning work),[5] reflects two principal considerations. First, the FCC's inherently bureaucratic processes invite and reward "rent-seeking" behavior. In particular, the FCC's oversight of spectrum has allowed firms to acquire and protect competitive advantages and associated profits (i.e., "economic rents") through regulation that limits competition. Second, often in response to complaints by existing holders of spectrum rights, the FCC fears the possibility of interference between adjacent users of spectrum and thus has erected a series of prophylactic rules (including how particular bands of spectrum can be used) to avoid interference. In practice, concerns about interference and rent seeking go hand-in-hand, as incumbent spectrum users, seeking to protect and enhance the value of their spectrum, regularly invoke interference concerns as a reason to prevent spectrum use by others.

For Coase, the most offensive aspect of the FCC's regulatory regime was its ban on bargaining between spectrum licensees. As he explained in his 1959 paper and later work, two neighboring property owners—such as a dentist and confectioner—should be able to agree on safeguards to optimize both of their uses of their property. It might be efficient for the confectioner to pay for insulation that protects the dentist from any noise made by the confectioner's machinery. Rather than allowing and encouraging such win-win bargains (often referred to as "Coasian bargains"), however, the FCC decides for itself what uses and technical requirements are optimal. Thus, in the case of the dentist-confectioner hypothetical as applied to spectrum policy, the FCC would arrogate to itself whether and under what circumstances the two parties could coexist. In so doing, the

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FCC generally ignores the possibility that the two parties could reach mutually beneficial accommodations under a property rights regime, making them both better off.

In the 1990s, more than 30 years after Coase's powerful critique of spectrum policy, its compelling logic made his criticisms the starting point for any discussion of spectrum policy.[6] The movement toward reform culminated in an FCC "Spectrum Policy Task Force Report," which set forth comprehensive findings and recommendations for spectrum policy reform.[7] The central conclusion of this report was that the key failing of spectrum policy was not the scarcity of available spectrum, per se, but rather the administrative rigidities that prevent more efficient use of this unique resource.[8]

In almost all arguments for spectrum policy reform, commentators emphasize that developing an effective regime of well-defined and enforceable rights is essential to facilitating the improved use of the radio spectrum. Without protections against arbitrary government seizure or harmful trespass upon a licensee's property interest, individuals and firms are unlikely to make the long-term capital investments necessary to create innovative, high-tech products and services that use the radio spectrum.

Some property rights advocates simply assume that rights in spectrum can be as clearly defined and readily enforced as their real property counterparts. More sophisticated property rights advocates recognize the differences between spectrum and real property but nonetheless make assumptions that oversimplify the nature of such rights. Consequently, more careful analysis is necessary to design an appropriate property rights regime for spectrum.

Property Rights and Property-like Rights in Spectrum

The Notion of Property Rights in Spectrum

To attorneys, the concept of property denotes "a bundle of distinctive rights."[9] As one commentator put it, "The term [property rights] implies the ability to buy; hold; use; sell; dispose of, in whole or in part; or otherwise determine the status of an identifiable, separable and discrete object, right or privilege."[10] Stated more succinctly, the essence of property is the right to exclude others. Following from this principle, the quintessential protection of both real property and intellectual property law is an action for trespass (or infringement in the case of intellectual property) to prevent or redress the use of property without the consent of the owner. Along with damages, the remedy for either trespass or infringement often includes an injunction to prevent the illegal conduct from continuing or recurring.

In the wake of Coase's landmark work, a number of commentators sought to develop the particulars of how to "propertize" the radio spectrum. One notable early effort was led by Arthur DeVany, who worked with an interdisciplinary team in the late 1960s to develop a proposal for property rights in spectrum.[11] Over the last 35 years, others have amplified and reinforced the argument for property rights in spectrum. In much of that work, however, commentators have ignored, downplayed, or deferred addressing the realities of radio propagation and how it relates to the definition and enforcement of property rights in spectrum.

As a matter of practical classification, property in spectrum is neither like property in land (real property) nor property in an invention or creative work (intellectual property). Under current law, the FCC is only empowered to provide a license to use spectrum, not to sell off a particular swath of spectrum. Nonetheless, the FCC has recognized certain rights (and obligations) of spectrum licensees, including varying degrees of exclusivity or protection against interference. In so doing, however, it has not expressly recognized the license as a property-like right, thereby leaving many of the practical issues in this approach open to debate and dispute.

The conclusion that firms should be allowed to own property-like rights in spec-

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trum is, however, increasingly beyond dispute. In 1997, Congress underscored its commitment to that policy by requiring an auction for all new spectrum licenses.[12] In early 2003, the Supreme Court made clear that the policy limits how the FCC can treat licenses, invalidating an attempt to pull a license (based on its regulatory jurisdiction) from a party who had declared bankruptcy.[13] Since then, the FCC has indicated its commitment to promoting property-like rights in spectrum and has provided for increased licensee flexibility to allow greater trading in spectrum rights (including the promotion of a Secondary Markets Initiative).[14]

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Even though the merits of the case for property-like rights in spectrum are beyond dispute, the details about how such a regime would work must still be defined. To be sure, the commitment to a property rights approach for spectrum management does call for two important and clearly defined reforms that the FCC is already embracing (at least to a degree). First, the FCC is following the property rights model's lead in rejecting the use limitations that historically accompanied spectrum licenses—(i.e., rules requiring a particular type of service to be offered using a particular allocation of spectrum). Historically, those limitations have locked in particular services and business models even if others could put the licensed spectrum to high-value uses. Second, and similarly, the FCC is learning from the property rights model by moving away from requirements to use particular technologies, instead allowing licensees to use flexible architectures and to use spectrum much more dynamically. These steps, however, leave significant issues open to development and continuing debate.

Specific Rights Proposed for Spectrum

In their classic 1969 work, economist Arthur DeVany and his coauthors recognized the importance of—and the formidable technical obstacles to—establishing unambiguous and enforceable rights in the electromagnetic spectrum. Ultimately, the DeVany study proposed a multidimensional set of rights based on time, geographic area, and spectrum (band)—TAS for short. As they saw it, the owner of the TAS-based rights would have the exclusive right to produce (information-bearing) electromagnetic waves for a specified period of time (T), over a specified geographic area (A), and in a specified range of frequencies (S).[15] Moreover, they maintained, this system would enable spectrum licensees to trade their licenses and to use them however they chose, thereby giving rise to the more efficient uses of spectrum advocated by Coase in his landmark paper.

The DeVany study recognized that the exclusive possession of spectrum along the TAS dimensions would pose notable technical challenges. Fundamentally, DeVany et al. recognized that radio signals do not respect the time, area, and spectrum boundaries related to the TAS-based spectrum-use rights. In particular, it is much harder to keep a radio signal from "trespassing" along each of these dimensions than it is to keep a person or object from entering onto a particular piece of real property.

Geographic Spillover. The basic problem with geographic boundaries is easy to understand because it stems from the simple and easily observable fact that the strength of radio waves is highly variable. In particular, radio waves emanate from a transmitter antenna and, although they get steadily weaker with distance, they do not respect or automatically stop at pre-set borders. Consequently, at the border between one defined geographic area and another, there is inevitable encroachment by one spectrum licensee's signals on another's. The traditional response to this phenomenon (still widely used today) is to control the characteristics and locations of the transmitter systems. Command-and-control restrictions on the placement or types of transmitters are, however, antithetical to a flexible, market-based approach.

To address the wide variability associated with radio propagation, the DeVany study proposed rules that would limit the maximum strength of the signal at the geographic boundary. Under their approach, the owners of spectrum-use rights in adjacent regions were to be protected against interfering signals from surrounding areas at a level greater than the defined limit. Their approach also called for similar constraints with respect to the time and spectrum/frequency dimensions.

It is important to appreciate that the DeVany approach calls for a fundamental reorientation of spectrum policy. In particular, it calls for a shift from prescriptively regulating practices and activities (e.g., individual transmitter locations, powers, and antenna heights) to focusing only on the desired result (e.g., the strength of the signal at the boundary). Under such a reformed regime, the holder of the spectrum-use right can—without FCC permission—choose, for example, to deploy a high-power, wide-coverage system, a low-power, "cellularized" system with multiple transmitters and low antenna heights, or an "infrastructureless" system employing mesh network technology—as long as the out-of-area emission restriction is obeyed.

By developing a thoughtful model for spectrum property rights, the DeVany study helped to transform the debate over spectrum policy reform. Consider, for example, how, in 2000, Lawrence White, an economist at New York University's Stern School of Business, outlined the parameters of an ideal system of property rights in spectrum in 2000:

> The property right to use the spectrum should be defined in terms of a specified spectrum frequency band, a specified geographic area, and a specified time period. The property right (in perpetuity) would be expressed as the right to transmit over the specified spectrum [frequency] band, so long as the signals do not exceed a specified strength (expressed in volts/meter) beyond the specified geographic boundaries during the specified time period.[16]

In setting forth that vision, White develops a number of useful recommendations for the future role of the federal government under a reformed spectrum policy regime (including acting as a registrar of spectrum holdings, as an owner of some of the rights, and as the administrative agency responsible for resolving widespread instances of interference where private enforcement is impractical because of transaction costs). White does not, however, grapple with any of the implications of the often highly variable nature of radio propagation and radio system performance. Most fundamentally, White does not address the question of whether the dimensions used by DeVany (and adopted in his model) will be reliable in the same sense as those used by real property law.

In another important study on spectrum property rights, Evan Kwerel and John Williams of the FCC's Office of Plans and Policy adopted the essential elements of the DeVany framework, but they discuss in some detail the interference issues in both the space and frequency dimensions.[17] With regard to these dimensions and to allow maximum flexibility, Kwerel and Williams follow the DeVany precedent of proposing objective limits on the amount of signal power that can spill over into adjacent frequency bands and into adjacent geographic areas. More specifically, they suggest that this proposal follows from the success of the system currently used in controlling out-of-area and out-of-band emissions in the bands reserved for the Personal Communications Service.

Adjacent Channel Spillover. Going beyond the DeVany study, Kwerel and Williams acknowledge not only the possibility of interference between services operating in the same band in adjacent geographic areas, but also between adjacent bands in the same geographic area. The adjacent band problem underscores that interference is not a natural phenomenon—that is, radio waves do not collide in a destructive fashion—but one that manifests itself in receivers. Interference can result from (a) a transmitter emitting radio energy outside the licensee's assigned bandwidth and into an adjacent band, (b) a receiv-

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er being unable to adequately filter out the energy in an adjacent band even when the transmitter in the adjacent band is operating without spilling over, and (c) combinations of the two. Depending on the characteristics of transmitters and receivers, "adjacent channel" interference can actually extend beyond immediately adjacent channels.

Adjacent channel spillover is pervasive in spectrum use and, unlike in the typical approach with real property, part of the solution may be for the "victim" of a "trespass" to change his or her use of the property.[18] Consider, for example, a scenario in which a receiver is trying to receive a very weak (e.g., very distant) signal in band. In that case, a high-power use (e.g., broadcast television) in an adjacent band is likely to create a spillover problem. Interference in the frequency dimension can be controlled either by controlling the power of the transmitter or by requiring better filters and other techniques on the part of the receiver in the adjacent band. Each option imposes costs on one or the other user of neighboring spectrum bands, especially when very high-powered or small, portable devices are involved. There is, in short, no inherent, natural demarcation where one spectrum user's transmission power "trespasses" on the adjacent channel user's receiver sensitivity.

As Kwerel and Williams see it, the adjacent channel issue warrants a regulatory safeguard. In particular, they suggest the need for rules that would bar "extreme power levels [that exacerbate the problem receivers have with rejecting very strong adjacent signals at reasonable cost] that have little practical benefit but which, if left unchecked, could lead to excessive interference risk and harmful strategic behavior."[19] Despite the appearance of embracing a command-and-control-type rule (like the service rules generally eschewed by property rights advocates), Kwerel and Williams suggest (apropos of the Coase theorem) that a default transmitter power rule can be relatively crude because different licensees can then renegotiate the applicable limits. Reflecting their faith that such Coasian bargains will take place, Kwerel and Williams conclude that the government need not recommend minimum receiver performance standards except in special circumstances.

Toward a Legal Regime for Spectrum. The final, and most significant, development since the DeVany-led study is a recent paper by Robert Matheson. In his paper, he presents the most complete set of property-like rights in radio spectrum as well as the fullest discussion of the practical challenges and limitations of actually employing such rights in the management of the resource.[20] Whereas DeVany et al. set forth a model based on time, area, and spectrum (TAS), which has four dimensions—time, two dimensions of geographic location (latitude and longitude), and frequency—Matheson proposed a model based on seven dimensions. To minimize confusion with the term "spectrum" (which normally only refers to the frequency dimension), Matheson calls his seven-dimension model the "electrospace."

The seven dimensions of electrospace include frequency; three dimensions of location (latitude, longitude, and elevation); time; and two possible directions of arrival (azimuth and elevation angles). By adding altitude as a dimension, Matheson envisions that a holder of spectrum-use rights might choose to sell or lease "air rights" above a ground-based system. As for direction of arrival, Matheson bases that dimension on the fact that a receiver can discriminate between radio waves arriving from different directions. In particular, by using directive antennas, a receiver can gather a greater amount of energy from a signal arriving from one direction while minimizing or "nulling out" the energy of an otherwise interfering signal arriving from a different direction.

Like other proponents of spectrum property rights, Matheson emphasizes the importance of allowing technological flexibility in, and free trading of, spectrum rights. In particular, Matheson suggests that the holders of spectrum-use rights be free to divide or aggregate spectrum along any of the electrospace dimensions. Notably, however, Matheson's added complexity, while more sophisticated and realistic, also raises new difficulties. It is just as impractical to build antennas that focus all of the transmitted energy in a single direction or cone as it is to build transmitters that confine all of the transmitted energy to one frequency range or channel. By arguing for spectrum owners' rights against (and in protection of) direction of arrival, Matheson's proposal begs (and does not answer) the question of how that measure could be effectively enforced.

On the issue of whether a maximum power level must be specified to avoid adjacent channel interference, Matheson refines the approach taken by Kwerel and Williams. He notes that the power impinging on the receiving system is the critical issue and thus it is better to regulate the actual power level received at ground level or a specified location (as opposed to at the transmitter). This approach would regulate results and not practices and activities, thereby giving the spectrum licensee greater flexibility in how to meet the relevant constraint while still offering protection to the receivers at risk of interference.

Unlike earlier proponents of the property rights approach, Matheson appreciates many of the difficulties and implications of defining exactly how the rights are to be specified. In particular, Matheson realizes that setting limits on the spillover outside each of the electrospace dimensions and on the maximum power levels that can be used inside those dimensions is much more difficult and costly than policing trespass on land. He explains, for example, that a very stringent limit on the spillover effects into an adjacent geographic area may force the rights holder to reduce power such that significant "holes" in coverage are produced near the boundary. Or it may force the rights holder to select a cellular architecture with multiple low-power/low antenna-height sites in order to control the spillover and still provide the necessary coverage. By contrast, a very generous limit on spillover into adjacent geographic areas would impose costs on the rights holder across the boundary who, for example, would have to adopt more expensive interference mitigation techniques.

Of all commentators since DeVany, Matheson makes a particularly important contribution in advancing the state of the debate and discussion about how property rights in spectrum would operate. Notably, he highlights how choices about maximum power levels do not lend themselves to easy answers. They may well dictate the use of particular technologies, even if those technologies are not otherwise cost-effective. Moreover, there are important enforcement questions only beginning to be examined—such as whether it is possible to "game" the system through the use of multiple transmitters/spillover limits. Unfortunately, even Matheson does not analyze the nature of radio propagation and the implications of its wide variations for establishing clear and enforceable property-like rights in the radio resource. We proceed to discuss this very difficult challenge.

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Radio Wave Propagation and Its Effect on Spectrum Property Rights

The Basics of Radio Wave Propagation

As discussed earlier, radio waves weaken as they travel away from the transmitter. In free space, radio waves steadily weaken in a very uniform, predictable way and at a rate that depends on frequency.[21] In particular, the higher the frequency, the faster the waves weaken. In the real world—on the earth and in its environs—the situation is much more complicated, and radio links are affected by the earth itself, the atmosphere, and the intervening topography and natural and manmade objects such as foliage and buildings. The magnitude of those effects depends heavily on the relevant frequency (again, with the higher frequencies generally affected more).

At the lowest radio frequencies, below 100 kHz or so, radio signals travel in a reliable way between the earth and a portion of the atmosphere known as the ionosphere.[22] Thus, using very high power transmitters, guided signals sent at this frequency can travel over great distances and penetrate into the ocean. At higher frequencies, in roughly the 300 kHz to 3 MHz range, radio technology relies on two basic modes of propagation: ground waves and sky waves. Ground waves, as the name suggests, travel close to the earth's surface (and thus cover limited distances unless repeated), whereas sky waves travel into the earth's atmosphere and are reflected or bounced back (often over a very long distance) by the ionosphere.

Transmissions using these lowest frequencies are far less predictable. The strength of signals from traditional AM broadcasting stations (and the interference between and among them) is likely to vary significantly from daytime to nighttime, location to location, and season to season. In the daytime, coverage is provided by the ground wave and the service is comparatively reliable but relatively limited in range. In the nighttime, however, the radio signals in this range are carried beyond the horizon by reflections from the ionosphere, permitting coverage over much greater distances but with a penalty in terms of stability because of the highly variable conditions of the ionosphere.

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The next highest range of the spectrum, the 3 MHz to 30 MHz range, is traditionally referred to as the shortwave region. In this region, the ground wave component becomes less important and the signals are carried over vast distances by reflections from the ionosphere or even serial reflections between the earth and the ionosphere. At one time, before the advent of communications satellites and high-capacity undersea fiber optic cables, this portion of the spectrum was particularly prized for long-haul, intercontinental communications in military, governmental, and commercial applications. Propagation conditions in this region of the spectrum, however, vary widely with the condition of the ionosphere (including the maximum frequency that will be successfully reflected), and those conditions depend upon location, season, time of day, and level of solar activity. Because of this high variability, the relatively limited bandwidth available, and the size of the antennas required, this portion of the spectrum is no longer as desirable as it once was.

The region of the spectrum between 30 MHz and 300 MHz is known as the very high frequency (VHF) region and it is home to a number of popular services including VHF television, FM radio broadcasting, and a number of mobile services. The lower portions of the VHF range exhibit some of the negative characteristics of the shortwave region because very long distance ionospheric propagation (and associated interference) occurs in certain seasons, efficient antennas are still somewhat unwieldy for mobile/portable applications, and building penetration is often difficult.

The ultrahigh frequency (UHF) portion of the radio spectrum—the portion between 300 MHz and 3,000 MHz (3 GHz)—is widely regarded as the most desirable range for a variety of applications, especially those involving communications with mobile/portable devices. In this region, efficient and directive antennas are reasonable in size, the frequencies are high enough to avoid undesirable ionospheric reflections, the necessary power is easy to generate, natural and man-made sources of unintended interference (e.g., from fluorescent lights or digital computers) are negligible or significantly lower than in other bands, and radio wave propagation into and around buildings is not unreasonably difficult. The region is home to UHF television broadcasting, both cellular telephony and the Personal Communications Service, and a host of other important services.

Despite its desirable, more stable characteristics, radio signals in this portion of the spectrum are still subject to a host of vagaries that cause the strength of signals to vary widely. The signals are subject to being (a) refracted (bent) by the earth's atmosphere, (b) diffracted (turned) by edges of obstructions such as buildings, and (c) reflected (bounced) off of natural and man-made obstacles such as mountains and buildings.

Unlike even higher regions of the spectrum, frequencies in this range are not affected significantly by rain, snow, and fog, but they are absorbed to varying degrees by foliage and other clutter.

Frequencies in the UHF range are also subject to multipath fading. As the name implies, multipath fading occurs when multiple copies of the same signal arrive at a receiver via different paths. This might include a direct or "line-of-sight" path from the transmitting antenna to the receiving antenna and one or more indirect paths created by reflections from buildings, nearby vehicles, water, or other terrain features such as mountains.[23] Because the reflected signals travel over a longer distance than the direct signal, they arrive at slightly later times or, to use the more technical term, with different phases. In some cases, when the different signals are "in phase," they will add together in the receiver and increase the strength of the received signals. In other cases, when the signals arrive "out of phase," they will tend to cancel each other out, producing sometimes very deep fades in the signal power received.

The above description of radio propagation in the 300 MHz to 3 GHz range implies rather static conditions, but, of course, the actual situation is typically much more dynamic. For example, the amount of atmospheric refraction is not constant but rather changes with weather conditions. Atmospheric refraction of radio waves is useful in that it normally extends the transmission range somewhat beyond the physical horizon but, as the refractive index changes with weather patterns, it produces variations over time in the received signal strength at a single location. Indeed, in certain summertime conditions, over bodies of water, or both, a rather dramatic situation may occur in which the radio signal is carried over great distances (hundreds of kilometers) because of a phenomenon known as "ducting." Again, this may produce much stronger signals (and hence greater interference) in distant receivers than normal. Time variations in received signal strength can also be produced by changes in the multipath conditions such as when a nearby truck producing a reflection moves or the antenna tower sways or twists in the wind. Longer term variations in received signal strength can also be produced by seasonal variations in the amount of foliage and, hence, in the amount of absorption that the radio wave is subjected to.

In addition to time variations in received signal strength at a particular location, even slight changes in location can produce wide variations as well. For example, in the multipath situation, a slight change in location (a few tens of centimeters) may mean that signals that formerly combined to produce a strong signal subtract or cancel one another to produce a much weaker signal. In addition, a person using a cellular radio handset may be in the radio "shadow" of a tall building. Moving around the corner may increase the signal significantly when the line to the transmitter is no longer blocked. Similarly, as mentioned earlier, the strength of the received signal can vary significantly with altitude. For example, a receiver located at ground level under a thick covering of foliage may receive a very weak signal from a distant base station while a receiver located in the upper stories of a nearby building with line of sight to the transmitter may receive a very strong signal. In short, even in the high-value portion of the radio spectrum between 300 MHz and 3 GHz, radio signals received from distant locations are likely to vary significantly with time, with small changes in location, and with changes in altitude.

Because they travel different paths, the strength of the desired signal and interfering signals will often vary independently, so that interference may manifest itself one moment and virtually disappear the next. That variability means that the desired and interfering signal strengths at particular locations can, as a practical matter, be predicted only in a statistical sense. To date, however, commentators have largely glossed over this critical point, proceeding as if the signal strength at the boundary is a reliable and constant level that can be easily managed in the manner of

Even in the high-value portion of the radio spectrum, radio signals received from distant locations are likely to vary significantly with time, with small changes in location, and with changes in altitude.

detecting trespass to land. To underscore how proponents of the property-rights model have not adequately addressed this point, the next section discusses the case of AM radio.

AM Radio

As one of the first regions of the spectrum to receive commercial, legislative, and regulatory attention, AM radio constitutes a notable and historic case study. More important, that region exhibits some of the widest variability in propagation conditions. Consequently, it presents some of the most difficult challenges for defining the appropriate property rights.

In sharp contrast to AM radio, the use of "the PCS bands" (those used for cellular telephone service) present some of the easiest cases for property rights advocates. Services in that favorable frequency range are cellularized—an architecture that is easy to manage. And users of this spectrum are repeat players with long-term interests that give them incentives to cooperate with one another. By focusing on the easiest case and ignoring the wide variety of difficult challenges, property rights advocates often understate the difficulty of reforming spectrum policy to facilitate a market-based environment.

AM radio presents some of the most difficult challenges for defining the appropriate property rights.

As explained above, in the AM broadcast band between 550 kHz and 1.71 MHz, the propagation conditions change dramatically due to the influence of the ionosphere. During the daytime, the lower layers of ionosphere absorb radio waves in this range, making it difficult (and rare) for signals to travel very long distances. Thus, during the day, the transmission ranges are limited to ground-wave distances. During the nighttime hours, however, the lower layers of the ionosphere disappear and the waves are reflected far beyond the horizon by the upper layers. During the transition hours between daytime and nighttime, the signal levels are particularly volatile.

The conditions of the upper layers of the ionosphere not only vary widely at night and during transition hours, they vary from hour to hour or with the season of the year, the level of solar activity, and the location (e.g., latitude) of the transmission path. Moreover, this portion of the spectrum is particularly susceptible to natural interference (i.e., static) produced by lightning strikes from both local and distant thunderstorms. During the summer months static may effectively mask interference from distant stations, whereas, during the quiet winter months signals from thousands of kilometers away produce noticeable interference to local stations. Finally, the interference between the groundwave and skywave signals can, at certain distances, cause severe multipath fading effects, making the desired signal more or less susceptible to interference from one moment to the next.

For a band like that traditionally used for AM broadcasting, it seems impractical, if not impossible, to provide licensees with anything close to certainty in terms of interference protection—at least using the classic property law trespass concept. If, for example, a station in an adjacent—or more remote—geographic area could prosecute a trespass claim against a transmitter that created interference, it could seek damages or injunctive relief based on a series of natural conditions that happen only infrequently. Stated in the terms used by the DeVany study, the question is this: Under what conditions do you measure signal strength at the boundary? Unfortunately, there are no easy answers to this question because the realities of radio wave propagation in this region of the spectrum simply do not lend themselves to clear and enforceable boundaries for the geographic area dimension of the spectrum resource.

In a recent paper, Charles Jackson, an independent telecommunications consultant and former FCC official, recognized the long-range interference issues associated with the AM broadcasting band and argued that pervasive interference in the band "creates multiple interlocking externalities that cannot be taken into account in simple market transactions."[24] He concluded, as we do, that "a spectrum management system for the AM band using property rights based on station licenses would face enormous difficulties."[25] Jackson determined that the cellular and PCS bands are more amenable to a property rights regime because of "limited signal range, systems operating over large blocks of spectrum and over large geographic regions, and control over both transmitters and receivers by the system operator."[26]

Were licensees allowed property-like rights in spectrum along the lines available for landowners, there would be a risk that they would bring trespass claims as a means of extracting payments from unlucky transmitters. In particular, Firm A could acquire a license for an area reached, even very intermittently, from Firm B, who is already in operation and does not possess the right to transmit to that location at that signal strength. By bringing a trespass action to enjoin the transmission from Firm B to that location, Firm A would gain enormous leverage over Firm B, which would fear an injunction that would potentially shut down its service or, at a minimum, waste a substantial investment of its resources. To avoid such an outcome, Firm B might well agree to a costly and oppressive "licensing" or "easement" arrangement that provides great rewards to Firm A regardless of whether Firm A is using or intends to use its spectrum at all. In our view, this scenario would be far worse than the current system's reliance on "muddy entitlements"—that is, ill-defined rules that are enforced only to a limited degree (as in the case of AM radio).[27]

The above discussion of a property right being opportunistically acquired and enforced is hardly speculative. In fact, it parallels the intellectual property rights nightmare of the "patent troll." Patent trolls buy up patent rights—which provide a complete right to exclude others from the use of an invention—knowing that other firms are using the invention unaware of the patent or believing it will not be enforced. Then, without ever producing a product, the patent troll invokes its patent rights. Because the patent user has made irreversible investments, the patent troll can use its leverage—i.e., the threat of an infringement lawsuit—to extract a significant licensing fee.

Using Performance Predictions in Establishing and Enforcing Property Rights

As discussed above, property rights in spectrum cannot operate identically to their real property counterparts. Property rights in spectrum will also need to differ from the ideal vision set forth by the DeVany study and its successors. In particular, spectrum boundaries will often be measured statistically and enforcement will have to be tailored so as not to replicate the patent-troll problem. In this section, we begin to outline a model of property rights we view as realistic and appropriate.

In designing radio systems that utilize the 300 MHz to 3 GHz range of the spectrum, engineers make extensive use of mathematical models to estimate the performance of radio tranmissions. In basic terms, these models are used to compute what is known as "transmission loss," or the change in signal power from the transmitter to the receiver. By knowing the transmitter output power and the predicted transmission loss for a particular path, an engineer can estimate the strength of the signal that will be received. The same models predict the level of interference that will be received from other, distant transmitters on the same or adjacent channels. Calculating the level of the desired signal and the level of the undesired signal(s) (along with the assumed or measured characteristics of the receiver), the engineer can estimate the end-to-end performance of the radio link in terms of, say, availability and audio quality or bit error rate. The engineer can also conduct cost and performance tradeoffs, for example, among an increase in signal power at the transmitter, a more focused/directive antenna, or improved sensitivity of the receiver.

Any likely successor will need to rely on predictions of signal strength to a considerable degree, as does the existing regulatory regime of spectrum usage. Predictive models

Property rights in spectrum cannot operate identically to their real property counterparts.

In some cases, a predicted model of signal coverage and its real-world counterpart will look nothing alike.

range from relatively simple ones ("back of the envelope calculations") to very complex software programs. More complex models are typically based on electromagnetic wave theory; empirical results based on extensive field measurements in different environments; or, often, a combination of the two.

In addition to their complexity, models also differ in how they deal with site-specific factors. In some cases, the relevant information (e.g., the locations of both terminals and the intervening terrain) will not be known in any detail, leading engineers to rely on "site-general" models. A site-general model is likely to yield predictions of signal strength along a radial from the transmitter site that decreases monotonically with distance from the site. By adopting the simplifying assumption that signal strength drops off consistently with increased distance from the transmitter, site-general models produce coverage contours around the transmitter that are smooth neat maps of where a signal can be detected.

To some property rights commentators, a simple site-general model provides a picture of spectrum that is deceptively similar to real property. In reality, the actual terrain and the presence of buildings and other urban clutter is likely to affect signal strength, causing it to drop significantly in an area that is "shadowed" from the transmitter and then recover beyond. (For users of cellular telephones, this phenomenon is the explanation for some of the frustrating "holes" or gaps in coverage within a service area.) Similarly, beyond the contour of an otherwise neat coverage map, a signal may actually increase significantly—on a hilltop or other favorable location that permits a greater line-of-sight path to the transmitter site than a simple, general model might predict.

In some cases, a predicted model of signal coverage and its real-world counterpart will look nothing alike. In particular, there may be islands of coverage well beyond the predicted contour. There may be gaps and islands of coverage so numerous and complex in shape (on account of hilly or mountainous terrain or areas with tall buildings or other obstructions) as to render meaningless a predicted boundary. For television broadcasters, for example, the curves based on predicted signal strength (the so-called "Grade B contour") will often bear little resemblance to the actual broadcast area.

To make matters even more complicated, a statistical model does not produce a clear map of where signal strength will be detectable 100 percent of the time. Rather, it predicts that the signal in a given vicinity will exceed some power level *x* percent of the time and at *y* percent of the locations within that vicinity. Thus, for example, the Grade B coverage contour for a television broadcast station means that, at a point along the contour, the desired signal will be greater than the required value 50 percent of the time and at 50 percent of the locations in the vicinity of the point. The predicted strength of interfering signals at the point will have similar statistical characteristics. Stated simply, the contours of a coverage area are not sharply defined boundaries like those of real property.

There is more deviation between predicted models and reality, including assumptions and planning factors. Consider, for example, that in establishing allotments or assignments in television broadcasting, regulators make certain assumptions about the receiving antenna's height and directivity, the reduction in signal strength in the cable going from the receiving antenna to the receiver, and the required desired-to-undesired signal ratio for acceptable performance at the receiver input. If the systems do not actually conform to these assumptions, the possibility of interference becomes much more (or less) likely.

The margin for different outcomes based on planning factors is potentially a considerable wild card in any model. As noted above, a transmitter located at ground level (or, even worse, inside a building) is apt to produce a much weaker signal than one mounted on a rooftop above the surrounding obstructions. The antenna height problem is exacerbated when the corresponding transmitting/receiving unit is a handset that can be in the basement of a garage one minute and on the top floor of a building the next. The receiver itself might also vary from model to model or manufacturer to manufacturer. Part of what makes the receiver issue difficult to manage is that, in some services (like broadcasting and unlike cellular telephone service), the devices are not controlled by the licensee. The consumer is free to buy what may turn out to be equipment that either falls short of the capabilities assumed in the model or exceeds them, making the predictions of any model less likely to be accurate.

Implications for Establishing Property-like Rights in the Spectrum Resource

The historic use of propagation models to establish prescriptive service and technology rules to control interference reflected a fear that the possibility of interference would endanger the viability of valued services and thus should be avoided at all costs. This ex ante (before-the-fact) model often erred on the side of preventing entry where such entry created even the slightest possibility of creating additional interference. This model also played right into the weakness of the command-and-control model of spectrum management as it bolstered the rent-seeking claims of incumbents who viewed entry as a threat to their bottom line.

The old ex ante model also played to the New Deal sensibility that the FCC knew best about how spectrum could and should be used. Even on the most generous of assumptions, confidence in this approach was misguided. In particular, even if the planning factors (assumptions) were all correct (including the required desired-to-undesired signal ratios) and the models accurately predicted the contours and the strength of the interfering signals, a receiver could be at an "unlikely place and time" where the desired signal is weaker or the undesired signal is stronger due to normal variations in radio propagation conditions. Alternatively, even if the planning factors were all correct but the propagation model did not correctly predict the coverage contour or the level of the undesired signal, a receiver could still be in an "unlucky place and time." Finally, it is possible that the planning factors themselves were inadequate or otherwise incomplete, resulting in unanticipated interference.

Because they constructed their model for spectrum management on the basis of property rights and the promise of Coasian bargaining, past commentators naturally moved to the property line, operating under the theory that actual spillover (spectrum "trespass") would form the basis for boundary disputes. Although this may be plausible in certain cases (such as PCS), we have shown that geographic boundaries are less predictable and controllable in the AM band and others with suboptimal propagation characteristics. The movement to property-like rights and ex post enforcement thus may flounder if based on addressing spillover effects alone.

The movement to property-like rights and ex post enforcement may flounder if based on addressing spillover effects alone.

Using Predictive Models in Ex Post Property Rights

Building upon current practice in some services (e.g., television broadcasting), it is possible to develop a system of spectrum-use rights based on *predicted* signal strengths that could be enforced after the fact. Geographic boundaries could be established, and the owner of a block of spectrum in the frequency dimension would have the right to spill energy over into the adjacent geographic areas up to some maximum amount. Exceeding the maximum would violate the neighbor's property right. Rather than being measured at the boundary, however, the spillover amount or level could be computed using an established propagation model.

It is important to note that, as a threshold matter, this system would suffer all of the challenges described above in terms of establishing the initial maximum levels and establishing the receiver antenna height for predicting the actual level that would be present from the transmitters. Nonetheless, in designing a legal regime for spectrum rights, it may well be necessary to incorporate a predictive model into the definition of the rele-

A property rights system that relies heavily on ex ante predictions rather than ex post findings of actual interference would, involve several sacrifices.

vant right—a challenge, to be sure, not confronted by real property rights. Moreover, there is still the question of whether bargaining over predictive models would raise transaction costs beyond acceptable limits and be legally administrable.

Despite its associated challenges, using a predicted rather than a measured level at the geographic boundary has two major advantages. First, it is a relatively simple approach, although regulators may well opt for some degree of complexity to provide adjacent parcel owners greater initial assurance against actual interference. Second, this approach has the advantage of potentially lower enforcement costs since it uses computer modeling rather than expensive field measurements. In the case of television broadcasting and, to a certain extent, commercial mobile radio services, such models are already in use and are working reasonably well.

A property rights system that relies heavily on ex ante predictions rather than ex post findings of actual interference would, however, involve several sacrifices. First, any system that provides discretion for the FCC to determine the specifics of a predictive model risks inviting rent-seeking behavior by incumbents. Second, licensees may not get the certainty they require from a predictive model, requiring them to adopt additional measures (be they cooperative arrangements or technical contingency plans). Finally, a system based on predictions leaves open the question of how to enforce property rights when there is a major discrepancy between predicted and measured levels at the boundary. To be sure, allowing some measure of a safe harbor is advisable, but unless the predicted contours are reasonably close to reality (and checked to some degree against reality), spectrum licensees may well resist making investments in equipment that will be ineffective in delivering a promised service.

Up to this point, we have addressed two broad categories of interference problems associated with establishing property-like rights in spectrum. The first is geographic spillover between neighbors operating in the same frequency and the second is adjacent channel interference—spillover in the frequency dimension between systems that are in the same geographic area. There are other interference mechanisms that we have not addressed in this paper. These include spurious emissions from transmitters (as opposed to adjacent channel spillover in the frequency dimension), transmitter and receiver intermodulation, and receiver desensitization due to strong out-of-band signals. These can be important in certain situations and ultimately will need to be accounted for and addressed in any property-rights regime.

In the case of adjacent channel interference and geographic spillover, we have described the difficulties associated with choosing the initial limit on signal strength at the transmitter and at the geographic boundary. On one hand, setting a limit that is too stringent risks forcing the rights holder to reduce power to the point of creating coverage holes, forcing it to adopt a cellular architecture that may not be optimal for a particular service, or forcing it to deploy additional cell sites to provide adequate coverage while staying under the spillover limit. On the other hand, setting limits that are too lenient may impose excessive mitigation costs on the rights holder across the geographic or frequency boundary, including costs associated with increasing transmitter power to overcome the interference or abandoning service in areas where the interference is excessive.

Compounding the issues related to limits on signal strength, we also underscored that the actual signal strength at the geographic boundary can vary significantly. In particular, depending on the height of the receiving antenna as well as the time and location in the immediate area of the receiver (vis-à-vis their effects on radio propagation), results can vary widely. To emphasize this point, we analyzed the extreme but historically important case of AM radio. In so doing, we described the wide changes in signal strength due to diurnal, seasonal, solar cycle, and path location variations, concurring with Jackson's conclusion that introducing a property-rights regime in the AM radio band along the lines used for real property would face enormous—and likely insurmountable—difficulties.

The PCS Story: Precursor or Anomaly?

Despite the difficulties associated with establishing property rights in space and frequency dimensions, we cannot ignore the fact that the FCC has established similar rights in certain services, namely television broadcasting and the commercial mobile radio service, and that interference issues at the associated boundaries have been successfully resolved. Notably, valuable transactions involving the transfer of those rights take place on a routine basis. For example, in cellular and PCS, the geographic spillover limit is expressed in terms of the maximum signal strength permitted at the boundary, and, apparently, disputes over interference at the boundary are routinely and successfully resolved without the involvement of the FCC.

The success in cellular and PCS is usually attributed to two principal sets of reasons. First, the technical characteristics of PCS services make them less prone to interference. Not only do the large geographic areas associated with cellular and PCS bands make geographic spillover a concern in a relatively small percentage of the total area, but the fact that such systems are "cellularized" creates a greater opportunity to limit interference. Second, because providers of cellular and PCS services are stable "repeat players," there are considerable incentives for cooperative behavior and strong reasons not to engage in strategic behavior along the lines of patent trolls.

In short, like other environments where industry norms are effective regulators, the commonality of interest among cellular and PCS providers reflects a shared understanding that there is a mutual threat of interference and a mutual benefit to cooperation. Moreover, because such negotiations continue over time and often involve engineers who may adhere to a professional ethic to act in good faith (i.e., honestly report technical capabilities and limits), this environment is uniquely suited to cooperative behavior—even if the entitlements themselves are not clearly defined or enforced by the FCC. Consequently, even though the reality of the spectrum property right is "muddy," the affected parties are still able to agree on mutually beneficial accommodations.

The optimism that Kwerel and Williams take from the PCS model is potentially misplaced. To be sure, it is theoretically possible that transaction costs between identifiable neighboring users of spectrum will be low and that mutually beneficial arrangements (like that in the PCS context) will be the rule. We are skeptical that this confidence will be borne out and think it likely that the uncertainties or muddiness of geographic boundary rights caused by signal strength variations due to propagation effects will make it difficult for many parties to agree on reasonable arrangements to avoid interference. Instead, it is quite possible that regular or occasional islands of high signal levels, interference, or both across geographic boundaries that are tolerated today will become the subject of litigation with more clearly defined spectrum rights. In the worst possible case, such litigation will be strategic and brought by the spectrum equivalents of patent trolls.

Conclusion

Coase's vision of promoting a market for licenses to use the radio spectrum remains the guiding light for spectrum reform efforts. Building on that wisdom, numerous commentators have charted paths to facilitate markets for spectrum licenses and a legal regime to enforce property-like rights. Such paths, however, may fail to achieve their goals because defining rights to use spectrum is far more difficult than ordinarily suggested. The case study of PCS services is, for a number of reasons, potentially misleading about the broader possible success of spectrum property

The FCC has established similar rights in certain services, and interference issues at the associated boundaries have been successfully resolved.

rights for bands lacking some of the unique characteristics of that band and the providers offering PCS services. Consequently, there is a need for more careful analysis about what type of property regime will operate effectively to govern rights in spectrum. We concede that we have not solved all (or even most) of the numerous issues related to defining spectrum rights, but we believe that we have identified a number of questions that must be answered for the move to a property rights regime to be successful.

Notes

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1. For a discussion of the digital transition and the challenges of freeing up more spectrum, see Drew Clark, "Spectrum Wars," *National Journal*, February 18, 2005, http://nationaljournal.com/about/njweekly/stories/2005/0218njsp.htm.

2. Technically, the Communications Act does not allow any individual or firm to possess a property right in radio spectrum. See 47 U.S.C. § 301; see also Note, "Federal Control of Radio Broadcasting," *Yale Law Journal* 38 (1929): 250 (the premise that "'the government owns the ether' was an idée fixe in the debates of Congress" over the Radio Act of 1927). Nonetheless, the FCC, with the support of Congress, has moved toward a "property rights-like" treatment of spectrum licensees. Consequently, we will often use the phrase "property-like" rights, but we will also use the less precise (and often used) terms of "property rights," "property rights" advocates, or "property rights" model.

3. One kHz is one thousand Hz, one MHz is one million Hz, and one GHz is one billion Hz.

4. For an in-depth discussion of these functions, see Jonathan E. Nuechterlein and Philip J. Weiser, *Digital Crossroads: American Telecommunications Policy in the Internet Age* (Cumberland, RI: MIT Press, 2005) pp. 231–39.

5. See R. H. Coase, "The Federal Communications Commission," *Journal of Law and Economics* 2 (1959): 17–40.

6. For a listing of some of the leading scholarship in the wake of Coase's critique, see Ellen P. Goodman, "Spectrum Rights in the Telecosm to Come," *San Diego Law Review* 41 (2004): 271, n.3.

7. See Federal Communications Commission, "Spectrum Policy Task Force Report," November 2002, http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf.

8. Ibid., pp. 14–15.

9. Glen O. Robinson, "Spectrum Property Law 101," *Journal of Law and Economics* 41 (1998): 609.

10. William L. Fishman, "Property Rights, Reliance, and Retroactivity under the Communications Act of 1934," *Federal Communications Law Journal* 50 (1997): 2.

11. Arthur S. DeVany et al., "A Property System for Market Allocation of the Electromagnetic Spectrum: A Legal-Economic-Engineering Study," *Stanford Law Review* 21 (1969): 1499.

12. "Implementation of Sections 309(j) and 337 of the Communications Act of 1934 as Amended," *FCC Record* 15 (2000): 709.

13. *FCC v. NextWave*, 537 U.S. 293 (2003).

14. See "Promoting Efficient Use of Spectrum through Elimination of Barriers to the Development of Secondary Markets," *FCC Record* 18 (2003): 604; see also FCC Secondary Markets Initiative Web page, http://wireless.fcc.gov/licensing/secondarymarkets/.

15. The terms frequency and spectrum are sometimes used interchangeably. Here "S" refers to the frequency dimension of the spectrum resource, not the resource more generally.

16. Lawrence J. White, "'Propertyzing' the Electromagnetic Spectrum: Why It's Important, and How to Begin," *Media Law and Policy* 9 (2000): 29–30. Notably, White embraced the phrase "propertyzed" as opposed to "privatized" because, as he explains, the government may still own substantial amounts of spectrum for its own internal uses (e.g., national defense and homeland security) under a property rights regime.

17. Evan Kwerel and John Williams, "A Proposal for a Rapid Transition to Market Allocation of Spectrum," Federal Communications Commission, OSP Working Paper Series no. 38, November 2002, pp. iv–v, http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228552A1.pdf.

18. We say "typical" because there are exceptions where the law withholds protection from property owners under certain conditions, in effect requir-

ing them to protect themselves. See, e.g., *LeRoy Fibre Co. v. Chicago, Milwaukee & St. Paul Railway Company*, 232 U.S. 340 (1914) (announcing a rule that protects farm owner from harm caused by sparks emitted by passing trains).

19. Kwerel and Williams, p. 46. By "strategic behavior," the authors are referring to actions designed to optimize results favorable to a particular party even if those actions risk hurting others and may well undermine overall social welfare.

20. Robert J. Matheson, "Flexible Spectrum Use Rights Tutorial," International Symposium of Advanced Radio Technology, 2005, http://www.its.bldrdoc.gov/pub/ntia-rpt/05-418/05-418_matheson.pdf.

21. Free space is a theoretical concept of unlimited space devoid of all matter. Here the term implies remoteness from material objects that could influence the propagation of electromagnetic waves. See the definition of free space in Federal Standard 1037C, *Glossary of Telecommunications Terms*, http://www.its.bldrdoc.gov/fs-1037/.

22. The ionosphere is part of the earth's atmosphere that extends from about 70 to 500 kilometers above the earth. In that region, ions and free electrons exist in sufficient quantities to reflect and/or refract electromagnetic waves. The ionization is produced by radiation from the sun and hence varies with the position of the sun and with solar activity.

23. In over-the-air television, multipath is what sometimes produces a "ghost" image on a television screen.

24. Charles Jackson, "Limits to Decentralization: The Example of AM Radio Broadcasting or Was a Common Law Solution to Chaos in the Radio Waves Reasonable in 1927?" Telecommunications Policy Research Conference, 2005, p. 1, http://web.si.umich.edu/tprc/papers/2005/454/Limits%20to%20Distributed%20Decisionmaking%20TPRC%202005.pdf.

25. Ibid., p. 1.

26. Ibid., p. 34.

27. See Carol M. Rose, "Crystals and Mud in Property Law," *Stanford Law Review* 40 (1986): 592.

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