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BEYOND COASE: EMERGING TECHNOLOGIES AND PROPERTY THEORY

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INTRODUCTION

In 1959, Ronald Coase published his landmark paper on the Federal Communications Commission (FCC) that would forever change the study of property rights.[1] The primary focus of Coase's article was to critique the FCC's then-current approach to allocating spectrum, in which the FCC designated frequencies exclusively for particular uses (e.g., AM radio, television broadcasting, radio astronomy), divided those bands into individual licenses, and then conducted hearings to determine to whom the Commission should assign operating licenses created within those bands. These restrictions were thought necessary to prevent the chaos that occurs when multiple people attempt to use the same frequency simultaneously as well as to limit the interference that particular uses impose on adjacent frequencies.[2]

Coase offered two trenchant criticisms of the prevailing regime. First, he argued that the public would be better served if the FCC stopped relying on administrative processes to allocate spectrum and instead relied on auctions to determine who should receive licenses.[3] Second, he asserted that the government need not predetermine spectrum uses in order to prevent interference. The government needed only provide a clear definition of the rights encompassed within each license and to permit the license holders to reallocate interference rights as they saw fit.[4] Although Coase recognized that spectrum usage exhibited unusual interdependencies, he expressed confidence that

[1] R.H. Coase, *The Federal Communications Commission*, 2 J.L. & ECON. 1 (1959).

[2] *See id.* at 12-13, 25-26 (summarizing the rationale for the FCC's policy).

[3] *Id.* at 14, 17-19.

[4] *Id.* at 25-27, 30.

the parties could address such complexities through artful structuring of transactions and general legal principles.[5]

Coase's article on the FCC soon took on "iconic significance for law and economics scholars."[6] When pressed to expand on his vision of how market transactions could address externalities without direct regulation, Coase responded with *The Problem of Social Cost*,[7] which laid out what would become known as the Coase Theorem.[8] This work is often described as the most-cited article of all time in both law and economics,[9] served as one of the justifications for awarding Coase the Nobel Prize, and has become "the starting point of most modern discussions of the economics of property rights."[10]

Coase's impact on spectrum policy was equally dramatic. The FCC conducted its first spectrum auction in 1994,[11] and, with only a few designated exceptions, current law now requires that the FCC allocate all future licenses via auction.[12] But the FCC has yet to fully embrace the second half of Coase's vision, which calls for replacing use restrictions with property rights. The FCC has taken limited steps toward allowing licensees to include secondary uses of spectrum so long as they do not interfere with the designated primary use,[13] despite criticisms that it

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[5] *Id.* at 29-30.

[6] Thomas W. Merrill & Henry E. Smith, *What Happened to Property in Law and Economics?*, 111 YALE L.J. 357, 371 (2001).

[7] *See* R.H. Coase, *The Problem of Social Cost*, 3 J.L. & ECON. 1, 1 n.1 (1960) ("[C]omments which I have received seemed to suggest that it would be desirable to deal with the question in a more explicit way and without reference to the [FCC's regulation of spectrum].").

[8] *See* GEORGE J. STIGLER, THE THEORY OF PRICE 113 (3d ed. 1966).

[9] *See* Fred R. Shapiro, *The Most-Cited Law Review Articles Revisited*, 71 CHI.-KENT L. REV. 751, 759 (1996) (verifying that *The Problem of Social Cost* is the most-cited article in law, amassing almost two times the number of citations as any other law-related article, and noting that it is often said to be the most-cited article in economics).

[10] Merrill & Smith, *supra* note 6, at 366.

[11] *See About Auctions*, FED. COMM. COMMISSION, http://wireless.fcc.gov/auctions/default.htm?job=about_auctions (last updated Aug. 9, 2006) (chronicling the FCC's transition to a spectrum auction policy).

[12] 47 U.S.C. § 309(j)(1) (2006). The designated exceptions are for key public safety radio services, noncommercial educational broadcast stations, and the initial digital television licenses allocated in 1997 to replace analog television licenses. *Id.* § 309(j)(2).

[13] *See* 47 C.F.R. §§ 1.9001–.9080 (2011) (allowing and providing guidelines for spectrum leasing); *id.* §§ 15.701–.717 (authorizing unlicensed wireless service in the television bands); *id.* § 73.295(a) (authorizing FM broadcasters to use subcarrier frequencies to provide subsidiary services such as paging); *id.* § 73.624(c) (authorizing digital televi-

would do better to permit flexibility in primary uses instead.[14] The agency also followed the 2002 recommendation of the Spectrum Policy Task Force[15] to seek comment on a proposal to replace use restrictions with a concept it called the "interference temperature"[16] before abandoning the idea as unworkable in 2007.[17] The FCC's National Broadband Plan does not mention the need for a comprehensive metric for interference, opting instead for tweaks to the existing regime of use restrictions.[18] Restricting licenses to predetermined uses essentially requires the FCC to rezone spectrum and relocate the incumbents before any new uses for spectrum can emerge. I believe that the incomplete reception of Coase's ideas provides some fundamental insights into new forms of property arising in an increasingly high-tech world. In particular, this incomplete reception suggests that the complex interdependencies that Coase downplayed may play a more important role than he initially thought.

This Article explores these key differences and their implications for property theory. Part I identifies the interdependencies that characterize modern forms of property. It begins by examining the key technical characteristics of spectrum before examining the interde-

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sion broadcasters to offer telecommunications services on an ancillary or supplementary basis).

[14] *See* Comments of 37 Concerned Economists at 5-6, Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, 68 Fed. Reg. 66,252 (2003) (to be codified at scattered sections of 47 C.F.R.) (FCC 00-402), *available at* http://apps.fcc.gov/ecfs/document/view?id=6512460886 (urging the FCC to "broaden the rights generally granted licensees, permitting *flexible use of the allocated spectrum*").

[15] *See* FCC, ET DOCKET NO. 02-135, SPECTRUM POLICY TASK FORCE REPORT 27-30 (2002), *available at* http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf (outlining the Task Force's recommendations regarding "interference temperature").

[16] *Compare* Interference Temperature Operation, 69 Fed. Reg. 2863 (proposed Jan. 21, 2004) (to be codified at 47 C.F.R. pt. 15) (proposing an interference temperature limit and procedure), *with* Establishment of an Interference Temperature Metric to Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Fixed, Mobile and Satellite Frequency Bands, Notice of Inquiry and Notice of Proposed Rulemaking, 18 FCC Rcd. 25,309 (2003), *available at* http://transition.fcc.gov/Document_Indexes/Engineering_Technology/2003_index_OET_Notice.html (proposing the interference temperature model).

[17] *See* Interference Temperature Operation, 72 Fed. Reg. 29,929 (May 30, 2007) (to be codified at 47 C.F.R. pt. 15).

[18] *See* FCC, CONNECTING AMERICA: THE NATIONAL BROAD-BAND PLAN 83, 93 (2010), *available at* http://download.broadband.gov/plan/national-broadband-plan.pdf (proposing minor changes to the current regulatory scheme for secondary markets and spectrum sharing).

pendencies in two other emergent technologies: the Internet and the distribution grid for electric power. Part II discusses the key policy implications of those interdependencies, specifically the need to develop tools to identify sources of congestion and to allocate harm among them, and it rejects some of the bases developed under the common law to deal with the problems of multiple causation. Part III examines the policy implications for the various forms of property. It begins with the now-traditional debate between property rights and commons, taking each in turn. It also considers the possibility of having a market maker span different individual properties. Part IV examines the academic literature to identify justifications for the persistence of use restrictions in light of these interdependencies.

I. EXAMPLES OF NEW PROPERTY RIGHTS

Coase recognized that spectrum involved "interconnections between the ways in which frequencies are used" that could "raise special problems not found elsewhere or, at least, not to the same degree," such as the fact that certain sources of radio emissions could cause interference across multiple frequencies and over long distances.[19] Coase also acknowledged that "[i]t may be costly to discover who it is that is causing the trouble."[20] He nonetheless downplayed the significance of this point, averring that market transactions augmented by traditional notions of tort and property law would suffice to allocate spectrum efficiently.[21] That said, he conceded that the issue was ultimately an empirical question that "only experience could show."[22]

The failure of true spectrum property rights to emerge suggests that the aspects that Coase downplayed in his analysis may be more important than he believed. The first Section of this Part analyzes the interdependencies that characterize spectrum usage. The following two Sections explore similar problems arising with respect to the Internet and the electric power grid. This analysis makes clear that modern forms of technology create interdependencies that are more complex than previous forms of property. In particular, sources of interference are more cumulative, more unpredictable, more geo-

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[19] Coase, *supra* note 1, at 30.
[20] *Id.* at 29.
[21] *Id.* at 29-30.
[22] *Id.* at 30.

graphically discontinuous, and more variable than is typically the case with real property. Moreover, the information needed to address these problems tends to be decentralized and only locally available, which both inhibits any entity from possessing the information necessary to optimize usage and makes enforcement difficult.

A. *Spectrum*

Spectrum is unusual in that a wide variety of factors affects its available capacity. Its efficiency varies with the time of day, the season of the year, and the weather.[23] Moreover, different frequencies vary in their ability to penetrate buildings and foliage, diffract through obstacles, and refract over the horizon. In addition, every wire and device that involves electric current generates some degree of interference. All of these factors are environmental qualities rather than property rights that need to be defined legally. They tend to operate within the same band of frequencies as the original transmission. They are also stable relative to the period of time of particular transmissions. Other limitations are the result of the physics of wave propagation. These give rise to interference that changes rapidly over time and across small changes in location in ways that can be difficult to predict.

1. Shannon's Law and the Cumulative Nature of Interference

One of the most fundamental, yet frequently overlooked, principles of wave-based communications is Shannon's Law. Shannon's Law holds that the maximum error-free capacity of any bandwidth-limited channel depends on the signal-to-noise ratio.[24] The louder the background noise, or the weaker the primary signal, the lower the total capacity.[25]

Although the formal proof of this principle is somewhat complex, the intuitions underlying this insight are relatively simple. Consider a conversation at a cocktail party. As the background noise increases, guests have to speak more slowly and loudly in order to be intelligible,

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[23] Arthur S. De Vany et al., *A Property System for Market Allocation of the Electromagnetic Spectrum: A Legal-Economic-Engineering Study*, 21 STAN. L. REV. 1499, 1519 (1969).

[24] *See* Claude E. Shannon, *Communication in the Presence of Noise*, 37 PROC. INST. RADIO ENG'RS 10, 16-18 (1949) (proving the effect of background noise on signal strength).

[25] *Id.*

thereby lowering the effective throughput rate for communication. One guest's increase in speaking volume is perceived by all of the other guests as noise, who then must respond by increasing their volume and slowing their communication rate. Once the total number of speakers passes a certain threshold, any further communication becomes completely impossible.

For our purposes, the fact that capacity is a function of signal-to-noise ratio makes different people's use of the spectrum highly interdependent. Because each person's signal is perceived as noise by everyone else, every person's attempt to communicate necessarily reduces the capacity available to others transmitting in the same area. Indeed, as the density of people using a wireless network increases, the capacity of that network converges to zero.[26] Moreover, because low-power uses generate relatively weak signals, they are more susceptible to interference.[27]

2. Geographic Discontinuities

The fact that signals attenuate as they propagate outwards allows more than one person to use the same spectrum if they are sufficiently dispersed geographically. The physics of wave propagation inevitably gives rise to certain imperfections. For example, the fact that the strength of a wave attenuates as it travels through space does not mean its strength drops to zero when it reaches its contour boundary.[28] Moreover, because electromagnetic waves naturally propagate outward in a circle, some degree of geographic overlap is inevitable. Those allocating spectrum must either permit gaps in coverage or tolerate some degree of overlap (and thus interference).[29] The use of smaller or variably sized circles can ameliorate the problem, but not solve it completely. Directional antennas can alter the contour so that it is no longer circular. This is done to prevent broadcasters from intruding

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[26] *See* Piyush Gupta & P.R. Kumar, *The Capacity of Wireless Networks*, 46 IEEE TRANSACTIONS ON INFO. THEORY 388, 391 (2000) (noting the decrease in throughput when the number of nodes is large).

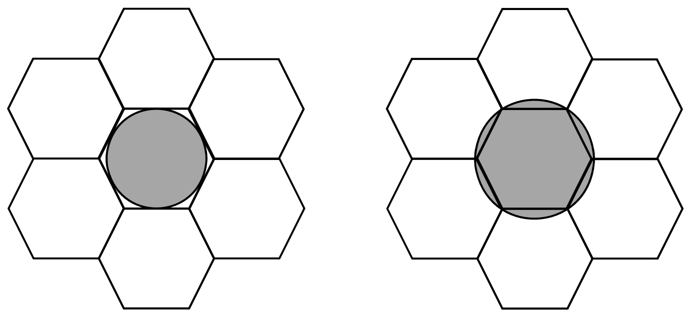
[27] *See* Phillip J. Weiser & Dale Hatfield, *Spectrum Policy Reform and the Next Frontier of Property Rights*, 15 GEO. MASON L. REV. 549, 572 (2008) (explaining how low-power use can lead to "spillover problems").

[28] *See id.* at 569-70 ("[R]adio waves emanate from a transmitter and, while they get steadily weaker with distance, they do not respect or automatically stop at preset borders.").

[29] *See infra* Figure 1.

into foreign territory or into other stations' service contours.[30] Yet such a solution only works for stationary transmission sources and is thus ill suited to the mobile wireless communications that dominate the current industry. That said, these geographic spillovers necessarily involve transmissions from adjacent areas that are relatively easy to identify and remediate.

Figure 1: The Inherent Geographic Imperfections in Coverage[31]



Interference can also arise from sources that are geographically distant. One source of interference known as "skip" occurs when radio signals bounce off the ionosphere after it descends at night.[32] As anyone who has unexpectedly picked up a distant AM radio station at night knows, skip can allow signals to cause interference hundreds of miles away.[33]

A more interesting and complex phenomenon is known as "multipath propagation," where the same signal arrives at the same point via

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[30] *See* Amendment of Part 73 of the Commission's Rules to Permit Short-Spaced FM Station Assignments by Using Directional Antennas, Notice of Inquiry, 2 FCC Rcd. 3141 (1987) (noting that directional antennas can permit the more efficient use of space by reducing required separation distances).

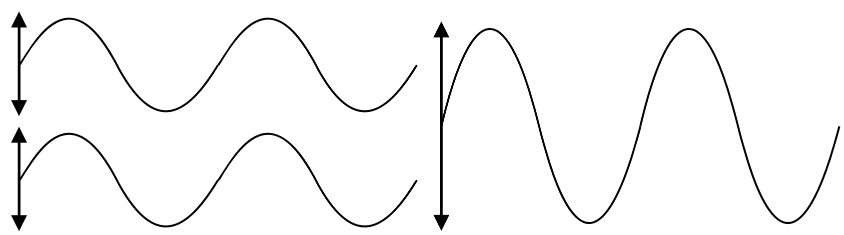
[31] If the hexagons in each image represent contour boundaries, the white areas in the center hexagon on the left represent coverage gaps, while the areas in which the center circle on the right overlaps onto the adjacent hexagons represent interference.

[32] *See* ANDREW S. TANENBAUM, COMPUTER NETWORKS 79 fig.2-12, 103 (4th ed. 2003) (depicting how the ionosphere, "a layer of charged particles circling the earth at a height of 100 to 500 km," reflects certain radio waves).

[33] *See* Richard W. Stevens, *Anarchy in the Skip Zone: A Proposal for Market Allocation of High Frequency Spectrum*, 41 FED. COMM. L.J. 43, 44 n.4 (1988) (noting that the reflection of radio waves off of the ionosphere and back to earth allows radio signals to travel long distances); *see also id.* at 46 fig.1 (depicting the skip phenomenon).

multiple routes, with one signal arriving directly and one or more other signals reflecting off some adjacent surface.[34] At a minimum, unless the receiver is able to distinguish between these signals, it will perceive the reflected signal as capacity-reducing noise.[35] Moreover, should the peaks from the direct signal arrive at the same time as the peaks of the reflected signal, the waves can reinforce each other, thereby creating a localized hot spot in which the signal is unusually strong.[36] We see such phenomena in whispering galleries, where the particular shape of the room allows sound to travel across a room even though a person speaks at a very low volume.

Figure 2: Reinforcement of Two Wave Forms that Are Perfectly in Phase



Conversely, should the peaks from the direct signal arrive at the same time as the valleys of the reflected signal, the waves can cancel each other out, as occurs with noise-dampening systems in headphones and cars. Christian Sandvig related a particularly vivid example of this. While living in London, he used an antenna to provide WiFi access to the famous Speakers' Corner in Hyde Park only to find that the signal intermittently failed.[37] He eventually discovered that the interference arose whenever a double-decker bus was forced to stop at a

[34] *See, e.g.*, De Vany et al., *supra* note 23, at 1519-20 & 1520 fig.3 (describing and depicting multipath propagation).

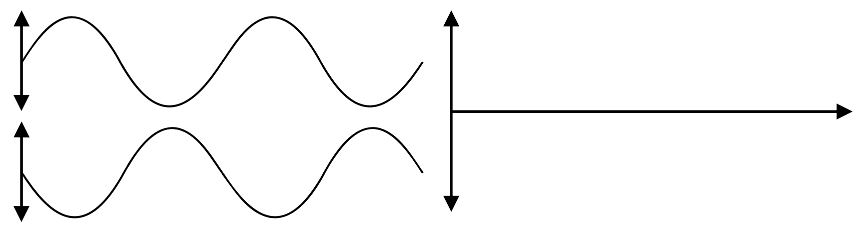
[35] *See id.* at 1520 (noting that multipath propagation resulting from two signals can have negative consequences, even where neither signal is harmful).

[36] *See infra* Figure 2.

[37] I previously recounted this story in Christopher S. Yoo, *"Rough Consensus and Running Code": Integrating Engineering Principles into the Internet Policy Debates*, 63 FED. COMM. L.J. 341, 356 (2011).

nearby traffic light.[38] Even though the bus did not directly obstruct the waves travelling to and from the Speakers' Corner, it created a multipath reflection that periodically cancelled out the direct signal.[39]

Figure 3: Cancellation by Two Wave Forms that Are 180° Out of Phase



When multipath propagation occurs, small changes in location can cause signal strength to vary widely. In addition, the precise effect can vary with the position of mobile objects, such as cars and trucks. The result is that the amount of interference can change dynamically and unpredictably minute-to-minute as a person walks across a room or if that person stays in the same location. Both the latest generation WiFi standard and the 4G standard known as LTE are able to use multiple antennas and sophisticated processing to distinguish between different multipathed signals through a technique known as "multiple input/multiple output" (MIMO).[40] However, these solutions do not prevent these multipathed signals from being perceived as interference by others.

3. Interference from Transmission on Other Frequencies

Geographic separation is not the only technique for allowing multiple parties to use the spectrum simultaneously. The FCC also divides the spectrum into different frequencies and assigns them to different

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[38] *Id.*

[39] *Id.*; *see also infra* Figure 3. For a description of the project, see PHILIP N. HOWARD, NEW MEDIA CAMPAIGNS AND THE MANAGED CITIZEN, at xi-xii (2006).

[40] *See* Kevin Werbach, *Supercommons: Toward a Unified Theory of Wireless Communication*, 82 TEX. L. REV. 863, 897 (2004) (describing "MIMO chipsets . . . that extend the range end capacity of WiFi systems").

licensees.[41] So long as the receivers are able to distinguish among transmissions on different frequencies, multiple users can transmit on different frequencies without interfering with one another even if they are operating in the same geographic area.

Frequency division multiplexing would work well if licensees could limit their transmissions to their assigned frequencies.[42] The problem is that every transmission inevitably spills over onto adjacent frequencies, with the degree of interference tapering as the distance from the base frequency increases.[43] Every transmission also generates harmonic emissions that are integer fractions of the frequency of the original transmission.[44] Transmissions can also create an unusual form of harmonic resonance known as "intermodulation," which occurs when two signals combine to cause a third transmitter to radiate on a different frequency.[45] Even though each of the original two signals does not cause any interference, the interaction between the two creates interference.

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In short, the physics of wave propagation can cause interference to be quite variable and to arise in locations that are quite distant from the original transmission in terms of both geography and frequency. As a result, interference can be difficult to trace. The fact that interference is cumulative and is sometimes produced by the interaction among multiple sources that are not themselves problematic creates the need for some basis for apportioning harm across multiple causal

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[41] *See supra* notes 11-13 and accompanying text.

[42] *See* TANENBAUM, *supra* note 32, at 104 (noting that frequency division multiplexing is characterized by "overlap between adjacent channels because the fillers do not have sharp edges").

[43] *See* Szu-wei Wang & Stephen S. Rappaport, *Balanced Channel Assignment Patterns for Cellular Communications Systems*, *in* 1 DIGITAL TECHNOLOGY . . . SPANNING THE UNIVERSE: IEEE INTERNATIONAL CONFERENCE ON COMMUNICATIONS 452, 453 (1988).

[44] *See* HARVEY J. LEVIN, THE INVISIBLE RESOURCE: USE AND REGULATION OF THE RADIO SPECTRUM 91 (1971) (alluding to "the problem of spurious emissions . . . of harmonic . . . channel interference"); Jora R. Minasian, *Property Rights in Radiation: An Alternative Approach to Radio Frequency Allocation*, 18 J.L. & ECON. 221, 226 (1975) ("The energy radiated on a particular frequency is also repeated with decreasing amplitude on frequencies that are a constant multiple of the initial frequency—'subharmonic' to it . . . .").

[45] In particular, intermodulation occurs when the third frequency equals either the sum or the difference of the other two frequencies. De Vany et al., *supra* note 23, at 1520-21.

factors. Moreover, because interference arises from the interaction of multiple sources at the location of the receiver, transmitters must have additional information about the behavior of other transmitters if they are to internalize the impact of their actions.

B. *The Internet*

The Internet is often described as a network of networks, which means it is comprised of many independent network providers, with the average Internet transaction traversing three to four different networks.[46] Internet transmissions are also susceptible to interference from other transmissions as they compete for finite router and link capacity.[47] In particular, the Internet is subject to cumulative interference and geographic discontinuities quite similar to those arising vis-à-vis spectrum.

1. The Cumulative Nature of Interference

One of the Internet's key attributes is that the amount of interference caused by one end user's decision to introduce more traffic into the network does not depend solely on the size of that traffic. It also depends on the size of the flows being introduced by other end users. Small flows can nonetheless become significant sources of congestion if the network is already near saturation. Conversely, large flows may have little to no effect if they are introduced when the network is uncongested. In short, interference on the Internet is the cumulative product of the bandwidth consumption of all of the end users as well as the configuration of the network.

2. Geographic Discontinuities

Interference on the Internet is further complicated by the ability of networks to compensate for congestion by rerouting traffic along alternate routes. When rerouting occurs, increases in network activity

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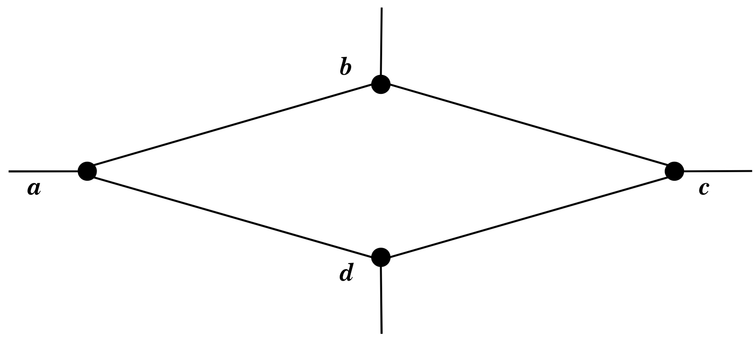
[46] *See* Jinjing Zhao et al., *Does the Average Path Length Grow in the Internet?*, *in* INFORMATION NETWORKING: TOWARDS UBIQUITOUS NETWORKING AND SERVICES 183, 184-86 (Teresa Vazão et al. eds., 2008).

[47] *See* Christopher S. Yoo, *Network Neutrality and the Economics of Congestion*, 94 GEO. L.J. 1847, 1862 (2006) ("[R]equests that routers and content servers can fulfill at any time [are] . . . constrained. When data packets arrive at a rate that exceeds the capacity of any particular element, they form a queue.").

may create adverse effects in locations quite distant from where the network added a new stream to the Internet.[48]

Figure 4: Reallocation of Traffic[49]



Consider the impact of an increase in traffic between nodes *a* and *b* in the simple ring network depicted in Figure 4. The network will respond by rerouting a higher proportion of the traffic between *a* and *c* onto *a-d-c* and by reducing the traffic along *a-b-c*. This increases the traffic along *a-d* and *d-c* while reducing the traffic along *b-c*. The network will similarly reroute traffic between *b* and *d*, shifting more of the traffic away from *b-a-d* toward *b-c-d*. Both adjustments will increase the traffic on the link between *c* and *d* even though that link is completely discontinuous with the original increase in traffic between *a* and *b*. In short, increases in traffic can create interference in locations that are geographically discontinuous from the increase in traffic flow. Understanding the impact of any given increase in traffic requires full knowledge of the network's topology and the other flows currently traversing the network. The distributed nature of the Internet means, however, that no single actor has access to all of this information.

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[48] *See* Daniel F. Spulber & Christopher S. Yoo, *On the Regulation of Networks as Complex Systems: A Graph Theory Approach*, 99 NW. U. L. REV. 1687, 1710-11 (2005) (explaining the potentially distant effects of a traffic increase along a single link).

[49] *Id.* at 1710 fig.9.

C. *Electric Power*

Another example of the highly interdependent nature of high-tech industries is the electric power grid. Like the Internet, the grid is a network that exhibits the same characteristics discussed in the previous section. Unlike the Internet, however, electric power is subject to a number of fundamental principles that create a much tighter set of interdependencies.

1. The Cumulative Nature of Interference

Two principles of physics cause electric power grids to exhibit distinctive characteristics. Kirchhoff's Current Law mandates that the sum of all currents flowing into every node must equal to the sum of currents flowing out of that node.[50] Ohm's Law holds that when multiple paths exist connecting two points, power travels along all of those paths simultaneously, allocated in inverse proportion to the electrical resistance of each path.[51] In turn, any change in supply or demand inevitably has an immediate impact on all other portions of the grid. Unlike the Internet, where an imbalance between demand and supply simply leads to delay or a dropped packet, the flows entering and exiting every point of the network must always balance. The result is complex interdependencies that are even more demanding than those associated with spectrum.

2. Geographic Discontinuities

The tight interdependencies created by Kirchhoff's Current Law and Ohm's Law can give rise to an effect known as "loop flow." Because electric power travels along every parallel path connecting two points, it cannot be channeled along the most direct path. Instead, some of the power inevitably travels along every path regardless of who owns the lines. In the extreme case, the grid may transfer power around the grid only to see it consumed where it was initially injected into the network.[52] In addition, changes in demand and supply

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[50] DAVID K. CHENG, FIELD AND WAVE ELECTROMAGNETICS 209 (1983).

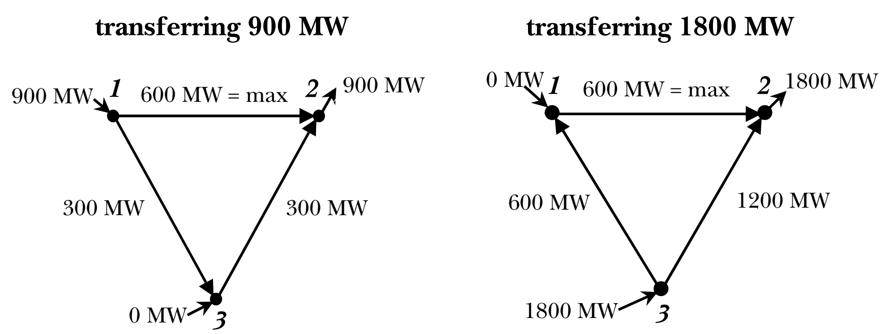
[51] *Id.* at 203.

[52] Seth Blumsack, *Measuring the Benefits and Costs of Regional Electric Grid Integration*, 28 ENERGY L.J. 147, 180 (2007).

can affect transmission lines located far from the added power flow.[53] These interactions make the impact of added flows difficult to predict.

Consider the following example, diagrammed in Figure 5.[54] Assume that nodes 1 and 2 are generating power, and node 3 is consuming power. Assume further that the link between node 1 and node 3 is limited to 600 megawatts (MW), while the links connecting nodes 1 and 2 and nodes 2 and 3 exceed the total demand and thus are for the purposes of this example unbounded. Lastly, assume that the resistance along each link is equal, so that any path that traverses two of the links will necessarily have twice the resistance of a path traversing a single link.

Figure 5: Loop Flow[55]



If the total consumption at node 2 is 900 megawatts, then the necessary ratio identified by Kirchhoff's Current Law dictates that the only possible solution is for node 1 to provide all of the power, with 600 MW passing along the link directly connecting nodes 1 and 2 and 300 MW of the power passing via node 3 (as depicted in the left-hand side of Figure 5). Increases in demand increase the amount of power generated at node 3 and reduce the amount of power generated at node 1 until demand reaches 1800 MW (as depicted in the right-hand side of Figure 5), when node 3 will provide all of the power, with 1200

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[53] *See* William W. Hogan, *Contract Networks for Electric Power Transmission*, 4 J. REG. ECON. 211, 216 (1992) ("[L]oop flows can affect third parties distant from the intended power flow . . . .").

[54] The example is taken from *id.* at 217.

[55] *Id.* at 217 fig.2.

MW passing directly from node 3 to node 2 and an additional 600 MW passing via node 1. Most notably, the flow of power between nodes 1 and 3 will reverse.

Loop flow makes setting prices for the transmission of electric power very difficult. Although compensation is typically based on the most direct route, the power actually passes along all of the available paths, which means that the amount paid may bear little relationship to the cost of the network resources consumed. Moreover, the fact that power flows along all possible paths means that part of the distribution will congest transmission lines owned by companies that are not parties to the transaction.[56] In addition, the complexity of the interactions makes it difficult to attribute such congestion to specific transactions.[57] The vertical disintegration of generation, transmission, and distribution dictates that these costs will not be internalized within a single firm.[58]

II. KEY IMPLICATIONS FOR PROPERTY THEORY

Although spectrum, the Internet, and the electric power grid represent distinctively different technological phenomena, they share a number of important characteristics. First, the cumulative nature of interference creates interdependencies that do not exist with real property. Second, interference can arise in unpredictable locations, far from the disturbance that causes it. Third, the localized nature of information makes solving this problem particularly difficult.

The tightly interdependent and localized nature of new technologies provides several lessons for property theory. As an initial matter, it suggests that property scholarship should move past the Coasean approach that focuses on bargaining-related transaction costs and focus instead on technical interdependencies as the key determinant of property boundaries. The cumulative and interdependent nature of interference also calls for new approaches both to identifying sources of interference and to attributing harm across those various sources.

[56] *See id.* at 216 (noting that, when loop flow causes power to flow down a third party's transmission lines, "third parties may and often do incur costs without compensation").

[57] Blumsack, *supra* note 52, at 181.

[58] *See* Douglas Gegax & Kenneth Nowotny, *Competition and the Electric Utility Industry: An Evaluation*, 10 YALE J. ON REG. 63, 73 (1993) (opining that "in today's complex system of interconnections," externalities cannot be internalized by a single business arrangement).

A. *Interdependencies: The Key Determinant of the Boundaries of Property*

The highly interdependent nature of new technologies militates in favor of moving away from the bargaining-oriented vision of property originated by Coase in favor of a return to a more technology-oriented approach. For example, Carliss Baldwin's insightful analysis of modularity contends that transactions are not the appropriate primitive unit of analysis of the boundaries of a firm.[59] Instead, she views interdependencies between the individual tasks required to produce a product as the proper primitives.[60] Tasks that are highly interdependent must be encapsulated within a single functional module.[61] Only when the interdependencies between tasks are weak can tasks be performed by separate firms.[62] Although Baldwin's primary focus was how interdependencies define firm boundaries, her work also has important implications for property theory. As she notes, property rights are necessarily suspended within the transaction-free zones within modules.[63] In addition, property rights "allow valuable things . . . to be held within the zone, without disruption, for as long as the technology demands."[64]

Baldwin's work suggests a technological vision of property that focuses on the interdependencies between tasks rather than the bargaining problems that can prevent the consummation of welfare-enhancing transactions. This vision treats transactions as the natural byproduct of the more fundamental architecture dictated by the underlying interdependencies.

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[59] Carliss Y. Baldwin, *Where Do Transactions Come From? Modularity, Transactions, and the Boundaries of Firms*, 17 INDUS. & CORP. CHANGE 155, 156 (2007). In brief, Baldwin

> look[s] at systems of production as networks, in which tasks-cum-agents are the nodes and transfers—of material, energy, and information—between tasks and agents are the links. At this new level of analysis, transactions are not primitive units of analysis . . . [but rather are] mutually agreed-upon transfers with compensation . . . located within the task network and serv[ing] to divide one set of tasks from another.

Id.

[60] *Id.* at 162.

[61] *Id.* at 157, 180-81.

[62] *Id.* at 166.

[63] *Id.* at 182.

[64] *Id.* at 183.

B. *The Complexity of Identifying Sources of Interference*

The interdependencies associated with new technologies can also greatly complicate the process of identifying sources of interference. Indeed, Coase recognized that "[i]t may be costly to discover who it is that is causing the trouble."[65] Although he recognized that the resulting market failure may justify some form of regulatory intervention, he nonetheless drew a broad analogy to the law of real property and expressed confidence that spectrum was not sufficiently distinct to require a different approach.[66] Framing the issues through the lens of real property obscured how difficult the task of identifying sources of interference can be. In the case of real property, interference came predominantly from adjacent sources (or at least from sources located nearby). This quality made the sources of interference easy to identify and required only that each actor have knowledge of local conditions.

The more interdependent nature of interference associated with new technologies makes identifying sources of interference more difficult. In addition, the highly localized nature of information makes it unlikely that any actor will be able to see all of the information needed to appreciate the impact of the interdependencies. Although it is possible to characterize these problems in terms of transaction costs, they are distinct from the bargaining-related transaction costs that dominate the current study of property rights. They are more technological interactions, more properly addressed in the design of the property itself.

Any system of property should be configured to provide the information necessary to support transactions. Modern property systems provide more opportunities than do conventional property systems for technological solutions to tracing. For example, wireless transmissions are increasingly based on a technique known as Code Division Multiple Access (CDMA) that allows multiple users to use the same spectrum by embedding a code to every transmitted signal. Receivers can be programmed to recognize the designated code and to disregard signals bearing other codes. CDMA is very efficient—it can increase transmis-

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[65] Coase, *supra* note 1, at 29.

[66] *See id.* at 30 ("It is easy to embrace the idea that the interconnections between the ways in which frequencies are used raise special problems not found elsewhere or, at least, not to the same degree. But this view is not likely to survive the study of . . . the law of property . . . .").

sion capacity over other technologies by a factor of two to ten.[67] It also offers the basis for identifying the source of a transmission. Internet traffic offers similar opportunities. The unifying characteristic of the Internet is that all traffic is routed based on the Internet Protocol (IP). The IP header contains a field listing the source address. If it were made verifiable, it could provide the basis for identifying the source of congestion.

That said, there are limits to how well such a function might work. Not every spectrum-based technology uses CDMA, and many interference sources, such as microwave ovens and other appliances, simply emit raw noise with no encoding whatsoever. In addition, as the discussion of propagation shows, interference may also depend on inanimate objects and terrain. Thus, some contributing factors to interference are not sources of emissions at all. With respect to the Internet, the source address in the IP header is insecure and can be forged to misrepresent the source, as often occurs with spam. A technology known as Internet Protocol Security (IPsec) allows parties to authenticate the source of every packet. Moreover, the National Science Foundation is supporting research into new possible network architectures, all of which include a higher degree of identity verification.[68] As of today, however, IPsec has not been widely deployed, and the new, clean-slate proposals are still in their conceptual stages.[69] Until those problems are addressed, identifying sources of interference will remain a difficult task.

C. *The Intractability of Attributing Harm*

Even if it were possible to identify all sources of interference, a property regime must also provide some basis for apportioning liability among those sources. As Richard Epstein has noted, however, "[t]he question of the allocation between joint forces is a bit like the question of joint costs in economics: there is simply no unique allocation of the

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[67] Charles Jackson et al., *Spread Spectrum Is Good—But It Does Not Obsolete* NBC v. U.S.*!*, 58 FED. COMM. L.J. 245, 253-59 (2006).

[68] *See* Press Release, Nat'l Sci. Found., NSF Announces Future Internet Architecture Awards (Aug. 27, 2010), *available at* http://www.nsf.gov/news/news_summ.jsp?cntn_id=117611&org=OLPA (enabling "researchers at dozens of institutions across the country to pursue new ways to build a more trustworthy and robust Internet").

[69] *See, e.g.*, Brent Rowe & Michael Gallaher, *Could IPv6 Improve Network Security? And, If So, at What Cost?*, 2 I/S: J.L. & POL'Y FOR INFO. SOC'Y 231, 235 (2006).

costs of the animal which is used to produce valuable meat and valuable furs."[70] The common law has developed two approaches for allocating liability: the "substantial factor" test and enterprise liability. Neither seems well suited to solving the problems of modern property.

1. The "Substantial Factor" Test

The Second Restatement of Torts requires that a defendant's conduct be "a substantial factor in bringing about the harm" before it can be considered a cause of that harm.[71] If courts can determine the extent to which multiple causes contributed to a single harm, they can apportion harm on that basis.[72] The Second Restatement's chapter on nuisance similarly provides that a person is liable only when he "participates to a substantial extent" in carrying on the activity allegedly creating the nuisance.[73] The effect is to establish a minimum threshold of culpability before attributing liability.

While the test has the virtue of screening out minor causal factors, the test allocates liability "on an all-or-nothing basis":[74] those whose actions fall above a certain causal threshold bear responsibility for the entire harm, notwithstanding the presence of other causal agents, while those whose actions fall below a certain causal threshold escape liability altogether.[75] This regime seems a poor fit for modern forms of property. The cumulative nature of interference means that even small actions have a direct adverse effect. The localized nature of interference complicates the inquiry still further, since it is not the magnitude of the interference *simpliciter* that matters, but rather its location in relation to other uses.

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[70] Richard A. Epstein, *Causation—In Context: An Afterword*, 63 CHI.-KENT L. REV. 653, 671 (1987).

[71] RESTATEMENT (SECOND) OF TORTS § 431(a) (1965).

[72] *See id.* § 433 (listing "considerations . . . important in determining whether the actor's conduct is a substantial factor in bringing about harm to another").

[73] RESTATEMENT (SECOND) OF TORTS § 834 (1979); *see also id.* § 834 cmt. d ("When a person is only one of several persons participating in carrying on an activity, his participation must be substantial before he can be held liable for the harm resulting from it.").

[74] Glen O. Robinson, *Multiple Causation in Tort Law: Reflections on the DES Cases*, 68 VA. L. REV. 713, 715 (1982).

[75] *See id.* at 715-16 (noting that this "limitation is a fairly crude one," but that loss-apportionment schemes in many jurisdictions now mitigate the severity of the law by "requiring contribution among joint tortfeasors and comparative appointment between negligent plaintiffs and defendants").

2. Enterprise Liability

The other primary approach developed by the common law is enterprise, or market share, liability, in which liability is allocated in proportion to market share. The doctrine was initially developed to cope with the challenge of allocating liability for the harm done by "fungible goods . . . which cannot be traced to any specific producer."[76] More recently, some courts have begun to explore whether market share liability should also be extended to nuisance.[77]

Even supporters of the doctrine concede that it is widely regarded as a failure,[78] and the doctrine has been largely ignored in the Third Restatement of Torts.[79] Whatever its overall merits, enterprise liability seems ill-suited to the modern system of property. George Priest has observed that enterprise liability implicitly presumes that all products comprising the market contributed equally to the harm.[80] To the extent that contributions to harm are differential (as is generally the case when the effect of interference is localized), enterprise liability underdeters those market participants who are the most responsible.[81]

III. IMPLICATIONS FOR THE CHOICE OF PROPERTY FORM

In addition to suggesting a more technological approach to property, the unique characteristics of these new forms of property also have implications for the choice among the various property forms.

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[76] Sindell v. Abbott Labs., 607 P.2d 924, 936 (Cal. 1980); *see also id.* at 937 ("[W]e hold it to be reasonable . . . to measure the likelihood that any of the defendants supplied the [pregnancy drug] which allegedly injured plaintiff by the percentage which the [drug] . . . bears to the entire production of the drug sold by all . . . .").

[77] *See* George L. Priest, *Market Share Liability in Personal Injury and Public Nuisance Litigation: An Economic Analysis*, 18 SUP. CT. ECON. REV. 109, 121-24 (2010) ("[T]wo courts recently have ruled that sufficient evidence exists to try a case against lead pigment manufacturers as a public nuisance.").

[78] *See generally* Virginia E. Nolan & Edmund Ursin, *Enterprise Liability Reexamined*, 75 OR. L. REV. 467 (1996) ("Today it is widely believed that the enterprise liability revolution has been a failure.").

[79] *See* Gregory C. Keating, *The Theory of Enterprise Liability and Common Law Strict Liability*, 54 VAND. L. REV. 1285, 1288 (2001) ("It is . . . surprising and disturbing that the theory of enterprise liability does not make any appearance *at all* in the [Third Restatement].").

[80] Priest, *supra* note 77, at 111.

[81] *See id.* at 113 ("[E]ven if perfectly allocated, [market share liability] is unlikely to affect incentives for the manufacture of safer products, as the DES and lead paint cases . . . illustrate.").

These unique qualities shed new light on the ongoing debate between property and the commons and also suggest the possibility of a role for third-party intermediaries.

A. *Well-Defined Property Rights*

One of the central preconditions for the market-based system of property rights that Coase envisioned was for "the legal system . . . to establish that clear delimitation of rights on the basis of which the transfer and recombination of rights can take place through the market."[82] He suggested that radio frequency rights could be defined by analogy to other emergent types of property rights, such as water rights, trademarks, noise nuisances, and rights to ice from public ponds.[83]

Coase's proposal spawned a vibrant literature during the 1960s and 1970s that attempted to define property rights in spectrum. The most generative proposal defined spectrum rights in terms of three attributes: the time during which transmission occurs; the area over which the transmission occurs, defined largely in terms of location and power; and the spectrum over which transmission occurs, defined in terms of frequencies.[84] The hope was that this definition would eliminate the need for the government to designate specific uses.[85] License holders would remain free to allocate their spectrum to any purpose so long as their activities did not exceed these parameters at

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[82] Coase, *supra* note 1, at 25.

[83] *Id.* at 30-31.

[84] *See* William K. Jones, *Use and Regulation of the Radio Spectrum: Report on a Conference*, 1968 WASH. U. L.Q. 71, 72 (describing how separating signals by time, space, and frequency could help to "eliminate or minimize electronic interference"); Harvey J. Levin, *The Radio Spectrum Resource*, 11 J.L. & ECON. 433, 433, 438-39 (1968) (noting that while technology could improve the spectrum, "a natural resource" is "clearly subject to . . . degradation through pollution and congestion," and must therefore be administratively regulated across time, space, and frequency dimensions); William H. Meckling, *Management of the Frequency Spectrum*, 1968 WASH. U. L.Q. 26, 26, 28-29 (arguing that the spectrum poses problems no different than those relating to "land, labor, and capital," and proposing that "government agencies responsible for spectrum utilization decisions . . . make . . . decisions on the basis of the market value of frequencies"); Minasian, *supra* note 44, at 227-35 (describing how licensing, by assigning temporal and spatial broadcasting rights to certain individuals while simultaneously excluding others from access, allows the maintenance of adequate signal quality).

[85] *See, e.g.*, De Vany et al., *supra* note 23, at 1518 ("The exclusive assignment of rights for all three [time, area, and spectrum] dimensions to specific individuals or firms eliminates potential common-resource problems.").

the boundary of their service areas.[86] This so-called TAS (time, area, spectrum) proposal served as the basis for many subsequent proposals.[87]

Whatever the merits of these designs during the simpler times of the 1960s, when broadcasting represented the sole mass-market use of spectrum, they seem singularly out of place in a world dominated by a much wider range of devices employing different technologies and operating at mobile locations at varying degrees of power.[88] In this environment, the more variable and discontinuous nature of sources of interference suggests that this approach is likely too simplistic.

The proposal advanced by the FCC's Spectrum Policy Task Force is illustrative. Although it took the TAS framework described above as its starting point, it also developed a metric known as the "interference temperature" as a measurement of noise levels that spectrum users must accept from other sources.[89] The Task Force's Report noted that this variable is the hardest to capture "[b]ecause all of the[] sources may not be known or anticipated."[90] The problems were exacerbated

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[86] *See id.* at 1512-18 (discussing the temporal and spatial dimensions of property rights in the spectrum and noting that, while "rights are transferable and divisible," they must respect their temporal, spatial, and frequency-based limitations).

[87] *See, e.g.*, Lawrence J. White, *"Propertyzing" the Electromagnetic Spectrum: Why It's Important, and How to Begin*, 9 MEDIA L. & POL'Y 19, 29-30 (2000) (noting a number of subsequent approaches based on the TAS framework); Evan Kwerel & John Williams, *A Proposal for a Rapid Transition to Market Allocation of Spectrum*, at iv-v, 16-24 (Fed. Commc'ns Comm'n OPP Working Paper Series, Paper No. 38, 2002), *available at* http://wireless.fcc.gov/auctions/conferences/combin2003/papers/masterevanjohn.pdf (advancing three proposals to reduce current "shortages and waste" in the spectrum); *see also* Yochai Benkler, *Overcoming Agoraphobia: Building the Commons of the Digitally Networked Environment*, 11 HARV. J.L. & TECH. 287, 393-94 (1998) (proposing "an appropriate regulatory space for unlicensed wireless operations"); Gerald R. Faulhaber, *The Question of Spectrum: Technology, Management, and Regime Change*, 4 J. ON TELECOMM. & HIGH TECH. L. 123, 160 (2005) ("I propose that license restrictions . . . have the force of trespass law . . . [so that if] a licensee violate[s] one of its restrictions, its neighbors could obtain injunctive relief without a showing of damages."); Ellen P. Goodman, *Spectrum Rights in the Telecosm to Come*, 41 SAN DIEGO L. REV. 269, 315-26 (2004) (describing, in particular, two alternatives designed "to correct the failings of administrative control of spectrum"); Meckling, *supra* note 84, at 28 (stating that the literature contains two main proposals—a goal of minimizing spectrum interference, and a goal of using spectrum efficiently).

[88] *See* Werbach, *supra* note 40, at 921 (noting that such doctrinal proposals were designed for cases "light years away from the situation of many roving ad hoc transmitters using some combination of spread-spectrum, directional antennas, meshed networking, and software-designed radio").

[89] *See* FED. COMMC'NS COMM'N, *supra* note 15, at 27 ("The interference temperature measures the RF power available at the receiving antenna per unit bandwidth.").

[90] *Id.* at 18.

by the constant emergence of new devices and technologies, the increasingly intensive use of the spectrum, the growing prevalence of mobile devices, the cumulative nature of interference, and the presence of out-of-band emissions.[91]

The analytical framework laid out here helps explain the failure of the interference temperature metric by underscoring the extent to which its approach was underspecified. A license holder who recognizes that it is receiving improper interference has no way to determine the sources of that interference. Absent such a basis, there is no way to determine against whom the rights should be enforced. As noted above, the FCC subsequently abandoned the concept and conspicuously omitted any statement of creating primary markets for spectrum from the National Broadband Plan.[92] Despite the admonitions of a distinguished and politically diverse group of economists,[93] the FCC appears to have abandoned efforts to establish true property rights in spectrum.

In addition, the interdependencies that characterize new technologies help explain why property-rights regimes in spectrum have failed to emerge. As Henry Smith has noted, the exclusion-based strategies associated with property rights necessarily require greater reliance on rough proxies that bundle mutual uses together.[94] The appropriate bundle of proxies does not present itself preformed when the resource being propertized is intangible.[95] Moreover, the complex interdependencies associated with new technologies caution against exclusion regimes by suggesting that the mutuality of uses will tend to run across different parcels rather than within them.

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[91] *See id.* at 25-26 (discussing the new challenges for interference management that have arisen recently as a result of new technology and "the increasingly intensive use of the radio spectrum").

[92] *See supra* notes 15-18 and accompanying text.

[93] *See* Comments of 37 Concerned Economists, *supra* note 14, at 5-6 ("To promote efficient secondary markets, the Commission must address its primary license rights.").

[94] *See* Henry E. Smith, *Exclusion Versus Governance: Two Strategies for Delineating Property Rights*, 31 J. LEGAL STUD. S453, S469 (2002) ("Because attributes and uses are costly to measure, rights to them are delineated and defended by means of proxies, and it is the use of rougher proxies that leads to more activities being bunched together in a more exclusion-like right.").

[95] *See* Abraham Bell & Gideon Parchomovsky, *Reconfiguring Property in Three Dimensions*, 75 U. CHI. L. REV. 1015, 1047 (2008) ("Due to their intangible nature, intellectual assets do not have clear boundaries. Indeed, defining the boundaries of intellectual assets is one of the most difficult challenges lawmakers must confront.").

B. *Spectrum Commons*

Many scholars have advocated for a spectrum commons based on three different rationales. First, they invoke the work of scholars, such as Nobel Laureate Elinor Ostrom, to show that commons can be governed even in the absence of property rights.[96] Second, they cite the theory of the anticommons popularized by Michael Heller to show how property rights can cause resources to be systematically underused.[97] Third, they argue that technology has eliminated scarcity to the point where spectrum need no longer be allocated.

1. Ostrom and *Governing the Commons*

One central argument advanced by proponents of the commons is that people who use a resource need not resort to legal means to ensure that the resource is used efficiently. Indeed, the most developed body of scholarship exploring how societies can regulate behavior without resort to law is the body of research into social norms.[98] Commentators widely recognize that the universe of Internet users can no longer be characterized as the type of "close-knit community" needed for social norms to arise.[99] Instead, these commentators base their faith on the work of scholars, such as Elinor Ostrom, exploring

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[96] ELINOR OSTROM, GOVERNING THE COMMONS: THE EVOLUTION OF INSTITUTIONS FOR COLLECTIVE ACTION (1990).

[97] Michael A. Heller, *The Tragedy of the Anticommons: Property in the Transition from Marx to Markets*, 111 HARV. L. REV. 621, 668, 673-79 (1998) (defining anticommons property as "a property regime in which multiple owners hold effective rights of exclusion in a scarce resource" (emphasis omitted)).

[98] For the classic work on this body of scholarship, see ROBERT C. ELLICKSON, ORDER WITHOUT LAW: HOW NEIGHBORS SETTLE DISPUTES (1991).

[99] *See, e.g.*, Steven A. Hetcher, *Norm Proselytizers Create a Privacy Entitlement in Cyberspace*, 16 BERKELEY TECH. L.J. 877, 887-88 (2001) (noting that the Internet has changed drastically since it was initially developed in the 1960s, when its primary user base was a small, close-knit community of academics able to regulate itself through norms); Mark Lemley, *The Law and Economics of Internet Norms*, 73 CHI.-KENT L. REV. 1257, 1267-70 (1998) ("No one would call the Internet a static community. Indeed, what Internet norms have managed to develop have regularly been blown apart by entry."); Margaret Jane Radin & R. Polk Wagner, *The Myth of Private Ordering: Rediscovering Legal Realism in Cyberspace*, 73 CHI.-KENT. L. REV. 1295, 1308 (1998) ("Achievement of stability in a self-regulated commons is often thought to be dependent upon whether the cooperators are a close-knit social group. Earlier users of the Internet may have belonged to a close-knit social group but this is not true of Internet users today.").

how effective governance regimes can arise even in large, heterogeneous communities.[100]

Ostrom's landmark book, *Governing the Commons*, begins as a descriptive endeavor that explores the qualities of a number of such systems and then proceeds to identify similarities that those systems share.[101] A number of these similarities have important implications for the debate over the commons. First, the property right must have clearly defined boundaries, a feature that Ostrom regards as "the single defining characteristic of 'common property' institutions."[102] In addition, such a commons must have appropriation rules that are well-tailored to the specific situations of different individuals.[103] In addition, such a regime must have effective monitoring to allocate access to the shared resource.[104]

As an initial matter, Ostrom presumes the existence of well-defined property rights upon which a governance regime can be erected. As such, it is not properly regarded as an alternative to property rights. Instead, it is more properly regarded as what has been called "common property" or "limited commons," which Carol Rose has aptly described as "property on the outside, commons on the inside."[105]

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[100] *See* Yochai Benkler, *Some Economics of Wireless Communications*, 16 HARV. J.L. & TECH. 25, 49 (2002) (noting that there has been a "burgeoning literature" suggesting that individually owned property might not always be the most efficient way of organizing the use of a resource); Stuart Buck, *Replacing Spectrum Auctions with a Spectrum Commons*, 2002 STAN. TECH. L. REV. 2, ¶¶ 42-77, http://stlr.stanford.edu/STLR/Articles/02_STLR_2 (drawing on Elinor Ostrom's work to develop a "commons-based regulatory scheme for the spectrum"); Goodman, *supra* note 87, at 284 (analogizing licensees' rights to the spectrum to "cooperative forms of land use by small, close-knit groups"); Werbach, *supra* note 40, at 937 (noting that "[s]cholars such as Elinor Ostrom have examined conditions under which commons are self-regulating" and that scholars have argued that spectrum can be thought of as a common pool resource).

[101] ELINOR OSTROM, GOVERNING THE COMMONS: THE EVOLUTION OF INSTITUTIONS FOR COLLECTIVE ACTION (1990).

[102] *Id.* at 91.

[103] *See id.* at 92 (explaining the need for a "[c]ongruence between appropriation and provision rules and local conditions").

[104] *See id.* at 94-100 (describing the role and necessity of effective monitoring and sanctions).

[105] Carol M. Rose, *The Several Futures of Property: Of Cyberspace and Folk Tales, Emission Trades and Ecosystems*, 83 MINN. L. REV. 129, 144 (1998); *see also* Thráinn Eggertsson, *Open Access versus Common Property*, *in* PROPERTY RIGHTS: COOPERATION, CONFLICT, AND LAW 73, 74-76 (Terry L. Anderson & Fred S. McChesney eds., 2003); Charlotte Hess & Elinor Ostrom, *Ideas, Artifacts, and Facilities: Information as a Common Pool Resource*, 66 LAW & CONTEMP. PROBS. 111, 121-23 (2003) (explaining the difference between open-access regimes "where no one has the legal right to exclude anyone from using a re-

Within the commons, individuals do not have the type of open access that commons advocates envision. Usage is not permissionless and is instead subject to strict internal regulation.[106] In addition, the internal governance rules do not envision equal access to the resource. Instead, they are supposed to account for differences in circumstances and to allow for differential usage.[107] Lastly, as Hanoch Dagan and Michael Heller have noted, Ostrom's mechanism for self-governance presumes that exit is impossible,[108] whereas for participants in markets for spectrum and the Internet, exit is always possible.

Other scholars have explored certain structural preconditions that must exist for such commons-based governance to exist. For example, Gary Libecap argues that the community must be sufficiently stable so that entry does not destabilize the management regime.[109] Moreover, the participants should be homogeneous in terms of capabilities, information, past production, costs, and size, as variability makes it more difficult to find that the benefits of collective action would exceed the benefits of acting unilaterally.[110] Again, none of these conditions appear to match the type of permissionless, unlimited access envisioned by commons advocates for spectrum or the Internet. Nor is the underlying population sufficiently stable or homogeneous to permit reliance on nonlegal governance mechanisms.

2. Heller and *The Tragedy of the Anticommons*

As noted above, commons advocates also frequently invoke the theory of the anticommons most strongly associated with the work of Michael Heller.[111] According to Heller, anticommons arise when "mul-

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source" and common property regimes "where members of a clearly defined group have a bundle of legal rights including the right to exclude nonmembers from using that resource").

[106] *See, e.g.*, OSTROM, *supra* note 101, at 126 (discussing the role of "watermasters" in allocating shared resources).

[107] *See id.* at 58-91 (examining different common property regimes and their differences which resulted from varying circumstances).

[108] *See* Hanoch Dagan & Michael A. Heller, *The Liberal Commons*, 110 YALE L.J. 549, 565-66 (2001) (noting that a price of Ostrom's mechanism for self-governance is that it "require[s] locking people together in static communities").

[109] Gary D. Libecap, *The Conditions for Successful Collective Action*, *in* LOCAL COMMONS AND GLOBAL INTERDEPENDENCE: HETEROGENEITY AND COOPERATION IN TWO DOMAINS 161, 163 (Robert O. Keohane & Elinor Ostrom eds., 1995).

[110] *Id.* at 163, 165, 187-88.

[111] *See* Benkler, *supra* note 100, at 30, 62-63 (noting that a pure spectrum property rights approach results in the "'anticommons' problem"); Buck, *supra* note 96, ¶¶ 89-

tiple owners are each endowed with the right to exclude others from a scarce resource."[112] When multiple owners are given the right to exclude others, multiple parties must unanimously agree before any use can be made. The difficulties in coordinating multiple interests mean that "no one has an effective privilege of use."[113] Heller's central concern is that the difficulty in getting these multiple parties to agree would lead to chronic underuse.[114]

This invocation of the anticommons is imprecise in important ways. The central concern that motivates commons advocates is the difficulty of convincing individual rightsholders—each possessing sole, exclusive rights—to aggregate their spectrum into a larger block. The problem is thus not the classic anticommons situation of one piece of property with too many owners, but rather the more traditional numerosity problem of too many small pieces of property, each with a single owner.

The difference may seem technical, but it is important. When the problem is too many small parcels with single owners, the incentive to hold out results in behavior that resembles the Prisoner's Dilemma. As Lee Anne Fennell has noted, tragedies of the anticommons tend to fall within another analytical structure known as the Chicken Game.[115]

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93 (discussing several situations in which large companies in the wireless industry bargain with each other to solve problems and positing that these arrangements came about because the companies are interdependent); Goodman, *supra* note 87, at 366 ("The obligation to negotiate leases with the tens or hundreds of rights holders in order to transmit their low-power signals would quickly subject wideband operators to a 'tragedy of the anticommons' as they encounter holdouts and excessive transaction costs."); Werbach, *supra* note 40, at 965 (arguing that it would be a practical impossibility for devicemakers to negotiate to pay spectrum owners for an easement, especially for technologies such as ultra wideband, and noting that "[s]cholars have labeled this scenario the anticommons"). *See generally* Kevin Werbach, *The Wasteland: Anticommons, White Spaces, and the Fallacy of Spectrum*, 53 ARIZ. L. REV. 213 (2011) (applying Michael Heller's anticommons theory to spectrum policy).

[112] *Id.* at 624.

[113] *Id.*

[114] *See id.* at 674 ("[E]ven if the number of parties and transaction costs are low, [a] resource still may not be efficiently used because of bargaining failures generated by holdouts . . . .").

[115] *See* Lee Anne Fennell, *Common Interest Tragedies*, 98 NW. U. L. REV. 907, 941-48 (2004) ("The Chicken Game has been explicitly invoked to describe land assembly problems which involve an anticommons-like structure; the link between the Chicken Game and the anticommons is also implicit in the focus on holdouts in the anticommons literature.").

For the seminal articulation of the Chicken Game, see Anatol Rapoport & Albert M. Chammah, *The Game of Chicken*, AM. BEHAV. SCIENTIST, Nov. 1966, at 10. The Chicken

Figure 6: Prisoner's Dilemma vs. the Chicken Game

Prisoner's Dilemma

		Player 2	
		Cooperate	Defect
Player 1	Cooperate	3, 3	1, 4
	Defect	4, 1	2, 2

Chicken Game

		Player 2	
		Cooperate	Defect
Player 1	Cooperate	3, 3	2, 4
	Defect	4, 2	1, 1

These two games have fundamentally different characteristics. The perverse aspect of the Prisoner's Dilemma is that if both prisoners act rationally, they will both defect despite the fact that both would be better off if they mutually cooperated. Much of the literature focuses on how devices such as iteration can induce cooperation.[116] In addition, iterated Prisoner's Dilemmas that take place within a spatial structure, in which players compete with their immediate neighbors instead of with the entire universe of other players, tend to exhibit greater cooperation, as cooperators survive by forming large compact clusters that minimize their exposure and potential exploitation by defectors.[117]

Game is also called the Snowdrift Game or the Hawk-Dove Game. *See* ROBERT SUGDEN, THE ECONOMICS OF RIGHTS, CO-OPERATION AND WELFARE 58-62, 128-32 (1986).

[116] For the classic work on this phenomenon, see ROBERT AXELROD, THE EVOLUTION OF COOPERATION (rev. ed. 2006). For a recent survey, see Michael Doebeli & Christoph Hauert, *Models of Cooperation Based on the Prisoner's Dilemma and the Snowdrift Game*, 8 ECOLOGY LETTERS 748 (2005).

[117] *See, e.g.*, Martin A. Nowak & Robert M. May, *Evolutionary Games and Spatial Chaos*, 359 NATURE 826 (1992). For a recent survey, see Doebeli & Hauert, *supra* note 116, at 750-57.

In the Chicken Game, there is no strategy that is always rational for either player. Player 1's optimal strategy differs based on what she assumes about Player 2's strategy and vice versa. Thus, the Chicken Game is said to have no dominant strategy. The one who wins is the one who convinces the other side that she is sufficiently irrational to be willing to die rather than turn aside.[118] As such, it inherently encourages and rewards commitments not to cooperate or, if that is impossible, bluffing. Moreover, the number of cooperators that exists in equilibrium depends on the cost-to-benefit ratio of cooperation.[119]

The Chicken Game has qualities that are quite different from the Prisoner's Dilemma. The structure of the game does not trap parties into a vicious circle in which it is never rational for them to cooperate.[120] In short, the spirit of the Prisoner's Dilemma is the opportunity for mutual cooperation frustrated by the lack of trust. By contrast, the spirit of the Chicken Game is inherently adversarial; there is no missed opportunity for cooperation that would have left both parties better off.[121] Moreover, rationality in the Chicken Game "depends on a player's expectations about the other's behavior, not primarily on the game's payoff structure."[122] As is the case in the Prisoner's Dilemma, the Chicken Game leads to less cooperation than is socially optimal, since the average payoff in equilibrium is less than the average payoff of a population comprised entirely of cooperators.[123]

The inherently adversarial nature of the Chicken Game led some scholars to suggest that cooperation would be harder to establish in

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[118] *See* WILLIAM POUNDSTONE, PRISONER'S DILEMMA 200-01 (1992) (noting that "an *irrational* player has the upper hand in chicken," including when the player is suicidal or acts randomly); Peter Kollock, *Social Dilemmas: The Anatomy of Cooperation*, 24 ANN. REV. SOC. 183, 187 (1998) (explaining that one has an advantage in the Chicken Game if one can "convince the other person that [h]is strategy is crazy, irrational, suicidal, or otherwise incapable or unwilling to change course").

[119] *See* Christoph Hauert & Michael Doebeli, *Spatial Structure Often Inhibits the Evolution of Cooperation in the Snowdrift Game*, 428 NATURE 643, 644 (2004) (asserting that in the snowdrift game, the "average population payoff at . . . equilibrium is smaller than the average payoff in a population of only cooperators").

[120] *See* Glenn H. Snyder, *"Prisoner's Dilemma" and "Chicken" Models in International Politics*, 15 INT'L STUD. Q. 66, 83 (1971) ("In chicken, there is no 'tragedy' or 'vicious circle.'").

[121] *Id.* at 84.

[122] *Id.* at 85.

[123] *See* Hauert & Doebeli, *supra* note 119, at 644.

the Chicken Game than in the Prisoner's Dilemma.[124] Later work revealed a more complex set of dynamics. A number of studies conclude that iterated Chicken Games exhibit higher levels of cooperation than iterated Prisoner's Dilemmas.[125] Chicken Games exhibit lower levels of cooperation than Prisoner's Dilemmas when iterated in a spatial framework.[126] Whatever the resolution, it is clear these games have different structures and different intuitions. Those who confuse the problems assembling spectrum with the tragedy of the anticommons misunderstand the key differences in the form of stalemate associated with each.

Stated more generally, when parties co-own the same property and cannot dispose of it or improve it without the unanimous consent of the other owners, they are locked in with one another, with little value derived from partial agreement. The situation is quite different when the problem is acquiring smaller pieces of property from single owners and assembling them into a larger block. There may be some value to partial assembly, so that the failure to achieve unanimity does not eliminate all of the value of partial agreement. Moreover, when unanimity is not required, bluffing is more likely to be self-defeating.[127] In fact, the risk that a party may be excluded from a deal may give that party a stronger inducement to sell.[128] Moreover, it is possible that the party attempting to assemble a large block may be able to substitute a different adjacent parcel. Such substitutions are impossible when

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[124] *See* Snyder, *supra* note 120, at 85 (arguing that rationality in the Chicken Game is "equivocal").

[125] *See* Bengt Carlsson & K. Ingemar Jönsson, *Differences Between the Iterated Prisoner's Dilemma and the Chicken Game Under Noisy Conditions*, 2002 PROC. ACM SYMP. ON APPLIED COMPUTING 42, 46 ("With increased noise . . . forgiving strategies become more and more successful in [an iterated Chicken Game] while repeating and revenging strategies are more successful in [an iterated Prisoner's Dilemma]."); Garrison W. Greenwood & Shubham Chopra, *A Numerical Analysis of the Evolutionary Iterated Snowdrift Game*, 2011 PROC. IEEE CONGRESS ON EVOLUTIONARY COMPUTING 2010, 2015-16 (using an iterated Snowdrift Game to demonstrate how cooperation can be encouraged in social dilemma situations like the Chicken Game); Rolf Kümmerli et al., *Human Cooperation in Social Dilemmas: Comparing the Snowdrift Game with the Prisoner's Dilemma*, 274 PROC. ROYAL SOC'Y B 2965, 2965 (2007) (demonstrating higher levels of cooperation in iterated Chicken Games because the cooperation "yields a benefit . . . to both players").

[126] *See* Hauert & Doebeli, *supra* note 119, at 644 (noting the "contrary effects of spatial structure in the Prisoner's Dilemma and in the snowdrift game" and attributing the difference to the type of clusters which arise in each case through microscopic processes).

[127] Fennell, *supra* note 115, at 971-72.

[128] *Id.* at 974.

agreement must be obtained from multiple owners of the same piece of property.

Equally important, many legal scholars regard the anticommons as an argument against propertization and in favor of a commons. Far from representing a blanket condemnation of property rights, the archetypical solution to the anticommons is not common property, but rather the unification of the rights in a single owner.[129] In later work with Hanoch Dagan, Heller offers alternative solutions to policing overuse of the commons that rely more on governance mechanisms.[130] But even when this is the case, the imperfections in these mechanisms dictate that they be backstopped by high-powered, well-defined background rules that would internalize each common user's costs, such as making all violators liable for the fair market value of their uses.[131]

It comes as no surprise, then, that Heller is quite critical of spectrum commons as a solution.[132] The real basis for unlicensed spectrum success stories such as WiFi may lie instead in their ability to piggyback on other property regimes. Despite the fact that WiFi signals often spill across property lines, the metes and bounds of real property provide a rough approximation of the footprint of WiFi signals. Thus, although the unlicensed nature of WiFi may limit the ability to curb overuse

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[129] *See* Heller, *supra* note 111, at 640 ("Moving a storefront from anticommons to private property ownership requires unifying fragmented property rights into a usable bundle. In other words, creating private property requires moving from too many owners, each exercising a right of exclusion, to a sole decisionmaker, controlling a bundle of rights."); *id.* at 678 ("In the commons case, property theorists have proposed that societies may overcome tragedy by evolving toward private property relations. . . . The theoretical arguments on the commons carry over, by analogy, to the problem of overcoming an anticommons. In the anticommons case, moving to a private property regime may better align each owner's interest with efficient use, because a private property owner faces the full cost of underconsumption.").

[130] *See* Dagan & Heller, *supra* note 108, at 590 (arguing for a system of democratic self-governance based on a majority rule rather than a unanimity rule because "by requiring complete agreement on management issues and by emboldening holdouts, unanimity rules may lead to anticommons tragedy, that is, mutual vetoes that waste a resource through underuse").

[131] *See id.* at 584 (arguing for ex ante rules to guarantee that overexploitation is minimized).

[132] *See* MICHAEL HELLER, THE GRIDLOCK ECONOMY: HOW TOO MUCH OWNERSHIP WRECKS MARKETS, STOPS INNOVATION, AND COSTS LIVES 94 (2008) ("[F]irst we must unify rights in spectrum into coherent, well-defined ownership bundles. Otherwise, we are stuck where we started, with spectrum wasted in a tragedy of the anticommons.").

directly, the exclusion rights provided by real property may represent a useful proxy by which spectrum exclusion may be approximated.[133]

3. The End of Scarcity versus Shannon's Law

Finally, commons scholars argue that improvements in the efficiency of spectrum usage have reduced scarcity to the point where property rights are no longer needed.[134] One such technique involves smart radios (also called agile radios or software defined radios) that permit transmitters to shift dynamically to open frequencies. The other technique is spread spectrum, in which a signal is broadcast at low power across a broader range of frequencies than are usually used. Because these emanations are below the current noise floor, commons advocates argue that they can exist without interfering with other licensed uses. Although the end of scarcity represents a very strong assumption, it is not a straw man. It is the logical lynchpin required for this argument in favor of a spectrum commons to hold.

Shannon's Law underscores the notion that no amount of artful management can eliminate scarcity. Smart radios simply use spectrum more efficiently; they do not increase its carrying capacity. With respect to spread spectrum, the addition of another signal below the

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[133] *Cf.* Yoo, *supra* note 47, at 1873-74 (discussing how Coaseian proxies can allow metering of nonexcludable goods).

[134] *See* LAWRENCE LESSIG, THE FUTURE OF IDEAS: THE FATE OF THE COMMONS IN A CONNECTED WORLD 47, 241-44 (2001) (arguing that much of the spectrum should be left in the commons unless it becomes clear that it needs to be allocated); Benkler, *supra* note 87, at 324 ("The technological shift derives from various techniques—such as spread spectrum and code division multiple access, time division multiple access, frequency hopping, and packet switching—for allowing multiple users to communicate at the same time using the same frequency range. . . . What is crucial to understand about these technologies is that they challenge the underlying assumption of both licensing and privatization: that the only way to assure high quality wireless communications is to assign one person the right to transmit in a given frequency band." (footnote omitted)); Buck, *supra* note 96, ¶¶ 20-26 (explaining that, even though the commons has been described as "scarce" for many years—and even though its scarcity was used to justify government allocation—cutting-edge technologies promise to eliminate that scarcity by making it possible for multiple users to share the same spread of frequencies without interference); Werbach, *supra* note 40, at 897-98, 911 (describing new technologies that transform the spectrum into a commons by eliminating scarcity); *see also* Yochai Benkler & Lawrence Lessig, *Net Gains: Will Technology Make CBS Unconstitutional?*, NEW REPUBLIC, Dec. 14, 1998, at 12, 14 (advancing the argument that technological changes have made it so that the spectrum no longer has to be allocated and that these technological changes' eliminating scarcity of the spectrum make FCC allocation of the spectrum constitutionally suspect).

current noise level simply raises the noise floor. Because throughput is a function of signal-to-noise ratio, the addition of these low-power signals inevitably reduces the capacity available to others.[135] Although previous improvements may have made it appear that capacity improvements could go on indefinitely, engineers now observe that the bandwidth channels are beginning to approach the theoretical limits implied by Shannon's Law.[136]

C. *Bargaining as an Alternate Solution*

Redefining the scope of property rights is not the only way to address the problems associated with interference. The Coase Theorem showed how rights can be redistributed via contract instead of property.[137] But in this case, the crux of the problem stems not from direct externalities, but rather from the inability to observe the information needed to manage the resulting interdependencies. This suggests an alternative approach that solves coordination problems by making the information needed to allow the reorganization of entitlements more visible and thus more contractible. Indeed, this is precisely the approach taken with respect to the electric power grid by comapnies such as PJM Interconnection LLC, which gather widely scattered information and suggest prices.[138] Such smart markets have been proposed by Jeff MacKie-Mason and Hal Varian for the Internet[139] and by Eli Noam for spectrum.[140] This approach also resembles the proposed database for sharing information about unlicensed spectrum uses in

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[135] *See* Jackson et al., *supra* note 67, at 259-62 (showing how spread spectrum uses are perceived by other users as noise that reduces the radio systems' available bandwidth).

[136] *See* Andrew D. Ellis et al., *Approaching the Non-Linear Shannon Limit*, 28 J. LIGHTWAVE TECH. 423, 424-27 (2010).

[137] See Coase, *supra* note 7.

[138] *See* Daniel F. Spulber & Christopher S. Yoo, *Rethinking Broadband Internet Access*, 22 HARV. J.L. & TECH. 1, 53-54 (2008) (noting that PJM uses its electrical monitoring information to "establish both a day-ahead market and a real-time spot market").

[139] *See* Jeffrey K. MacKie-Mason & Hal R. Varian, *Some Economics of the Internet*, *in* NETWORKS, INFRASTRUCTURE AND THE NEW TASK FOR REGULATION 107, 126-31 (Werner Sichel & Donald L. Alexander eds., 1996).

[140] *See* Eli Noam, *Spectrum Auctions: Yesterday's Heresy, Today's Orthodoxy, Tomorrow's Anachronism. Taking the Next Step to Open Spectrum Access*, 41 J.L. & ECON. 765, 778-81 (1998) (proposing an open-access model where assured price for access to a spectrum band could be determined by an automated clearinghouse of spectrum uses and assured access could be obtained from a futures market).

part of the bands reserved for television currently laying fallow (commonly known as "white spaces").[141] Centralizing such information can solve the multiparty bargaining problems that plague the Internet.[142]

This alternative approach would fundamentally redefine the proper role of property law. Rather than adjusting the scope of rights to mediate relationships between property holders directly, property could instead focus on providing owners with the building blocks needed to permit them to reallocate those rights via contract. That said, reallocating rights through decentralized decisionmaking presents a number of challenges. As an initial matter, most of these proposals envision that users will have to pay for access to the resource. As such, they are not particularly responsive to concerns about maintaining access for low-value or novel uses. In addition, the functioning of such coordination will be greatly complicated if individuals vary in the way they use spectrum. This will pose particular problems for applications that require large blocks of spectrum. As Thomas Hazlett observes, such a solution simply replaces one big auction with many little ones.[143] Moreover, as the experience with the Internet reveals, any deviation between private and social optima creates incentives for users in decentralized systems to cheat. This is why most proposals envision that there must be an enforcement mechanism.[144] The information sharing and price coordination associated with market-making inevita-

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[141] Werbach, *supra* note 97, at 252-54 (delineating the benefits of white space devices in "facilitat[ing] efficient utilization of . . . spectrum").

[142] *See* Christopher S. Yoo, *Free Speech and the Myth of the Internet as an Unintermediated Experience*, 78 GEO. WASH. L. REV. 697, 710-17 (2010) (discussing how third-party market makers can resolve bargaining dilemmas).

[143] *See* Thomas W. Hazlett, *Spectrum Flash Dance: Eli Noam's Proposal for "Open Access" to Radio Waves*, 41 J.L. & ECON. 805, 814 (1998) (analogizing such a scheme to a government land monopoly that leased tiny plots for short periods).

[144] *See* Noam, *supra* note 140, at 781 ("Enforcement of the system is straightforward for those flows of information that are transferred across networks. Without authorization code, they could not flow. For nonnetwork usage, the presence of transmissions without access codes would be closely watched by their competitors, and violators would be sued or reported."); Werbach, *supra* note 97, at 252-53 ("The FCC certifies all wireless devices. Therefore, its service rules for the white spaces can mandate that devices incorporate the database functionality, and also that they comply with directives from the database. The devices can even include a 'remote kill switch' to cease transmitting entirely if nearby systems experience interference or the devices are operating outside their parameters." (footnotes omitted)).

bly raises antitrust concerns.[145] That said, such intermediaries may represent the best opportunity for allowing greater flexibility in uses. The task would shift from trying to define the proper scope of property rights to providing verifiable information needed to support enforceable contracting.

D. *The Persistence of Use Restrictions*

The difficulties that interdependencies create for implementing a full-fledged property regime help explain the inability to follow Coase's call to abolish the current regime of use restrictions. Ithiel de Sola Pool first made the case with respect to spectrum in his landmark book, *Technologies of Freedom*. Although Pool saw the advantages of allowing rights holders to employ their spectrum for whatever use they saw fit, the lack of equipment standardization would impose high costs on third parties.[146] It is to avoid these costs that the government zones different bands of the spectrum for different uses (much like zoning for real estate) and sets equipment standards within each band.[147] In a similar vein, Thomas Merrill and Henry Smith argue that governments standardize real property forms in order to minimize measurement costs borne by third parties.[148] Abraham Bell and Gideon Parchomovsky also contend that the multiplicity of uses may make it difficult to determine the optimal dimensions of certain property attributes. Here, the law may compensate by placing restrictions on owners' freedom to reconfigure the property for alternate uses.[149] For example, the greater susceptibility of low-power uses to interference may justify placing some restrictions on other uses operating in the same band. Another strategy is to concentrate ownership in a single fictional owner, there-

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[145] *See* Ray S. Bolze et al., *Antitrust Law Regulation: A New Focus for a Competitive Energy Industry*, 21 ENERGY L.J. 79, 103-06 (2000) (reviewing the antitrust concerns raised by RTOs).

[146] *See* ITHIEL DE SOLA POOL, TECHNOLOGIES OF FREEDOM 144-45 (1983) (arguing that a market-based approach to spectrum distribution would "reduc[e] the opportunity for standardization of . . . equipment").

[147] *Id.* at 145 (analogizing spectrum distribution to property zoning because in both cases the government acts to decrease social costs on "neighbors").

[148] *See* Thomas W. Merrill & Henry E. Smith, *Optimal Standardization in the Law of Property: The Numerus Clausus Principle*, 110 YALE. L.J. 1, 46-47 (2000) (discussing how one nonstandard property user out of one hundred can raise costs for the entire group).

[149] *See* Bell & Parchomovsky, *supra* note 95, at 1049-53 (discussing rules that either directly or indirectly restrict property owners' ability to "reconfigure their assets").

by preserving the reduction in transaction costs associated with a single owner while facilitating reallocation by the government should it become necessary.[150]

CONCLUSION

The emergence of new technologies is providing fresh insights that challenge preexisting notions of property. Most importantly, these insights suggest adopting a more technological, interdependency-based vision that would reorient property in fundamentally different directions. In addition, the greater complexity of identifying sources of interference and allocating responsibility to multiple sources of joint causation may require new legal tools and new configurations of property. This complexity underscores the potential of intermediaries to help solve many of these problems. This reconfigured view of property also sheds new light on why true property rights in spectrum have been so slow to emerge. In so doing, it points toward a new agenda for the necessary elements in a properly articulated property regime.

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[150] *See id.* at 1044-46 ("[F]ictional owner strategy . . . enhanc[es] social utility derived from asset management" and "minimizes the dissipation of utility caused by splitting assets among too many owners.").