Exclusion Principles and Receiver Boundaries on Spectrum Resources

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Introduction

Old receivers impede spectrum efficiency when they are not compatible with transmission patterns of new receivers. Spectrum reallocation policy requires speedier rates of exit by outdated receivers. The challenge, however, is a sequential one, as old receivers draw boundaries with new receivers. This article explores exclusion principles for old and new receivers in the framework of complement and substitute uses in light of receiver configuration costs. Interference margins depend on the design of old and new receivers under governance rules or exclusive rights for the assembly of complementary

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configurations. Part I of this article discusses the asymmetries and symmetries of radio borders that impact efficient default rules. Part II explores the status of a new receiver as a complement or substitute to the old receiver, which directs the benefits of spectrum efficiency toward the costs of receiver reconfiguration. Part III describes shared spectrum as public governance of limited complements.

A. Receivers & Connectivity

Spectrum efficiency depends on closer configuration of existing receivers with new wave patterns.[2] Reallocation efforts are gridlocked as old receivers bear upgrade costs to resolve unexpected interference claims.[3] The design and reconfiguration costs of receivers can provide a systematic point of reference for spectrum policy reform. Indeed, interference between old receivers and new receivers is a matter of compounded change across technical, economic, and legal boundaries.[4] Technically, receivers are tuned to probabilistically expected emissions patterns along a select group of variables, with more/less power, more/less noise, degrees of antenna direction, and modulation format.[5]

[2] Pierre de Vries, *Radio Regulation Summit: Defining Inter-Channel Operating Rules, Silicon Flatirons Summit on Information Policy*, December 2, 2009, at 20 (*Radio Regulation Summit*) ("interference is often a function of the receiver characteristics, not the licensed transmitter.").

[3] de Vries, *Radio Regulation Summit*, at 20 ("the use of cheap receivers with poor out-of-band interference rejection creates a de facto right limiting the ability of adjacent licensees, or even incumbents, to change their use of a band.").

[4] Philip J. Weiser & Dale Hatfield, *Spectrum Policy Reform and the Next Frontier of Property Rights*, 15 Geo. Mason L. Rev 549 (2008) (*Spectrum Policy Debate Part I*) at 553 ("radio signals defy boundaries and can propagate in unpredictable ways."). *See also* Thomas W. Hazlett, *A Law & Economics Approach to Spectrum Property Rights: A Response to Weiser and Hatfield*, 15 Geo. Mason L. Rev. 975 (2008) (*Spectrum Policy Debate Part II)*; Philip J. Weiser & Dale N. Hatfield, *Property Rights in Spectrum: A Reply to Hazlett*, 15 Geo. Mason L. Rev. 1025 (*Spectrum Policy Debate Part III)*; Thomas W. Hazlett, *A Rejoinder to Weiser and Hatfield on Spectrum Rights*, 15 Geo. Mason L. Rev. 1031 (*Spectrum Policy Debate Part IV).*

[5] Weiser & Hatfield, *Spectrum Policy Debate Part III,* at 1027 ("Indeed, beyond the Class B boundary, say, to a contour where 20% of the areas along the contour will receive the signal 20% of the time, the signal still may well create interference with another user licensed in that location…"). In this view, the nature of radio propagation as the defining feature of the technology invites "more tailored remedies" with the "inevitable conflicts" and "expensive" solutions to predict radio propagation behavior. *Id.*

Economically, old receivers can install filters to ignore new signals, at theoretically random design costs.[6] In the alternative, new receivers may build around or technically bypass the ears of old receivers.[7] Lastly, legally, old receivers with license rights exercise at-will occupancy in deciding the degree of efficiency in use of the resource.[8]

Over- or under-inclusive rights boundaries must negotiate the reality that old receivers are designed without forward compatibility with new devices.[9] Operators of old receivers without incentives to upgrade, reluctantly reconfigure devices under direct reclassification or political pressure.[10] Knowing that upgrade costs are someone else's problem, receivers are designed with varying degrees of quality, impacting spectrum

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[6] de Vries, *Radio Regulation Summit*, at 12 ("interference they had not bargained for at the time they obtained their license," and "one of the most difficult situations is where the rules are defined at different times.").

[7] Weiser & Hatfield, *Spectrum Policy Debate Part I,* at 604:

> But, in many cases, the value of such technologies to a licensee will depend greatly on its neighbor's adoption of interference mitigation techniques. If, for whatever reason (say, transaction costs or strategic behavior), Firm A is unwilling to upgrade its interference mitigation system to benefit a neighbor, its neighbor will presumably be (at least without regulatory action) unable to deploy a more socially valuable product because the interference that it would produce would subject it to legal action.

[8] *See* Howard Shelanski & Peter Huber, *The Administrative Creation of Property Rights in Spectrum,* 41 J.L. & Econ. 581, 592 (1998).

[9] *See generally* Gregory L. Rosston, *Testimony before the U.S. Senate Commerce Committee*, Mar. 6, 2003:

> Users are stuck with old technically inefficient equipment [in the land mobile radio band]. Why? Because none of them has the incentive to adopt new equipment on their own that would free up spectrum for use by others. Instead, they came to the FCC with a proposal to transition over twenty-seven years to equipment that was not quite state of the art at the time of their proposal.

Cited in William J. Baumol and Dorothy Robyn, *Toward an Evolutionary Regime for Spectrum Governance: Licensing or Unrestricted Entry?*, Brookings Joint Center for Regulatory Studies (2006) at 28 n.14.

[10] de Vries, *Radio Regulation Summit*, at 17 ("in general, it will be difficult to get end devices to upgrade. One example is the long upgrade cycle in maritime radio equipment compared to cellular; in another example, the Land Mobile Radio industry… proudly assured the FCC some time ago that they could upgrade from 25 kHz to 12.5 kHz to 6.25 kHz over the next 25 years.") (footnote omitted).

efficiency.[11] How to pay for configuration between old receivers and new receivers is a critical question for spectrum reallocation.[12] Challenges arise from the asymmetries and symmetries of receiver boundaries.

I. Boundaries: Asymmetries & Symmetries

Receiver design is sequential, where new radios are deployed into sensitive electromagnetic landscapes. New transmitters create new ripples in intended frequencies and extended out-of-band frequencies. Old receivers experience distortions in expected signal patterns which alter the operator's optimization matrix.

A. Asymmetries in Receivers

Physics and time generate asymmetries as receivers listen for signals.[13] Equilibrium is disturbed when signal patterns change to a significant degree. If a new transmitter threatens an old receiver's ability to hear signals, a technical conflict arises. How much interference rises to the level of a claim of appropriate intrusion is a determination that depends on the sensitivity of neighboring devices.[14] An objective

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[11] de Vries, *Radio Regulation Summit*, at 19 ("[T]here was general agreement among the participants that the quality of receiver front ends was declining. It is expensive to build a receiver with a narrow, linear, tunable front end that can reject out-of-band interference."); Weiser & Hatfield, *Spectrum Policy Debate Part I*, at 557 n.38 (quoting Marguerite Reardon, CNET, "The real culprits [for interference] are the speaker, car stereo, PC and other consumer electronics manufacturers for not designing their products to fend out this interference.").

[12] Weiser & Hatfield, *Spectrum Policy Debate I*, at 607 (describing the need for equipment upgrades, suggesting "the FCC consider requiring the entrant to subsidize such upgrades").

[13] de Vries, *Radio Regulation Summit*, at 19:

> While co-channel property rights are easy to manage, inter-channel rights are more tricky because radio system designs make a huge number of assumptions about the interference that will be generated by neighbors; when these assumptions fail to hold, difficulties ensue. Inter-channel interference issues also tend to emerge over time, as services are deployed, often with characteristics different from those that were envisaged at the outset.

[14] For policy attempts to define appropriate interference, s*ee* FCC Receiver Standards: ET Docket No. 03-65 (recommended by the Spectrum Policy Task Force); FCC Interference Temperature: ET Docket No. 03-237 (recommended by the Spectrum Policy Task Force); NTIA Report No. 03-404 (receiver spectrum standards); NTIA Comments on Interference Immunity Performance Specifications for Radio Receivers, November 12, 2003; NTIA Comments on the Establishment of an Interference Temperature Metric to

quantity of signal interference, regardless of energy magnitude, can be characterized as brief, unintentional, trivial – or – harmful, costly, and disruptive.

Propagation and attenuation also introduces asymmetries that raise costs of receiver configuration.[15] Waves of energy have non-discrete borders, where signals originate on an intended frequency and spill across borders known as in-band and out-of-band interference.[16] Radio signals are not yet laser precise and react to terrestrial environments with passive modulation and natural harmonics.[17] Climate effects and weather events further increase margins of risk.[18] The hidden terminal problem, near-far problem, multipath propagation problem, are well-known configuration challenges in transmitter-receiver links.[19] To cabin the wildness, quantitative engineers create math

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Quantify and Manage Interference and to Expand Available Unlicensed Operation in Certain Frequency Bands, August 13, 2004; FCC, Spectrum Policy Task Force Report, November 2002, http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf; FCC, Spectrum Policy Task Force, Report of the Spectrum Efficiency Working Group, November 2002, http://transition.fcc.gov/sptf/files/SEWGFinalReport_1.pdf (citing technical margins of spectrum efficiency in time, space, receivers).

[15] *See* Dale Hatfield, *The Challenge of Increasing Broadband Capacity*, 63 Fed. Comm. L.J. 43 , 56 (2010) *Id.* (waves attenuate according to the inverse-square rule with loss from terrestrial environments).

[16] *Id.* (describing irregular borders of waves).

[17] Steve Thomas, *Finding Interferers Using Handheld Spectrum Analyzers*, Anritsu Corporation, GoToWebinar Presentation, February 24, 2011 ("In-Band Interference") ("Light-dimmers, made [proper] 60-cycle sin waves, not sin waves anymore, and create[d] harmonics. One hospital had 100s of light dimmers not properly selected, and they had to replace them every few weeks, and failure would cause interference with their telemetry system.").

[18] Charles Jackson, *Limits to Decentralization: The Example of AM Radio Broadcasting or Was a Common Law Solution to Chaos in the Radio Waves Reasonable in 1927?*, TPRC 2005 (describing climate effects).

[19] Gerald R. Faulhaber, *Deploying Cognitive Radio: Economic, Legal and Policy Issues*, 2 Int'l J. of Comm. 1114, 1116 (2008) (describing the hidden terminal or hidden node problem in sensing); Hatfield, 63 Fed. Comm. L.J. at 56 (signals bounce off buildings at different angles, where the receiver waits and gets a distorted result); Nicholas Cannon, *Troubleshooting Passive Intermodulation Problems in the Field*, Anritsu Corporation, Doc. 11410-0586, Rev. A, 2010-12, at 6 ("The signals can back-feed into an antenna system, find non-linear devices, mix with other carriers, and create PIM."); Thomas, *Finding Interferers* ("Could be a transistor, a diode, an integrated circuit someplace, it could be corrosion, especially with dissimilar metals, a rusty barbed wire fence around site with a cell-site and public safety repeater on the same site.").

models to generate maps of expected emissions.[20] To hunt anomalies on the ground, experts equipped with spectrometers and refined diagnostic judgment cultivate and weed out physical obstacles on emissions fields.[21] Such features of radiation are not new to policymakers or legal scholars.[22] Due to these jagged edges, communications regulators have historically defined licenses narrowly along narrow vectors of stable variables.[23]

B. Symmetries in Receivers

Viewed as a resource allocation game, however, a theoretical equilibrium of private and social costs exists across economic boundaries of spectrum users. Professor Ronald Coase articulated the interchange of private and social costs when transaction costs are zero,[24] correcting the Pigouvian view that externalities were separate from private costs of the parties at issue.[25] This framework of private and social externalities became the foundation of law and economics scholarship for the study of default rules

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[20] Weiser & Hatfield, *Spectrum Policy Debate Part I,* at 583-87 (describing predictive models of simple and complex form, based on wave theory and terrestrial environments).

[21] Thomas, *Finding Interferers:*

> You may be receiving only multipath in an urban canyon…You go to the corner so you can look in all directions… Figure out the strongest direction. Then keep going, walk down the block to find the next block. Don't waste your time looking mid-block, until you get a dramatic change in direction. This means you're getting close. Then you continue to follow… They walked around the building and found the signal emanated. Took a few more weeks because upper floors of the building were locked without public access, but got solved eventually.

[22] Ronald H. Coase, William H. Meckling, Jora Minasian, *Problems of Radio Frequency Allocation*, Rand Corporation, Unrestricted Draft No. DRU-1219-RC, estimated date of publication 1962, released to the public in September 1995.

[23] *See* William J. Baumol & Dorothy Robyn, *Toward an Evolutionary Regime for Spectrum Governance: Licensing or Unrestricted Entry?*, Brookings Joint Center for Regulatory Studies (2006) at 2 (*Evolutionary Regime*) ("[Spectrum] use is governed by a set of rules and narrow restrictions, designed to limit interference, whose origins go back nearly a century….There is widespread agreement that the current institutional arrangements are a source of major inefficiency and waste, and that the public interest calls urgently for some substantial modifications.").

[24] Ronald H. Coase, *The Problem of Social Cost*, 3 J. L. & Econ. 1-44 (1960).

[25] Thomas Hazlett, David Porter & Vernon Smith, *Radio Spectrum and the Disruptive Clarity of Ronald Coase*, J.L. & Econ. (Nov. 2011) (for a discussion of the institutional symmetry that Coase revealed over Pigouvian asymmetry of social cost).

that define entitlements in the face of technological change.[26] Classic examples include disputes over the shifts of railroad sparks to farm fields, odorless communities to pig farms, doctor's offices to candy factories, and cattle ranching to corn fields.[27]

Professor Coase evaluated the Federal Communications Commission's approach to social and private costs in spectrum resources as well.[28] Economic fundamentals apply to the uses of the radio spectrum, although much asymmetry still characterizes spectrum boundaries currently in the form of "lumpy" entitlements.[29] Across the range of radio hardware designs and industry applications, furthermore, the marginal costs and marginal benefits of delineating precise or broad use rights vary today.[30]

At a time of a spectrum crunch, however, the need arises to upgrade receivers from old to new.[31] The knowledge problem of which receivers should change transmission patterns, and when, depends on decentralized market information.[32] Indeed, in the eye of which beholder, the old receiver or the new receiver, is a

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[26] *See generally* The Technology of Property Rights, The Political Economy Forum (eds. Terry L. Anderson & Peter J. Hill) (2001); Terry L. Anderson & Peter J. Hill, The Not So Wild, Wild West: Property Rights on the Frontier (2004).

[27] *See Spur Industries, Inc. v. Del E. Webb Development Co*., 494 P.2d 700 (Ariz. 1972); *Sturges v. Bridgeman* (1879), cited in Ronald H. Coase, *The Federal Communications Commission*, 2 J.L. & Econ. 1, 26 n.51

[28] Ronald H. Coase, *The Federal Communications Commission*, 2 J.L. & Econ. 1 (1959); Ronald H. Coase, William H. Meckling, Jora Minasian, *Problems of Radio Frequency Allocation*, Rand Corporation, Unrestricted Draft No. DRU-1219-RC, estimated date of publication 1962, released to the public, September 1995.

[29] Henry E. Smith, *Self-Help and the Nature of Property*, 1 J.L. Econ. & Pol'y 69, 76 (2005).

[30] Smith, *Self-Help*, at 88-89.

[31] Prepared Remarks of Chairman Julius Genochowski, FCC Spectrum Summit, Unleashing America's Invisible Infrastructure, October 21, 2010, http://transition.fcc.gov/Daily_Releases/Daily_Business/2010/db1021/DOC-302331A1.txt ("spectrum crunch").

[32] *See generally* Kenneth Arrow, Economic Welfare and the Allocation of Resources for Innovation, Rand Corporation Doc. P-1856 (1959), *available at* http://www.rand.org/pubs/papers/P1856.html; F. A. Hayek, The Use of Knowledge in Society, American Economic Review (1945), *cited in* Fundamental Issues in Strategy: A Research Agenda (eds. Richard P. Rumelt, Dan E. Schendel, David J. Teece) at 364.

reallocation a development gain or a damaged entitlement? To the regulator, the newer neighbor may cause interference just as much as the older receiver hogs airspace with old technology.[33]

That is where Harold Demsetz described the economist's neutrality to avoid "cause" or "harm" language at entitlement borders.[34] One side's entrepreneurship can be alleged a taking of a legal entitlement of the other. The value of new receivers compared to old at a given point in time varies on which party you ask. The new receiver could be a competitive threat to investment horizons of the old receiver's model. The new innovation might simultaneously generate net gains from otherwise social waste of the radio spectrum. The value of use of the airwaves at that interference margin incorporates a host of financial metrics and physical investment projections.[35] Receivers are sensitive or robust to interference, but their business models depend on design choices and reconfiguration costs.

C. Receiver Design Costs

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[33] *See generally* de Vries, *Radio Regulation Summit*, at 24 (receiver standards discussion).

[34] Harold Demsetz, *When Does the Rule of Liability Matter?*, 1 J. Legal Stud. 1, 28 (1972).

[35] *See* Coleman Bazelon, *The Economic Basis of Spectrum Value: Pairing AWS-3 with the 1755 MHz Band is More Valuable than Pairing it with Frequencies from the 1690 MHz Band* at 5, The Brattle Group, Inc. April 11, 2011:

> Spectrum value is the present value of a stream of future profits… As with any capital investment, the net return of investing in a band of spectrum will be realized over time. The upfront capital investment is expected to result in a stream of net returns (revenue, minus cost), over the lifetime of the asset. The value of the investment and expected stream of profits depends critically on the timing of this stream of returns. The present value of any future payment is equal to the amount you would need to invest today to receive that future return..

See also Connecting America: The National Broadband Plan, Federal Communications Commission, Chapter 5.6, March 16, 2010:

> The prices observed from the auction of licenses for comparable spectrum are one indicator [of value], but are imprecise due to differences in the technical characteristics, rules, interference environment and temporal variations in the supply and demand of the spectrum being compared.

Orderly change to the population of receivers on the field can happen through a variety of forms of rights delineation, such as flexible private ownership, regulatory settlement, trespass and nuisance remedies, compensatory damages, and zoning decrees. Operators must adjust the configuration of receivers at an additional design cost that reduces waste.[36] The value of reconfiguring a radio in a particular manner is inseparable from the operator's incentives within a strategic revenue model as well.[37]

Engineering new receivers is an iterative process, even for next generation radios that employ signal back-off and advanced information capacity channels. Designers rely on their knowledge of current emissions patterns when building next generation receivers to specification.[38] A new negotiation of incomplete borders happens when new emissions come into play.[39] For example, if an old receiver faced no threat from any high powered neighbors at the deployment stage, it had no need to build filters to create a

[36] *See, e.g.*, Stephen Lawson, IDG News, *GPS Group Slams Lightsquared's New Plan*, PCWorld, July 5, 2011, http://www.pcworld.com/businesscenter/article/235095/gps_group_slams_lightsquareds_new_plan.html (describing opposing views on the cost of installing filters into GPS units. Lightsquared has argued that GPS devices were made with inadequate filters causing interference. The article states that Coalition to Save Our GPS argued that "Retrofitting existing GPS receivers so they could work after LightSquared's launch would take at least 15 years, because devices such as in-car navigation systems are replaced on long cycles. LightSquared said there are already suitable filters for cell phones that cost about five cents each.").

[37] *Id*. (the Coalition to Save Our GPS argues that Lightsquared offers competing GPS-related services which acts as a competitive threat).

[38] *See* Nate Anderson, *GPS Industry Rages: Lightsquared 4G Network Would "Defy" Laws of Physics*, ArsTechnica, June 2011, http://arstechnica.com/tech-policy/news/2011/06/how-gps-interference-could-derail-a-new-national-4g-networkgps-industry-rages-lightsquared-4g-network-would-defy-laws-of-physics.ars (LightSquared says "interference is caused by the GPS device manufacturer's decision over the last eight years to design products that depend on using spectrum assigned to other FCC licensees.").

[39] *Id*. (where Lightsquared offered a three-part solution to upgrade 200,000 GPS devices, including 300 million GPS-enabled cell phones, compared to Coalition to Save Our GPS position that Lightsquared should "move out of the MSS band altogether" for "such widespread harmful interference" to "a national utility").

separation at the time.[40] Preempting imagined wave borders is too costly to predict and build in competitive markets.

Due to the wild card of reconfiguration cost, receivers need to be protected from interference changes. Whether a foe can be turned into a friend, or a 4% expected present value of a certain type of interference incorporated into the cost of doing business,[41] depends on the economic status of two neighbors as complements or substitutes. A new receiver can be a complementary addition or a substitutionary rival to an old receiver's design scheme. How devices align engineering goals and configuration costs to minimize interference margins is a matter of economic incentives.

II. Complement and Substitute Emissions

The relationship between an old receiver and new receiver defines what combined uses will be innovated, to what degree, and how configuration cost payments will flow.[42] A new device can be seen as a harmless addition to the frequency space, or a significant source of signal interference. The technical shapes of potential new borders embody thousands of permutations, and which of those will be realistic combinations depends on the ability of an operator to profit from such choices.[43]

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[40] *Id*. (where Lightsquared's plans for 40,000 ground stations would transmit at higher power, close proximity compared to GPS signal reception capabilities).

[41] Recall the Weiser & Hatfield, *Spectrum Policy Debate Part III*, at 1027 with the example of radio interference predicted in probabilistic behaviors. Whether a 20% chance of interference at 20% time gives 4% expected present value of a presumption of interference, rises to random or trivial degree may differ on the sensitivity and quality of service required by the operators.

[42] *See generally* Carliss Y. Baldwin & Kim B. Clark, Design Rules: The Power of Modularity (MIT Press 2000); Carliss Baldwin, *Modularity, Transactions, and the Boundaries of Firms: A Synthesis*, HBS Working Paper Number: 08-013 (September 2007) (deconstructing transaction locations, modularizations, and breakpoints where firms and industries split); *id.* at 29 fig.3 ("Finding the 'Optimal' Transaction Design") (modeling the costs of a formal contract over that of a relational contract where the horizontal axis denotes transactional complexity and the vertical axis the benefits of a transaction).

[43] Martin B.H. Weiss, Mohammed Al-Tamaimi & Liu Cui, *Dynamic Geospatial Spectrum Modelling*, TPRC 2010, at 7 (identifying twelve potential operating environments and four context awareness approaches including on-board sensing , databases, sensor networks, and cooperative sharing, along with

A. Complement-Substitute Governance

Who decides the appropriate mix of complement and substitute uses?[44] A particular signal emission can be considered a complement in one situation or time, while a substitute in another.[45] The definition and boundaries of complementarity will determine whether a marginal change in electromagnetic activity is disruptive or trivial.[46] A legal framework for who decides the character of such design changes can be articulated in the exclusion and governance model.[47]

Governance rules set by a public agent or standards coalition require higher precision, imposed on multiple independent parties. [48] Whether a radio signal is determined as friendly or invasive depends on rules set for a particular frequency band.

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static, periodic, fast periodic, and stochastic temporal characteristics with static, periodic and stochastic spatial categories.); Robert Matheson & Adele Morris, *The Technical Basis for Spectrum Rights: Policies to Enhance Market Efficiency*, March 3, 2011, Brookings Institute (suggesting partitions of spectrum along "dimensions of space, time, frequency, and direction of propagation" given an "licensed electrospace right (LER)."); Spectrum Policy Task Report, FCC, *Report of the Spectrum Efficiency Working Group*, *supra*.

[44] Smith, *Self-Help*, at 79 ("For example, Blackacre may be suited to having multiple people cultivating crops or might be subjected to multiple uses as long as the two uses are constrained from conflicting too much… I call these use-oriented rules examples of a governance strategy, as opposed to the basic exclusion strategy.").

[45] For the flexibility of a cognitive node to receive or avoid signals, *see* Andrea Goldsmith, Syed Ali Jafary, Ivana Maric & Sudhir Srinivasa, *Breaking Spectrum Gridlock with Cognitive Radios: An Information Theoretic Perspective* (describing "side information [that] typically comprises knowledge about the activity, channels, codebooks and/or messages of other nodes with which the cognitive node shares the spectrum."). Much research in cognitive radio protocols define etiquette rules for backoff: Carlo Boano, et al., *Making Sensornet MAC Protocols Robust Against Interference*; Wenyuan Xu, et al., *Defending Wireless Sensor Networks from Radio Interference through Channel Adaptation*, ACM Transactions on Sensor Network (2008) (describing handshakes, congestion backoff schemes, and channel surfing and switching to avoid interference on sensor networks).

[46] Kevin J. Boudreau, *Does Opening a Platform Stimulate Innovation? The Effect on Systemic and Modular Innovations*, MIT Sloan Research Paper No. 4611-06 (2007) ("innovators need to choose both the extent and mode of their openness if they are to manage the tradeoffs between creating a diverse supplier pool, managing suppliers' investment incentives and ensuring effective coordination."); Kevin J. Boudreau, *Opening the Platform vs. Opening the Complementary Good? The Effect on Product Innovation in Handheld Computing*, London Business School, Working Paper (2008) (exploring degrees of openness of complements to a platform with rates of technology development).

[47] Henry E. Smith, *Exclusion Versus Governance: Two Strategies for Delineating Property Rights*, 31 J. Legal Stud. 453, 454 (2002); Thomas W. Hazlett, *Spectrum Tragedies*, 22 Yale J. on Reg. 242, 261 (2005).

[48] Smith, *Self-Help*, at 79.

A public owner of a spectrum band might govern a commons as, "*Only complements are allowed here, defined by minimum rules that avoid substitutes*." Such a rule limits the innovation possibilities for radios but enables a form of coexistence. Governance may also support the establishment of joint databases of location data.[49] White space rules, for example, follow this model.[50]

B. Complement-Substitute Exclusion

In contrast, an exclusion strategy relies on low precision over-inclusive rules.[51] With the right to define uses of a resource, a private owner might contract with third-party developers, "*It's in my interest to bargain for complements to my resource, and through business negotiations, we will define and exchange complements*."[52]

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[49] *See* Hang Zhou, Randall A. Berry, Michael L. Honig, and Rakesh Vohra, *Spectrum Markets with Interference Complementarities*, Proc. WiOpt Conference, Princeton, New Jersey, May 2011 ("Such interference can result in complementarities among the spectrum goods being traded, which complicates the design of an efficient market."). This work focuses on interference complementarities achieved by the purchase of neighboring assets to preclude other interfering agents for on-demand guard zones. *Id. See also* Linda Doyle & Tim Forde, *Towards a Fluid Spectrum Market for Exclusive Usage Rights*, IEEE DySPAN 2007; Tim Forde & Linda Doyle, *Exclusivity, Externalities & Easements: Dynamic Spectrum Access and Coasean Bargaining*, IEEE DySPAN 2007.

[50] White Spaces, ET Docket No. 04-186, *Second Report & Order*, 23 FCC Rcd 16807 (Nov. 2008) (setting transmit antenna height limits, transmit power control, out-of-band emissions limits, spectrum sensing requirements, measurement procedures, equipment certification); White Spaces, *Second Memorandum Opinion & Order* (Sept. 2010) (revising the rules for unlicensed wireless devices).

[51] Smith, *Self-Help*, at 87.

[52] Baumol & Robyn, *Evolutionary Regime*, at 19 n.3 (describing the private exchange between the owner of a private pond for fish stock with fish suppliers to monitor, fence, and contract to reach mutually beneficial levels of fish populations over time). Smith, *Self-Help*, at 79:

> [C]onsider the owner as a chooser among the possible uses of Blackacre. As already discussed, the right to exclude makes no reference to these uses, but, by installing the owner as a gatekeeper over the asset, the owner's interest in these uses is protected. The degree of delegation can be measured by the size of the "mismatch" between the right (to exclude) and the privileges of use that it indirectly protects…. Conversely, if the law makes detailed reference to uses and seeks to solve use conflicts between the owner and various neighbors or even been the owner and strangers, then the delegation is a lesser one; the law has removed from the owner some of the choice over uses and the choice over modifications of legal relations pertaining to those uses.

The exclusive right to define a (complementary) use, is a unique feature of platform boundaries of information goods.[53] Open source software and open access platforms have agreed norms on what constitutes a complementary contribution.[54] The open or closed distinction can be a fluid one, however, depending on the evolution of a business model and nature of limited resources.[55] Contracts are then negotiated in arms length transactions to determine allocative shares of property at the edges of platforms.[56]

Yet costs of delineating broad platform boundaries can increase when "the uses to which an asset might be put become more multiplex, more uncertain, and generally harder to measure."[57] In dynamic settings, information uses become "more uncertain as they become more valuable," where costs and benefits of resource protections both rise and shift outward, at varying rates.[58] Efficient uses of spectrum is a "multiplex and

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[53] Thomas Hazlett, *Modular Confines of Mobile Networks: Are iPhones iPhony?*, 19 Supreme Court Economic Review (2011) ("Coordination among complementary asset owners and simultaneous rivalry among platforms suggests that the process of creative destruction [in wireless handsets] is robust.").

[54] *See* Josh Lerner & Mark Schankerman, The Commingled Code: Open Source and Economic Development (MIT Press 2010). Whether wireless innovation accelerates with open entry or market entry depends on where devices fall on the complement-substitute scale. For the open entry view, *see* Kevin Werbach, *Supercommons: Toward a Unified Theory of Wireless Communication*, 82 Tex. L. Rev. 863 (2004); Yochai Benkler, *Sharing Nicely: On Shareable Goods and the Emergence of Sharing as a Modality of Economic Production*, 114 Yale L.J. 273 (2004); Yochai Benkler, *Some Economics of Wireless Communications*, 16 Harv. J.L. & Tech. 25 (2002).

[55] *See* Boudreau, *Opening the Platform*, supra.

[56] *See* Richard Posner, Economic Analysis of Law (7th ed. Aspen), at 67:

> A property right excludes (in the limit) the whole rest of the world from the use of the property except on the owner's terms. A contract right excludes only the other party to the contract. Freedom to make and enforce contracts but not to create legally enforceable property rights would not optimize resource use…

See also Thomas W. Merrill & Henry E. Smith, *The Property/Contract Interface*, 101 Colum. L. Rev. 773-852 (2001) (where the common law has dealt with information cost discrepancies in bailments, landlord-tenant law, security interests, and trusts depending on the nature of in personam relations, in rem relations and third-party information costs to default to particular obligations and remedies).

[57] Smith, *Self-Help*, at 88; Henry E. Smith, *Intellectual Property as Property: Delineating Entitlements in Information*, 116 Yale L.J. 1742-1822 (2007).

[58] *Id*. at 87-88.

uncertain" equation that reflects market conditions.[59] The degree by which a spectrum user could waste, or, in a competitive market, productively divide, a delineated entitlement ranges widely.[60] Business models are subject to uncertain returns on investment which require strategy to reduce other forms of downside risk. And, like creative ideas protected by intellectual property,[61] radio signals are transmitted only after being queued up by larger distribution and network operations that generate probabilistic revenue streams.[62]

On other technology platforms, the right to determine complements emphasizes a design prerogative to combine efficiencies, reject inefficiencies, and to vertically integrate features of a business model.[63] Devices are harmonized with strategic purposes, to exchange signals as extensions of larger communications infrastructures.[64] If new receivers degrade or contaminate data processing of old receivers, the degree of waste at

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[59] *Id.* at 88.

[60] *See* Howard Shelanski & Peter Huber, *The Administrative Creation of Property Rights in Spectrum,* 41 J.L. & Econ. 581, 592 (1998):

> That right is analogous to a building owner's right to occupy the entirety or to choose instead to lease space out in any proportion—a floor, a room, a rooftop sign—and for any length of time—10 years, a month, or an hour. Complete rights to spectrum would similarly allow a licensee to occupy, subdivide, and sublease at will.

[61] *See generally* Henry Smith, *Intellectual Property as Property,* 116 Yale L.J. 1742-1822 (2007).

[62] The property holder's interest in the assets of productive use is the functional purpose of the right. *See* Claeys, *Property 101,* at 633-34 (footnote omitted):

> An exclusive right of use determination has more focus and determinacy than a right to exclude. Exclusive use determination describes property as an interest. The bearer of such an interest enjoys a domain of negative liberty, but the domain is structured to encourage owners to deploy ownable assets to most of the productive uses for which property is typically used. By contrast, a right to exclude from the thing merely states a particular outcome. It abstracts away from the general context and principles that explain why the outcome is justified.

[63] *See* Bruce Owen, *Antitrust and Vertical Integration in "New Economy" Industries with Application to Broadband Access*, Stanford Law and Economics Olin Working Paper No. 400, November 10, 2010.

[64] *See* Hazlett, *Spectrum Policy Debate Part II*, at 1033 (reviewing the "observation of complementarities in spectrum ownership" in the MediaFLO example with possible combinations of "high power" and "low power" uses.).

the interference margin can be a function of the economic interests of neighboring emissions areas.[65] An absolute right to complement-substitute determination in radio emissions would require far broader license and merger terms than available in the United States today, but international jurisdictions provide models of flexibility.[66]

C. Substitute-Substitute Rivalry

Despite engineering possibilities, operators often appear before the FCC in a substitute-substitute posture of rival legal footing.[67] To the regulator, the preferred use of the spectrum is unknown, and principles are needed to minimize social waste while defining legal protections for resource investments of existing users. Examples of legal conflicts appear at the WCS-XM border, PCS-800 MHz border, and Lightsquared-GPS border.[68]

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[65] Computing products increasingly rely on the quality of data sorting and acquisition for valued outputs. Compatibility concerns have been raised as a competitive platform dispute between Google, Skyhook and Motorola regarding mobile location data. *See generally* Complaint, *Skyhook Wireless, Inc. v. Google, Inc.*, Massachusetts Superior Court, September 15, 2010.

[66] *See, e.g.*, Pablo Spiller, *The Frontier of Telecommunications Deregulation: Small Countries Leading the Pack*, J. of Econ. Perspectives (1997) (reviewing Australia, Chile, Guatemala and New Zealand); Giancarlo Ibarguen, *Liberating the Radio Spectrum in Guatemala*, 27 Telecommunications Policy 543-54 (2003).

[67] Ellen P. Goodman, *Spectrum Rights in the Telecosm to Come*, 41 San Diego L. Rev. 269, 394 (2004):

> Especially in intraservice interference conflicts, we see that disputes over spectrum can be more like disputes over possessory rights than like pollution rights. The values placed on the spectrum by the victim and the interferer tend to be correlated because both parties are using the same kind of architecture with the same kind of spectral efficiency. Although the two operators might place different values on the spectrum they use, just as Sally and Jane might value Jane's car differently, it is the utility of the spectrum for the same kind of use that they value.

[68] de Vries, *Radio Regulation Summit* (with a focus on three case studies of the 800 MHz, WCS/SDARS, and AWS-3, recognizing the role of receiver performance and the technical architectures and commercial interests at rights borders).

Spectrum efficiency enters the realm of law at these borders.[69] Trespass and nuisance laws in property, and negligence and strict liability in torts, each embody norms of deference to property owners of known and unknown conflicts of short and long duration of productive or disruptive purpose.[70] Intellectual property rules build on this history to promote the discovery, cultivation and improvement of information goods by competing firms that generate economic activity today.[71]

Judges have refined default rules to enjoin or compensate parties to promote productivity in light of information costs and transaction costs.[72] The costs and benefits of *ex post or ex ante* delineations of rights depend on policy priorities,[73] views on the

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[69] *Compare* Sahai, *Spectrum Zoning*, whose model presupposes liberal rights "whether an ISP will buy out a TV station's primary rights." *Id.* The runtime model also presupposes integration of private costs between two independent radio operators:

> When the margin is small… all shared channels in which the TV primary is operating are essentially given entirely to TV, while ISP recovers no utility in these channels. When … allocated at runtime to ISP, it achieves the same utility it would in an exclusive channel if the overhead is 0.

[70] *See* Posner, Economic Analysis of Law, at 69 ("The law of trespass, by refusing to consider the value of the invader's activity, channels the transaction into the market, where it belongs. The law of nuisance, by permitting a comparison of the value of the conflicting activities, simulates the result of a market transaction, which is infeasible.").

[71] Mark A. Lemley & Phil Weiser, *Should Property or Liability Rules Govern Information?*, 85 Texas L. Rev. 783, 805 (2007) (suggesting holdup from injunction rights hurts innovation more than reasonable rates for access by competitors under liability remedies in patents, copyright and spectrum licenses); Alan Devlin, *Indeterminism and the Property-Patent Equation*, 28 Yale L. & Pol'y Rev. 61 (2009) (contrasting real property and intellectual property to support liability rules over injunctions). *Compare* Richard A. Epstein, *A Clear View of the Cathedral: The Dominance of Property Rules*, 106 Yale L.J. 2091 (1997), cited in Lemley & Weiser, 85 Texas L. Rev. at 787 n.21 (supporting property rules over liability rules where courts suffer from information costs of identifying holdup situations and calculating damages); Henry Smith, *Property and Property Rules*, 79 N.Y.U. L. Rev. 1719, 1781 (2004) ("Property rules are most called for where an entrepreneurial owner, broadly defined, is good at gathering information cost-effectively but results are not verifiable (entrepreneur makes bets), but a potential taker is good at informationally free-riding on the entrepreneur."), *cited in* Lemley & Weiser, 85 Texas L. Rev. at 820 (where property rules "rely on the property owner to evaluate the relevant unknown circumstances, reflect a sound delegation strategy as property owners are more likely to judge those circumstances effectively").

[72] *See* Lemley & Weiser, 85 Texas L. Rev. at 784 (discussing concurrences written by Chief Justice Roberts and Justice Kennedy in *eBay Inc. v. MercExchange, LLC*, 126 S.Ct. 1837 (2006) differing on when injunctive relief is appropriate.).

[73] The FCC's 2002 Spectrum Policy Task Force and 2010 National Broadband Plan were policy initiatives to determine priorities for rulemakings and administrative decisions.

structure of the wireless industry, and institutional capabilities to adjudicate efficient outcomes.[74]

Information costs influence efficient outcomes, but do not preclude value-maximizing transactions.[75] In spectrum, the valuation of the use of an old receiver against a new receiver is an information cost, where spectrum traffic cannot easily be compared.[76] The comparative difficulty lies in the value of a possessory right compared to a usage right.[77] Compare for instance the use value of a car that drives once a week to the movies, compared to the same vehicle that drives daily to place of employment. Both users might pay $6,000 for the possessory right, while extracting divergent values of productivity.[78]

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[74] *See* Louis Kaplow & Steven Shavell, *Property Rules Versus Liability Rules: An Economic Analysis*, 109 Harv. L. Rev. 713 (1996), cited in Posner, Economic Analysis of Law, 69 n.3 (The common law approach depends on a judge, jury, and fact finding, taking into account the context of business scale, the nature of the technology, the information needed by the adjudicator, and the speed by which resolution is needed).

[75] Posner, Economic Analysis of Law, at 71 (describing the value-maximizing transaction between a homeowner and factory, with the costs of installation of a filter):

> If to avoid this overpayment the factory offers only the filter, then it will forgo sales to the others even though, but for this asymmetric information (each homeowner knows how much pollution harm he is suffering, but the factory does not), these sales would be value-maximizing transactions. There is no single price that will not prevent some value-maximizing transactions from taking place.

[76] Posner, Economic Analysis of Law, at 69:

> Information is costly to acquire, and less information is required to determine whether the plaintiff's use is more valuable than the defendant's than to determine the value of the plaintiff's use (or the reduction in that value caused by the defendant), just as it is easier to determine whether one person is taller or heavier than another than it is to determine how tall and heavy each person is.

[77] The comparative value of "free" over-the-air broadcast television and the economic benefits of increased mobile broadband varies according to economic estimates. *Compare* Woods & Poole Economics, *An Analysis of the Importance of Commercial Local Radio and Television Broadcasting to the United States Economy*, June 2010 (estimating $49.32 billion GDP generated in local commercial broadcast radio and television, employing 300,000 jobs, with "cascading effects" on $1.4 trillion GDP and 2.52 million jobs), with David W. Sosa & Marc Van Audenrode, Analysis Group Report, *Private Sector Investment and Employment Impacts of Reassigning Spectrum to Mobile Broadband in the United States*, August 2011 (estimating $230 billion GDP growth and 300,000 job growth with reassignment of 300 MHz over five years).

[78] *See* Goodman, *Spectrum Rights*, at 393-94:

Radio technologies depend on physical infrastructure to shorten the distance from a wireless device to wired networks as well.[79] The problem of artificial scarcity of spectrum licenses released by government auction distorts valuation metrics also.[80] Even with limited prospective data, analysts and firms differ on projections for spectrum auction results, when auctions vary in the license terms offered.[81]

Transaction costs also impact efficient rules, depending on whether bargains must be made between many parties, or whether bilateral monopoly or repeat player situations exist.[82] In real property, nuisance law provides a model for high-transaction cost

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> [T]he value that two contending parties place on a possessory right tends to be more highly correlated, and thus more easily known, than the value that two contending parties place on a usage right. Suppose, for example, that Sally has taken Jane's car. Sally and Jane both value the utility of the car, even though they might value it to different degrees. By contrast, in the case of a conflict over air pollution, the polluter values the entitlement to pollute as a means to enhance the value of an enterprise, while those adversely affected by pollution value the absence of pollution. There is likely to be far less correlation between the two valuations of the air than the two valuations of the car. As a result, Sally and Jane will have better information, as compared to a court, than will the factory and homeowner.

[79] *Id.*

[80] Connecting America: The National Broadband Plan, Chapter 5: Spectrum ("Given the length of the spectrum reallocation process, these reforms should reflect expectations of how the wireless world will look 10 years from now. These reforms should ensure that there is sufficient, flexible spectrum that accommodates growing demand and evolving technologies.) *Id.* at Exhibit 5-C: Time Historically Required to Reallocate Spectrum (where the approximate lag time was eleven years for cellular (advanced mobile phone system), six years for PCS, ten years for Educational Broadband Service (EBS)/Broadband Radio Service (BRS), thirteen years for 700 MHZ, and six years for AWS-1).

[81] *Compare* CTIA, CEA, *Broadcast Spectrum Incentive Auctions White Paper*, February 15, 2011 (estimating 120 MHz of reclaimed broadcast TV spectrum to produce over $33 billion in auction proceeds), with Jeffrey A. Eisenach, *Revenues from a Possible Spectrum Incentive Auction: Why the CTIA/CEA Estimate is Not Reliable*, March 31, 2011 (presenting a critique of a regression model that lacks precision in predicting revenues under auction rules that differ from past spectrum auctions). *See also* Jeremy Bulow, Jonathan Levin & Paul Milgrom, *Winning Play in Spectrum Auctions*, NBER Working Paper No. 14765, March 2009 (describing "factors that make bidding in large spectrum auctions complex, including exposure and budget problems, the role of timing within an ascending auction, and the possibilities for price forecasting…").

[82] *See also* Posner, Economic Analysis of Law, at 51 ("Transaction costs are never zero. In fact they may be quite high even in two-party transactions, as we shall see many times in this book. Generally, however, the costs of a transaction rise with the number of parties to it – and very steeply; the formula for the number of links required to join all members of a set of n members is suggestive: n(n-1)/2."). Posner describes the exponential number of outcomes from multi-party transactions.

situations such as pollution that need tailored remedies.[83] In cases where the common law does not reach socially efficient outcomes, statutory regulation has dealt with massive class action lawsuits where polluters and victims are difficult to identify.[84]

Trespass rules for invasions, on the other hand, rely on clear exclusion boundaries when parties are few in number and transaction costs are low.[85] The enforcement of such a broad right through injunction allows an "initial presumption" to the owner to have protection from interference in determining the use of a particular resource.[86] The common law can also mix traditional trespass and nuisance standards. In *Boomer*, a judge shaped an otherwise appropriate nuisance case toward a trespass outcome.[87] Judge Posner analyzed the approach, "[T]he court held that *any substantial interference with another person's enjoyment of his land* is a nuisance. This is a trespasslike standard, and as there were only a few plaintiffs (and one defendant – a dust-spewing cement factory), one might have thought that the court would have granted an injunction."[88] The distinction perhaps, was the "dramatic illustration of a bilateral monopoly", where the court protected enjoyment of the land from any substantial interference.[89]

[83] Posner, Economic Analysis of Law, 69-71.

[84] Posner, Economic Analysis of Law, 69-71.

[85] Weiser & Hatfield, at 553 n.22, n.23, *citing* Richard A. Epstein, *The Property Rights Movement and Intellectual Property*, Regulation, Winter 2008, at 58, 60; Henry Smith, *Property and Property Rules*, 79 N.Y.U. L. Rev. 1719, 1732 (2004) ("In the law of real property, trespassers face injunctions and often punitive damages as well.").

[86] Eric Claeys, *Property 101: Is Property a Thing or a Bundle?*, 32 Seattle U. L. Rev. 617, 631-34 (2009) ("property exclusion does not exclude non-owners from the res or thing, but rather from the 'dominion or indefinite right of user or disposition' associated with the thing.") (footnote omitted); Adam Mossoff, *What Is Property? Putting the Pieces Back Together*, 45 Ariz. L. Rev. 371, 396 (2003) (emphasizing "right to use").

[87] Posner, Economic Analysis of Law, 69-71.

[88] Posner, Economic Analysis of Law, 69-71.

[89] Posner, Economic Analysis of Law, 69-71.

Liability rules in tort that avoid injunctive relief and award damage payments require instead quantitative determinations of harm or infringement. When ideas are built upon others to create value, some scholars argue damages promote the discovery of productive uses for information at less significant loss of innovation than injunctive remedies. Such tailored determinations "whether… interference exists" arguably cost less to innovation, than "absolute" "front-end assurance" in favor of the status quo.[90] Broad front-end entitlements for wireless traffic operators are supported by other scholars, where protections promote deployment and discovery of productive uses.[91] In either regime, parties engage in rent-seeking to game the system, with the least worst scenario of more waste or likelihood a matter of debate.[92]

D. Substitute-Substitute Integration

Ideally, technology could eliminate substitute-substitute borders. Avoiding a border requires political reclassification, merger, business deals, or sharing agreements, each of which still require a calculus of resource allocation between rivals. Integration of old and new receivers could occur in horizontal or vertical alignment. Old and new receivers may be substitutes when operated by rivals in a horizontal manner, but complements when owned in a vertically integrated network.[93] Horizontally, operators

[90] Weiser & Hatfield, *Spectrum Policy Debate Part III*, at 1027.

[91] Hazlett, *Spectrum Policy Debate Part II*.

[92] *See* Lemley & Weiser, 85 Texas L. Rev. at 787, discussing "Epstein's Law" where "[t]he risk of undercompensation in such [liability situations] is pervasive," undermining investment, while even under liability rules, parties will continue to engage in government rent-seeking in court and before administrative agencies for "cheap option[s]" of compensation, *citing* Epstein, 106 Yale L.J. at 2093.

[93] *See* Bruce Owen, *Antitrust and Vertical Integration in "New Economy" Industries with Application to Broadband Access*, Stanford Law and Economics Olin Working Paper No. 400, November 10, 2010.

can contract through roaming agreements and equity shares.[94] Vertically, efficiencies can be combined in bundles of services and products.[95]

Integration can also occur in more transformative forms, one example in an overlay plan to grandfather frequency rights into new super licenses.[96] Such greenfields would lower transaction costs by decreasing the number of radio operators.[97] The residual claimant of the frequency band would consolidate a larger set of financial risks and business judgments on integration of existing and emerging radio combinations. As the final owner of the resource after income, costs, and creditor claims, the licensee would waste or produce according to its fiduciary duties to shareholders and business partners.[98] Reclassification of license terms raise antitrust concerns and media ownership considerations as well. To the extent that greater spectrum efficiency is needed in the information economy, integration gains ought to be considered.

IV. Shared Spectrum

An alternative to private integration is public integration, or shared spectrum. Shared spectrum depends on the governance of complementary radio protocols. If too

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[94] *See* Thomas W. Hazlett & Evan Leo, *The Case for Liberal Spectrum Licenses: A Technical and Economic Perspective*, George Mason Law & Economics Research Paper No. 10-19, March 13, 2010, Berkeley Tech. L.J. (forthcoming 2011).

[95] *See, e.g.*, AT&T Wi-Fi, http://www.att.com/gen/general?pid=5949 (roaming partner locations for HotSpot access); Verizon Wireless, http://www.verizonwireless.com/b2c/mobilebroadband/?page=plans (dedicated USB modems, dedicated mobile hotspots).

[96] Spectrum Policy Task Force, at 51 (describing transitional mechanisms to move legacy uses to flexible new uses, such as overlay licenses with grandfathering of incumbents, voluntary band-clearing or restructuring incentives for incumbents, or expanded rights to incumbent licensees).

[97] *Id.*

[98] Alfred E. Kahn, *The Economics of Regulation: Principles and Institutions, Volume I: Economic Principles* at 88, n.2 (MIT Press 1988) ("And for a strong demonstration of the inefficiencies caused by our failure to impose charges for the use of the radio spectrum reflecting these opportunity costs – measured by the value of any particular allotted channel to the next-excluded potential user, *see* Harvey J. Levin, *The Radio Spectrum Resource*, J.L. & Econ. (October 1968), XI: 433-501.").

many radios saturate the airwaves, they may become substitutes over time.[99] Unlicensed spectrum operators may become more, and not less, concerned with boundaries that organize old devices from new.[100] As described above, the regulator of a governance regime will define which radio designs are complements or substitutes in multi-year administrative proceedings.[101]

Spectrum efficiency is counter-intuitive in this light. Sharing more as a policy, should mean innovators seek to share less of a resource entitlement for the same outcome. Efficient use of the spectrum means greater information capacity channels, and more data on less energy with less noise.[102] Competitors vie to design and deploy better devices on the receiver and transmitter ends. Researchers transform battery life, power consumption, computing capacity, sensing capacity, modulation formats, and antenna sophistication.

While sharing implies complementarity, it ignores trade-offs required in economic decisions of rivalry.[103] The term of art avoids dynamic adjustment of what constitutes a complement or substitute, and assumes that primary and secondary users are

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[99] *See Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update*, 2010–2015, February 1, 2011 ("There will be nearly one mobile device per capita by 2015. There will be over 7.1 billion mobile-connected devices, including machine-to-machine (M2M) modules, in 2015-approximately equal to the world's population in 2015 (7.2 billion)").

[100] *See* David Meyer, ZDNet UK, *Wi-Fi Slowed by Interference, Not Congestion*, May 11, 2009, http://www.zdnet.co.uk/news/networking/2009/05/11/wi-fi-slowed-by-interference-not-congestion-39650942/ (describing findings of an Of-com commissioned study that studied the 2.4 GHz band in Europe with signs of congestion in "busy inner city locations" where non-Wi-Fi radio types outside the standardization process also created interference.).

[101] *Id.*

[102] C.E. Shannon, *A Mathematical Theory of Communication*, 27 Bell Sys. Technical J. (1948); C.E. Shannon, *Channels with Side Information at the Transmitter*, IBM Res. & Dev. (1958).

[103] *See* National Broadband Plan, *supra* (calling for revision of Parts 74, 78, and 101 for "increased spectrum sharing among *compatible* point-to-point microwave services.") (emphasis added).

appropriately identified and aligned.[104] When a particular technology or business model is not obviously a winning bet,[105] the determination of resource use and how frequently to revisit the determination suffers from regulatory error.[106]

Wi-Fi in this framework, is a protocol of complements. Part 15 rules for device operators to "not interfere" with one another is an example where the rules limit the design of complements that are allowed to share.[107] Device design is a standards-driven process by the IEEE with certification at the FCC. Wi-Fi access links are enormously scalable when costs are distributed to decentralized, local wired broadband access points

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[104] *See, e.g.*, Reforming Airwaves by Developing Incentives and Opportunistic Sharing Act, S.455, Section 2, March 2, 2011 (Kerry-Snowe legislation: "the term 'spectrum sharing' means the temporary use by a secondary user of unused spectrum in a band at a geographical location licensed to a primary user during idle periods of the primary license use"); Rathapon Saruthirathanaworakun & Jon M. Peha, Dynamic Primary-Secondary Spectrum Sharing with Cellular Systems, IEEE Crowncom 2010 (describing cooperative and coexisting sharing scenarios).

[105] *But see*, Francis J. Kerins, Janet K. Smith & Richard L. Smith, *Opportunity Cost of Capital for Venture Capital Investors and Entrepreneurs*, Claremont Graduate University Working Paper, February 2003 ("the entrepreneur's opportunity cost generally is two to four times as high as that of a well-diversified investor."). The winning bets of venture capitalism are high risk and high reward, with much wasted investment for each rock star win. Whether a public administrative process supports high rates of private failure required in high-technology discovery is an important question for innovation policy.

[106] *Compare* Alfred Kahn, *The Economics of Regulation* (Massachusetts Institute of Technology, 1988), Volume I, p. 6 n.22, citing *Munn v. Illinois*, 94 U.S. 113, 140-41 (1877) (Field, dissenting):

> The public has no greater interest in the use of buildings for the storage of grain than it has in the use of buildings for the residences of families… The public is interested in the manufacture of cotton, woolen, and silken fabrics, in the construction of machinery, in the printing and publication of books and periodicals, and in the making of utensils of every variety… indeed, there is hardly an enterprise or business… in which the public has not an interest in the sense in which the term is used by the court in its opinion.

But see, *id.* (When, therefore, one devotes his property to a use in which the public has an interest, he, in effect, grants to the public an interest in that use, and must submit to be controlled by the public for the common good…") (C.J. Waite, majority).

[107] Thomas Hazlett, *Tragedy TV: Rights Fragmentation and the Junk Band Problem*, 53 Ariz. L. Rev. 83 (2011) (discussing the governance rules that reduce rivalry on unlicensed airwaves), citing Henry E. Smith, *Exclusion versus Governance: Two Strategies for Delineating Property Rights*, 31 J. Legal Stud. 453 (2002).

where much human activity occurs in fixed and predictable locations.[108] Given the mass market for Wi-Fi configuration, radio standards are coming to market with consistent succession.[109]

Wi-Fi signals have complementary boundaries, and enforcement is decentralized to private property owners of fixed nodes, with no guarantees of interference quality. Private owners, however, have fiduciary relationships with customers, where for example, the owner of an NFL stadium provides attendees with a limited license to attend a game and use its facilities.[110] In similar fashion, the owner of the retail coffee chain provides access, setting terms and conditions before the user accepts access to a network.[111]

Conclusion

The complement-substitute determination changes as consumer demand and technology supply changes. Defining complements and substitutes is an important element of the property bundle for technology platforms. A spectrum license that some may call "too much property" that does not grant the ability to determine an exclusive

[108] Such as public places, football stadiums, the home, the workplace, and expanding to airplanes, airports, restaurants, metro transit. Efforts at municipal Wi-Fi buildout have failed due to shortages in public revenues and budget crises of federal, state, and local governments.

[109] 802.22, 802.11a/b/g/n

[110] Kim Bhasin, *Cowboys Stadium's Gigantic Tech Center to Give Everyone at the Super Bowl Free Wi-Fi*, Business Insider, Feb. 3, 2011, http://www.businessinsider.com/cowboys-stadium-technology-super-bowl-2011-2 (reporting the cost at $200,000 per month in fiber optic access fees for a wired network of IPTVs and 884 Wi-Fi access points); Erik Malinowski, *Cowboys Stadium Techs Up for Super Bowl Close-Up*, Wired Magazine, Feb. 1, 2011, http://www.wired.com/playbook/2011/02/super-bowl-nerve-center/ (reporting every major carrier has installed extra cellular signal power for over 100,000 fans).

[111] *See generally* Starbucks, Wi-Fi (United States), http://www.starbucks.com/coffeehouse/wireless-internet ("provided by AT&T Wi-Fi").

right of use determination, may indeed be “too little property” for platforms with evolving boundaries.[112]

Radios will enter the market quickly in the next decade. The exit and reallocation of old receivers in a market-driven manner depends on default rules that promote upgrade over holdout. Asymmetric interference and design costs vary across diverse radio uses. Whether a new receiver is a complement or substitute in its economic relationship to an old receiver defines the interference margins that can be narrowed and whether reconfiguration costs can be internalized through integration. If unaligned, information costs and transaction costs are institutionally established where property and liability remedies each have shortcomings.

This article presented organizing principles with emphasis on the costs of upgrading old receivers, and whether exclusion or governance operated in more efficient manners. The exclusive right to use determination to determine which radio uses are complements and substitutes is consistent with information platforms, while governance of shared spectrum as commons of complements is a cheap solution until the possibility of congestion. To reallocate spectrum, the policies by which old receivers are integrated and reconfigured will impact possibilities for spectrum efficiency.

[112] Richard A. Epstein, *Heller's Gridlock Economy In Perspective: Why There is Too Little, Not Too Much Private Property*, 53 Ariz. L. Rev. 51 (2011).