On the Coexistence of Disparate Spectrum Users

A Property Rights Mismatch Approach[1]

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Abstract: We consider an approach based on property rights mismatch to analyze conflict over radio spectrum. A mismatch occurs when the bundle of property rights created to enable social coordination fails to achieve this objective, leading to missed opportunities for productive exchange. With radio spectrum, these conflicts often result from technological changes that increase prospects (and satisfy demand for) sharing spectrum. Our focus is on how property regimes contribute to conflict as a result of mismatch, as well as how they might be resolved, for two examples of spectrum: passive and active spectrum uses and mobile services on the unlicensed band.

1. INTRODUCTION

A significant literature has arisen around the evolution of property rights to radio spectrum.[1], [2] To date spectrum policy research considers license design,[3] rights assignment methods (competitive auctions versus government allocation),[4] and various work on sharing,[5] self-governance,[6]–[8] and spectrum anarchy.[9] In addition, studies consider how risk to license holders [10] and politics [11] influence property rights over spectrum.

In this paper, we consider the *property mismatch* approach as a general framework for analyzing conflict over the radio spectrum.[12] To date, much of the analysis of electromagnetic spectrum is based on a resources commons approach in which the focus is on establishing property rights to a congestible, scare resource [13]. The property mismatch approach extends beyond the conventional resource commons approach to consider how an underlying resource (in this case spectrum) may operate *at different scales* than the prevailing property regime (such as liberal licenses that create private property rights to spectrum). The property mismatch approach thus addresses several criticisms of property rights regimes. Some research suggests that the spectrum is not a commons, calling into question the resource commons approach.[14], [15] A property mismatch approach clarifies that contentious spectrum bands are not non-rivalrous, as assumed in standard resource commons, and that costly conflicts between parties sharing non-exclusive access rights are inefficiently frequent. Though the canonical property rights approach

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considers these issues,[16] the mismatch approach adds categories such as temporal and spatial mismatch for analyzing conflicts over spectrum, thus adding additional insight to the canonical private property approach.[2] In addition, we show that alternative mechanism designs that have been shown to mitigate previously intractable disputes are based implicitly on a property mismatch approach and that a more explicit consideration of mismatch is useful to clarify how such mechanisms may be applied to other contexts.

This paper begins with a brief review of property rights in spectrum and proceeds to describe the concept of property rights mismatch. We then apply the idea of property rights mismatch to two use cases: the coexistence of active and passive spectrum use and the coexistence of WiFi and License Assisted Access (LAA) in the unlicensed bands. In these use cases, we adopt Ostrom's [21]–[23] general notion of "rules in use" as the institution of choice rather than focusing on "rules in form" since how spectrum is governed in practice, and how disputes are resolved, typically requires consideration beyond formal rules.[7]

2. TRADITIONAL LICENSES, LIBERAL LICENSES, AND UNLICENSED SPECTRUM

Like commodities such as land, where complementary resources such as farm implements determine value, radio spectrum had no economic value before the invention of radios. Rather, it is accessed as a complement to *manufactured* resources, and today fluctuates in value depending on the manufactured devices and networks, and applications produced that use it. Even norms and considerations for spectrum management are sensitive to the cost effectiveness of underlying technological capabilities. The value of spectrum, like land, creates the demand for property rights to capture those values.[24], [25]

Spectrum has features of a commons. Ostrom [23] defined commons as nonexcludable (inability to exclude users) and rival (resources can be used up). Physical signals have features of a commons in that the signals compete with one another for "space", resulting in interference (if the power levels at the receivers exceed thresholds and the transmission schemes/receivers are unable to mitigate the harm). In the case of electromagnetic spectrum, absence of property rights is thought to result in interference, reducing the value of any given slice of spectrum (although there are examples of simple regulations on transmit power and specific transmission schemes like spread spectrum that have worked well in unlicensed bands to allow coexistence).

Though commons may be subject to dissipation,[26] a rich literature considers how property rights can address commons problems of any type and, in principle, at any scale (community, local, council, and global), including to spectrum. Following early work by Coase,[27] whose work built on earlier insights from Leo Herzel,[28] competitive markets to allocate spectrum have been applied to spectrum both analytically and in practice.[3] But the most significant implications of the property rights school are that there are a diversity of property regimes and that they should evolve in response to local conditions, that is, in response to local demands.[30] Thus, land property rights generally include combinations of government ownership, communal ownership, and private ownership. Though exclusive property rights

[2] One response to such an approach is that all mismatches reflect the presence of transaction costs, which Allen [17], [18] defines as costs of establishing property rights. Thus, the presence of transaction costs explains why some mismatches go unresolved: according to this line of reasoning, mismatches would be resolved, if not for transaction costs.[19], [20]. One limitation with the transaction costs view is that is does not consider specific institutional challenges (such as spatial versus temporal mismatch), and so we see the mismatch approach as consistent with, but extending beyond, the canonical transaction costs treatments of evolution of property rights.

[3] Hazlett [29] considers Coase's role in spectrum policy.

are often most appropriate when considering land,[31], [32] there is no reason to presume privatization always works. In the case of spectrum, private property (some version of licensing) is common, but there is a rich diversity of arrangements within licensing regimes, which vary in the extent to which ownership is exclusive, as in the case with spectrum commons [15], [33] and spectrum sharing [9].

Here, we consider three basic variants of property rights: traditional licenses, liberal licenses, and unlicensed spectrum. A fourth type, government ownership, is also possible, though not as common as the others and hence not as relevant in considering mismatches.[4] In what follows, we make use of the distinction between property regime (traditional, liberal, unlicensed) versus the business model (e.g., private property versus sharing). Each of the different regulatory/legal categories can host a range of market structures of business models, and each typically exhibits a mix of "private rights" and "sharing". Confusion arises when the discussion aims to enable more bandwidth to support a certain application of technology, and the discussion is that one regime (e.g., private property or sharing), must be selected on that basis. But the choice is still among different regimes, which might the same (or different) networks. Thus, welfare analysis, including consideration of transaction costs, examines these options as empirical outcomes, rather than pre-determined by the initial regulatory design.

2.1 Traditional licenses

Traditional licenses retain most property rights for the government. This was the approach in the United States before liberalization. In 1927, Congress abruptly nationalized the airwaves with the Radio Act.[4] Once property rights are nationalized, it is necessary to choose an allocation rule. Three possibilities are beauty contests (political allocation), market allocation, and lotteries. Congress chose beauty contests, with government bureaucrats deciding on spectrum use based on its notion of public interest. The problem is that government does not (and cannot) have knowledge of individual values of goods and services absent a market.[34] Thus, planning the spectrum cannot result in efficient property rights. Coase [35] recognized that spectrum technology allowed many signals to be transmitted at once, and so assignment by the FCC created unnecessary conflict. As a result, what was sold was the right to use equipment to transmit in a certain way, rather than property right to the spectrum. However, it was not until the 1990s that Coase's ideas were implemented.[36]

There are several issues with exclusive rights. First, lobbying is an issue with any property regime, including government allocation of licenses. As soon as Congress nationalized property rights and chose beauty contests, broadcasters formed the National Association of Broadcasters (NAB).[4] Then and now, NAB is a powerful interest group. There are few reasons to expect optimal policies in the presence of lobbying.[37] Second, regulators have to optimally set bands. Any allocation system has to define how large a slice users need to reduce contention and meet application needs. Spectrum is underutilized if the government errs on the side of too much spectrum, and investment or consumer inefficiencies may result even with exclusive rights if the government errs on the side of too little spectrum. Third, since property rights involve monopoly privileges, any exclusive rights arrangement creates socially costly bargaining power for incumbents.[38] Fourth, geographic fragmentation may prevent a more efficient allocation[5]. Werbach [14] argues that TV white spaces are not amendable to allocation through auctions because they

[4] Government ownership refers to situations when public agencies get "assignments" that are regulated in ways different from the other three regimes.

[5] With technology advances, if capital costs reduce, one may argue that geographical fragmentation is a natural and beneficial outcome where hyper-local use of spectrum "reuse" maybe possible where it was previously impossible with strict property rights over large geographical areas.

are geographically fragmented and subject to overlapping rights of incumbent broadcasters, wireless microphone users, and others.

2.2 Liberal licenses

Liberal licenses cedes property rights to the licensees. There is large divide between liberal licenses and traditional licenses. Under the current liberal licenses regime, the government does not specify property ownership so much as it specifies what kinds of device can be used, how powerful their transmissions can be[6], and so on in a frequency band, while also restricting who can use the bands. Competitive auctions are an improvement over bureaucratic allocation as far as efficiency is concerned, though efficient markets in spectrum require liquid secondary markets. Secondary markets and unrestricted alienability would allow the market to find the best allocation, provided transaction costs are sufficiently low, as the Coase theorem states [39]. Besides creating more robust secondary markets[7], there are ways to improve the efficiency of allocation, including depreciating licenses, which require license holders to pay a percentage of the value of the license (as estimated by the license holders) to the FCC and requiring sales to anyone willing to pay the estimated value.[3]

Even liberal licenses still involve a role for government and hence for government failures of various sorts.[41] Hence, there are ongoing questions about what role the Federal Communications Commission (FCC) should have in spectrum. The cases for abolition include the following.[1]

- Huber [42] suggests abolishing the FCC with a regime of complete and alienable property rights to spectrum, with trade in property governed by common law. Under such an arrangement, the FCC would sell off all unallocated rights and probably give incumbents property rights, with judges resolving disputes. Presumably, government agencies could regulate interconnections and engage in antitrust activities, though common law could also be applied to those areas as well.
- Bell [43] suggests the institution of trademarks instead, which would give use rights rather than property rights. Under a trademark regime, rights could be established by usage (akin to homesteading airwaves) or registering with authorities (staking a claim to spectrum).

Under an exclusive rights regime, property rights remain shared to a considerable degree. This too is the case with property rights in land, where private property rights routinely have easements and other encumbrances.[8] But there are also formal sharing arrangements within the spectrum governance system, as sharing is an application of the rights regime.

Under spectrum sharing, primary users enjoy priority rights, with entrants or secondary users granted use rights subject to the primary users' requirements or usage. Like open spectrum, the case for spectrum sharing is based on technology. Cognitive radios and cognitive networks, and accessible databases facilitate the sharing and trading of spectrum access that give regulators access to

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[6] Parameters of the devices (e.g., allowed transmit power) are typically maintained for long periods of time although the pace of technology improvements may make it permissible to change them (e.g., fast power control schemes).

[7] The viability of spectrum trading markets cannot be assumed due to the structure of the industry and the technical aspects of radio waves, as shown in [40].

[8] Examples include private property rights for homesteaders, which included many more encumbrances than land sold for cash sales in the 19th century,[44], [45], property on American Indian reservations,[46] oil and gas split estates,[47] and so on.

information. Ideally, the sharing results in spectrum markets among service providers, including the ability to charge differential prices for periods of peak demand.

The rationale for spectrum sharing is the high growth in the demand for wireless broadband services that is only going to increase with deployment of fifth-generation (5G) mobile-communications technology. This is exacerbated by underutilization of spectrum with exclusive access. The central reforms include sharing frequency, time, geographic dimensions, or any combination thereof. Sharing arrangements such as Licensed Shared Access (LSA) and Spectrum Access System (SAS) facilitate the more intensive use of spectrum necessary to accommodate the exponential growth of mobile-broadband service. Increasingly, there is a belief that massive machine-type communications may also share this spectrum. LSA opens up underutilized spectrum to sharing, on a licensed basis, between incumbents and mobile operators, subject to agreement on frequency, location, and time-sharing conditions. With LSA, mobile operators access spectrum below 6 GHz. Regulatory certainty gives operators incentives to invest in the infrastructure for 5G services. SAS enables more users to coexist on the spectrum band through spectrum-sharing techniques.[48].

Weiss and Lehr [2] distinguish primary and secondary sharing arrangements. With primary sharing arrangements, all users have equivalent (or equal) rights to access the spectrum, such as unlicensed bands. Under secondary sharing arrangements (such as TV white spaces, CBRS, and LSAs), users have a hierarchy of rights in which primary users (incumbent license holders) have superior rights to secondary users (spectrum entrants). Weiss and Lehr further distinguish cooperative arrangements (voluntary exchange in secondary markets) from noncooperative arrangements (where use is not coordinated ex ante). Primary cooperative sharing occurs when users coordinate their uses ex ante, such as real-time spectrum markets, which are currently hypothetical. There are caveats, as “real time” dynamics tend to ignore transaction costs[9]. The development of pricing schedules shows how contractual forms are influenced by efficiency considerations, such as broadband data consumption (both in fixed and mobile networks) is generally priced at $10.00/GB up until some level, then either a new “tier” is purchased or throughput slows. That’s “real time,” and reflects the costs and benefits of the institutions. Thus, continuous auctions are not feasible unless there are no transaction costs, which is why we only see them in commodity markets where continuous auctions are relatively cheap given standard supply and demand characteristics.

Weiss and Lehr also distinguish between open-access commons, whereby any user meeting technical requirements may but may not be guaranteed protection from interference, and private commons, where spectrum users find ways to manage their collective rights. The success of Wi-Fi and ISM bands involve substantial self-governance and cooperation [6], [7], though rules are set by regulators without skin in the game. Ostrom is quite clear on the fact that the “commons” is run by regimes controlled by users, not governments. The primary cooperation in unlicensed, of course, is via power limits set by FCC (and devices regulated by “type acceptance”). Examples of secondary cooperative arrangements include mobile virtual network operators, users of LSA or CBRS, and TV white spaces, which are essential tiered markets where users inquire from primary holders about opportunities via databases. Cognitive radios, not widely used at this time, determine where sharing is possible by sensing their environment. Essentially, they are radios

[9] For example, different spectrum bands are not completely fungible [49].

that have the ability to noncooperatively (opportunistically) use spectrum that is otherwise (presumably) fallow[10].

2.3 Unlicensed spectrum

Unlicensed spectrum consists of non-exclusive rights governed by power limits, technology rules, and some behavioral restrictions. The unlicensed bands are shared according to device and behavioral rules set by regulators, while CMRS bands are shared under rules (and prices) established by mobile carriers (who receive 'exclusive use' rights but then contract to re-assign to subscribers).

Unlicensed spectrum seeks to abolish centralized rules governing use of spectrum.[33] Rather than a model of a congested commons, the open spectrum model is based on gains from sharing in a networked economy.[50] Property rights to spectrum, from this perspective, is not the only option[11]. Another possibility is to deploy wireless equipment without licenses or property rights. Under the open-spectrum model, intelligent end-user equipment, rather than infrastructure, is the key to the market. Proponents of open spectrum contend that is provides greater capacity, more growth, more innovation, and, ultimately, more consumer welfare.[51] But the RF hardware needed to use a wide band is expensive and the propagation features across a wide spectrum band has substantial variation. Further, the higher the frequency, the more the "bandwidth" – at 10^{10} Hz, you can have a 1 GHz BW between 0.1×10^{10} and 0.2×10^{10} Hz but radio signals are absorbed and do nor propagate well. But at 1000 MHz, the BW is limited even though the signal propagates very well.

Werbach [15] explicitly argues that the commons does not apply to spectrum. The reason is that spectrum can be divided up with new technology, undermining any case for exclusive property rights. Thus, commons metaphors, applied to natural resources, are inappropriate for spectrum, which is always changing in as a result of technological progress. Spectrum, from this perspective, should not be artificially constrained by attempting to establish exclusive rights over it. Werbach's solution – supercommons – does not result in anarchy, but an unlicensed regime in which law continues to have a place, though Werbach does suggest universal communication privilege as a baseline for wireless communications, with liability backstops addressed through legal channels or regulations. Thus, while Werbach contends the commons model is inappropriate, it is more accurately understood as technology requires redefinition of rights. Since there are conflicts over spectrum even in the supercommons model, it is clear that there is excess demand and hence subtractability (or rivalry) when uncoordinated usage occurs. How one most efficiently channels the competition that naturally evolves is the question. Property rights are an attempt to do that – and liability rules are an alternative form of property enforcement (relying on tort law, which is generally avoided, when possible, precisely because the transaction costs are seen to be relatively high).

The unlicensed spectrum model suggests the possibility of allowing anyone to transmit, with conflict over spectrum resolved through law without reliance on government agencies such as the FCC to deal with boundary disputes. It is not an open spectrum, as there are conflicts resolved by law. Such a system promises innovation and value creation, as well as empowerment for users, but could also contribute to increased transaction costs, gaming the system, or malicious behavior because of the absence of

[10] Sensing unused bands is technically challenging. Furthermore, some "bands" may be unused because they are "guard bands" that perform a useful function even if they contain no signal power.

[11] Note that the power limits imposed by regulators limit the spatial reach of a user. As a result (FCC's OTARD rules notwithstanding), there is a conflation between real estate rights and spectrum rights [5].

ownership and lack of accountability. Thus, what would be necessary is an institutional environment in which credible and enforceable contracts could be written in the absent of state enforcement, though such agreements would move into the realm of licensing.

Note all allocations, licensed and unlicensed, attract rent-seeking,[4] and all regimes involve some important elements of sharing, but differ in how the rules are decided. The reason is because each involves government allocation, as even the unlicensed band involves some initial authorization of use rights or involves some incentive for government not to intervene more, even if such intervention might be appropriate.

3. WHAT IS A PROPERTY RIGHTS MISMATCH?

The notion of a "property rights mismatch" has been used in connection with the property rights associated with overlapping resources. [52], [53] Yandle [54] writes:

> "A mismatch can be defined as "a problem of fit involving human institutions that do not map coherently on the biogeophysical scale of the resource either in time or space..."

Property mismatch occurs when the bundle of property rights to achieve certain ends lead to conflict among users or missed opportunities for exchange. In the context of the resource commons, Ostrom and Schlager [55] conceptualized of property rights as a bundle with the following dimensions (1) *access* (right to entry); (2) *withdrawal* (right to extraction); (3) *management* (right to regulate and make improvement); (4) *exclusion* (right to determine access and transfer; and (5) *alienation* (right to sell or lease management and exclusion rights). Yandle [54] extends this to include regime features that influence the quality of rights, including (6) *temporal* (period for which operational-level rights are guaranteed or time until the rights are renegotiated; (7) *spatial* (how well regime defines locations where operational-level rights may be exercised); and (8) *quantitative* (how much of a resource may be extracted in a given period).

The overlap between rights regimes can create both theoretical and practical challenges. For example, using surface property rights to define rights above and below the surface makes for inefficient use of air space (above the surface) and mineral resources (below the surface)[12]. Efficient use of each of these resources may require different usage rights boundaries for each resource, as illustrated by Bradshaw & Leonard [53] with resource boundaries with land parcels in McKenzie County, ND. Each of the resources illustrated may be subject to differing regulations, ownership, use rights, etc., and each of the resources may have a different boundary. The rights are said to *mismatch* because the boundaries, regulations, use rights, etc. for each of the resources may be different.

Crowder et al [58] consider US ocean governance as an example of property mismatch. US ocean management is organized by sector, with 20 agencies subject to 140 laws. Specific problems include spatial mismatches between scales of governance and ecosystems (state, federal, and international makes little sense for highly migratory species), typically arising from jurisdictional boundaries that are too small. One proposed solution is spatial planning with participation of – federal, state, international, and tribal authorities. Another issue is temporal mismatch, which occurs when biological and human systems occur on time scales too fast or too slow for the policy rhythms of annual appropriations and 2 and 4 year voting cycles. Crowder et al suggest zoning that considers biophysical characteristics of each zone, with design

[12] Rights to use airspace were largely worked out by Congress and the courts in the 1920s and 1930s as the use of aircraft increased.[56] The recent popularity of drones has caused these rights to be revisited .[57]

of systems (permits, licenses, and use rules) in response to challenges arising within each zone, as well as establishing compliance mechanisms and programs to monitor, review, and adapt the zoning system. It is hoped that such comprehensive zoning would address fragmentation and spatial mismatches, as well as adjust governance to "the rhythms of human institutions and the dynamics of spatially bounded ecosystems."

In the spectrum world, there are similar issues: spatial mismatches occur because radio propagation is not confined in space (nor deterministic). It is also time variant and depends on the environment (obstacles, buildings, terrain etc.). Temporal mismatches are also possible. For example, there is more demand in city centers during the day while demand increases in the suburbs in the evenings. The overall mismatch is explained in more detail next.

A conventional property rights analysis of spectrum involves comparisons of alternative regimes across the dimensions of rights of reception (who can access spectrum)[13], transmission (who can transmit on spectrum), management (who can make improvements to radio systems and establish terms of use), exclusion (who can exclude non-authorized users from spectrum), and alienation (rights to buy and sell spectrum). Weiss et.al [13] adapt Schlager and Ostrom's [55] property rights bundle to spectrum rights as shown in Table 1. In this table, the relevant rights are rows and prototypical user types are the columns. Clearly, the particular rights in question depend on the usage model. Broadcasters are license holders and have the sole right to transmit and their users have only receiver rights. Exclusion and management rights are not meaningful in this application since the business model is built around open access receive rights. Mobile systems operators hold licenses but its users can transmit and receive (with authorization provided by the mobile system operator). There are some examples of cooperative secondary use (such as Mobile Virtual Network Operators, or MVNOs), who do not hold a license but otherwise operate as a facilities based mobile provider. Operators of private WiFi networks (e.g., universities, coffee shops) can determine who may use their spectrum, but they have no ability to exclude others from using the spectrum. For example, a coffee shop may offer WiFi to its customers, but they cannot prevent a customer from using a portable WiFi hot spot on their phone that uses the same unlicensed frequency bands.

	License holder/exclusive rights (incumbent)	*Secondary Use (Cooperative),*	*Open Access Network Private WiFi*	*User (authorized or opportunistic)*	*Receiver (e.g. broadcast)*
Reception	x	x	x	x	x
Transmission	x	x	x	x	
Management	x	x	x		
Exclusion	x	x			
Alienation	x				

Table 1 - Rights bundle for spectrum. Adapted from Weiss et al [13]

Under exclusive rights, access, regulation, exclusion, and alienation are defined. With liquid secondary markets, the above might result in an efficient allocation. But as discussed in Section 2 and elsewhere (see, for example, de Vries [59]), traditional, spatially oriented definitions of property rights do not fit

[13] The right to receive may be subject to regulation. For example, the UK requires users to purchase a license to use a television set they purchase (https://www.legislation.gov.uk/uksi/2004/692/schedule/1/made). Further, content may be encrypted, so "right to receive" may be interpreted to include the decryption keys.

cleanly onto radio spectrum. In application to spectrum, we consider temporal, spatial, quantitative and quality mismatch:

1. How long are access rights to spectrum guaranteed or what is the time until renegotiation? (temporal)
2. How well does the governance regime define locations where operational-level rights can be exercised? (spatial)
3. How much of the spectrum may be used in any given time interval? (quantity)
4. What signal-to-noise (and interference) ratio is needed for successful use? (quality)

Temporal mismatch, such as when the demand for use of spectrum changes more rapidly than opportunities to formally reallocate property rights, is an issue. Real-time spectrum markets would be a solution but are not (yet) feasible for a variety of reasons [49], [60]. Cognitive radios, etc., can potentially be used as an alternative, as they do not require ex ante agreements can find opportunities in real time, though significant cost and technical challenges remain with this technology.

Spatial mismatch occurs when jurisdictions for spectrum do not match the use of spectrum. Geographical fragmentation may be an issue here, as in the case of TV white spaces. Also, radio propagation anomalies can result in signal energy that occurs outside the boundaries of the property rights (in time, space or frequency).

Quantity issues involve what can be allocated, and when. Sharing arrangements deal most precisely with this issue.

Quality issues are centered around the signal-to-noise ratio required for different uses. As reported in the National Research Council [61], passive spectrum uses often require the ability to measure very low signal energy (low signal to noise ratio) compared with active uses. Thus, there may be a mismatch in system requirements.

Relating this to some of the earlier discussion, the mismatch approach is not a perfect fit; "quantity extracted" as in the resource commons is not an exact, following Werbach's observations. That said, mobile operators "extract" transmission capacity based on the bandwidth available and the prevailing signal to noise ratio[14], so adding signal power usually reduces the available capacity for other users in the same spectrum. The efficiency with which capacity may be "mined" is the *spectral efficiency* of the technology. The other unique resource characteristic of spectrum is that it is infinitely and immediately renewable: available capacity is restored as soon as transmissions stop.

A significant thread of the emerging mismatched property rights literature [12], [62] examine "landscape level resources", considering in particular a model consisting of the juxtaposition of property rights parcels with (1) biological landscapes (such as animal habitats and fisheries), (2) underground landscapes (mineral rights), (3) fixed landscapes (scenic landscapes), and (4) "long and skinny" resources (roads, telecom infrastructure). Bradshaw and Leonard [53] observe:

> "…the creation of ostensibly private land creates the need for public or communal governance of other resources. Privatizing land to avoid the tragedy of the commons necessarily requires demarcating land to create a fixed parcel. Yet, the land parcel will inevitably be sized differently than the natural scale of management for landscape-level resources. Because a given tract of

[14] This is based on the well-known Shannon-Hartley theorem.

land necessarily contains numerous resources operating at unique scales, mismatch between land parcels and at least one resource is an inevitable feature of property rights to land. To efficiently manage the bundle of resources associated with a given parcel, each resource may need to be managed at a scale that differs from the underlying land ownership.

"Parceling land unwittingly creates inefficient scales for the management for large-scale resources such as air quality, mineral resources, and habitat if use and exclusion rights for these resources do not subdivide neatly.

They proceed to propose the concept of "virtual parcels" to consider address the differing scales and dimensions of these different resource types [53]. In this concept "parcels" of efficient scale for the resource are identified and created through a variety of techniques (e.g., market transactions, contract, communal governance, government coordination, resource seizure through eminent domain or nationalization, etc.).[15] One could, in theory, where there is fine grained information available, create such virtual spectrum parcels, where one (group of) user(s) would be having a smaller "geographical" parcel at lower power for a certain fraction of time while a higher power virtual parcel may be made available in a different time window.

4. SOME APPLICATIONS OF RIGHTS MISMATCH THEORY TO RADIO SPECTRUM

To illustrate how these ideas apply to spectrum management, we consider two cases of spectrum management. In the first case, we examine two disparate approaches to spectrum use: active and passive. In the second case, we examine a specific situation in a specific band: the use of the 5GHz unlicensed band for LTE.

4.1 Passive vs Active Spectrum Use

Much of the literature examining spectrum use has focused on *active* uses of spectrum. Active uses of spectrum involve the use of a transmitter and receiver and are often focused on systems supporting communications of some sort. Examples of these uses include mobile systems, broadcast systems, data communications systems, etc.

A brief overview of passive spectrum uses

Another important class of uses of radio spectrum involve the *passive* use of spectrum. Passive systems are those that detect radio signals of natural origin rather than human origin [61]. These passive uses are of interest to radio astronomers and earth exploration scientists, but they also play an important role socially valuable functions such as weather and climate forecasting, rainfall and soil moisture assessment, sea surface salinity, etc. The latter systems are of increasing economic importance as inputs to many forms of human activity, including the complex supply and production systems needed to sustain human life and well-being.

Because of the natural sources, systems built for passive use of spectrum have no frequency mobility: they must operate where the phenomena they are studying emit signals. Furthermore, it is often the case that these signals must be detected at very low power levels, requiring receivers of extraordinary sensitivity. These passive receivers may be terrestrial or they may be on satellites orbiting the earth with

[15] For example, shale gas fields in the US can transcend several states, and property rights are often divided with the mineral and surface estate.[63] Thus, landmen have to assemble leases, which may be complicated by a shale play underlying several jurisdictions (municipality, county, states, and sometimes, countries).[64]

antennas that point toward the earth. Because of the very low power levels of the signals, the (radio) noise[16] levels must also be extremely low.

Passive uses of the spectrum may be undervalued and thus weakly situated politically (in the spectrum management institutions) because they are intermediate products to a variety of services and because passive users are diverse, distributed and poorly organized. As an intermediate product, passive spectrum uses behave as an infrastructure, thus prone to under-investment [65]. Passive uses include radio astronomy and atmospheric sciences.[61] The spectrum related interests of the atmospheric sciences are principally represented by the Committee on Radio Frequencies (CORF)[17], a diverse group whose members have principal responsibilities in their home institutions. Radio astronomy uses are represented in the US by the National Radio Astronomy Observatory (NRAO) and the National Astronomy and Ionosphere Center (NAIC), who coordinate with radio astronomers at numerous institutions. While CORF, NRAO and NAIC may have strong, committed individuals advocating for their interests, they do not have the financial and political strength of commercial organizations (e.g., AT&T, Verizon, etc.).

Active/passive rights mismatches

As pointed out by the National Research Council [61], the increasing active uses of radio spectrum are creating challenges to the passive users from the increased interference from active uses and from the increased sensitivity of the instruments used for passive users. Using the language of the mismatch literature on resources, governance of property for passive users is more akin to considerations at the level of a landscape, rather than an individual parcel (or exclusive license). Mitigating the interference is possible in some cases through careful frequency allocation and other technological uses; however, because the scale of the problems are different, the mismatched property rights theory provides a useful framework. In particular, active radio systems operate at different scales from passive users.

Temporal – The frequencies needed for passive uses are dictated by the phenomena being studied. Unlike active users, the frequency "allocations" are stable and permanent and do not vary with demand. The particular moments (or intervals) when passive users' observations must take place are dictated by the phenomenon under study and the available technology[18]. The demand for active use is largely determined by the demand for the services provided on a spatio-temporal basis.

Spatial – Active users often have licenses (hence operations) that may be local, regional and sometimes national in scope. Some passive antennas span hundreds of kilometers; as well, a passive users may be sensitive to interference from multiple legal jurisdictions.

Quantity – Passive users do not require more spectrum no matter how much demand there is for their product. In contrast, active users' demand for spectrum is strongly correlated with demand for their service.

Quality – Passive users require receivers that are much more sensitive than those used for active use. This is the case because passive users do not control the strength of the emissions they are observing (as they result from natural phenomena) unlike active users.

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[16] Radio noise in this case includes any unwanted radio frequency (RF) energy in the passband of the receiver. This includes noise from natural and man-made sources.
[17] https://www.ametsoc.org/index.cfm/cwwce/committees/committee-on-radio-frequency-allocations/
[18] Some measurements are taken over long time periods to increase the sensitivity of the measurement.

The first pass in analyzing a mismatch is understanding the different requirements for users, or stakeholders. According to the framework in Table 1, passive users require reception rights but not transmission rights. Because of the sensitivity of their receivers, they would also value exclusion rights. Management rights (defined by Schlager and Ostrom as the right to determine authorized users) would have value to the extent that they could exclude users requiring transmission rights. Alienation rights have no value since the required spectrum bands are determined by the phenomena being observed.

	PASSIVE	**ACTIVE**
TEMPORAL	Frequency bands and time determined by the phenomena under study. Frequency requirements extremely stable.	Frequency bands and time determined by business model or customer demand. These can be dynamic in time, space and frequency band.
SPATIAL	Determined by the required level of interference; normally a "protected zone" around the antenna. Frequency allocation needs may cross license or jurisdictional boundaries.	Determined by license (e.g., on a Metropolitan Statistical Area, or MSA, basis)
QUANTITY	Required frequency bands extremely stable; determined by phenomena under study.	Increasing requirements in time, frequency and space to meet customer demand
QUALITY	Must work with very low Signal to noise ratios. Very low noise and interference tolerance	Quality requirements depend on the technology used and the service provided.

Table 2: Passive/Active mismatch

Using the mismatch dimensions discussed above, Table 2 summarizes the spectrum resource requirements of prototypical passive and active users.

Virtual parceling is proposed to address mismatches in resources. There are a few ways to think about virtual parceling that would better account for the demands of passive users. Time, transmit power windows together with frequency bands are each routinely used to establish property rights for active users, so they function as the equivalent of "parceling" in spectrum, as Coase understood. Since passive users do not control the "transmitter" (i.e., the phenomenon under study) the use of transmit power is not useful. Instead, passive users are very sensitive to the noise and interference present at their receiver, so *aggregate in-band received signal energy* is a more useful way for them to define the property rights they need. The notion of incorporating the receiver into the property rights discussion has been addressed by de Vries [66] .

But it is also important to understand that institutions have arisen to address mismatch, albeit imperfectly. To achieve the low interference and noise environments needed for passive service, a large geographic area (protection zone) is defined to reduce the co-channel interference at the passive receiver. This protection zone may overlap multiple license areas for active users. As well, passive users must seek to reduce other interference as well, such as adjacent channel interference and harmonic interference from more spectrally distant bands.

This mismatch has been resolved in a few different ways:

- For the National Radio Astronomy Observatory (NRAO), this mismatch was resolved through the establishment of the National Radio Quiet Zone (NRQZ) in West Virginia, in which many transmissions (e.g., mobile phone, WiFi) are prohibited[19]. This was achieved through regulatory action at the FCC in 1959. Explicit coordination procedures are described, as are specific quality requirements. Technology is causing this arrangement to break down. Inexpensive radiators, such as automotive radars, are costly (or near impossible) to control, resulting in high levels of noise.
- The MIT/Haystack Observatory is located in the Boston metro area. Being close to a large metropolitan area, sited on top of a hill, means that they are vulnerable to interference from many sources. Initially, interference protection came from an exclusive licensed band as well as operations in very high frequencies that were of no commercial interest. Mobile radiators (such as automotive radars) and technological changes that have made very high frequencies commercially viable have changed this environment. As well, spurious emissions (or harmonics from other licensed bands) from distances as far as 300km can cause interference. Lower frequency observations are virtually unavailable because of unintentionally radiated power from LED light bulbs[20].

Clearly, these parcels are “landscape level resources” in terms of their spatial dimensions. Passive users interact with the national and international spectrum management institutions through the Committee on Radio Frequencies (CORF). CORF submits comments on spectrum management proceedings at the FCC as well as the International Telecommunications Union (ITU)) and otherwise informs stakeholders about the passive uses of radio spectrum. While this is an institution to address rights mismatches because the frequencies needed for passive use are very stable (being determined by the phenomena under study), the time scales are long compared with technological change and changes in demand for spectrum from active users is more dynamic, resulting in a temporal mismatch.

4.2 Mobile services on unlicensed bands (LTE-U/LAA)

Our experience with wireless services suggest that a heterogeneity of rights arrangements have been successful. While exclusive licenses have promoted investment in mobile services, unlicensed bands have provided opportunities for innovation. For example, high speed wireless data became available on unlicensed bands long before they were widely available on mobile networks. Experience with WiFi supported investments in mobile technologies. In what follows, we consider how mismatches have been resolved, as well as some ongoing conflicts within the unlicensed bands.

Some 40 years ago, the FCC began the consideration to permit the unlicensed uses of spectrum in Docket 81-413, which were ultimately adopted in 1985 [67]. The three unlicensed bands that were authorized did not have a specific *allocation*, so they could be used for any purpose. The result has been a veritable explosion of uses, including garage door openers, cordless telephones, cordless headsets, wireless cameras and monitors, and, of course WiFi. When the demand for mobile services based on 3G and 4G technologies boomed with the introduction of the smartphone in 2007, it was natural for service providers

[19] https://greenbankobservatory.org/about/national-radio-quiet-zone/

[20] Private conversation with Philip J. Erickson, Associate Director & Principal Research Scientist, MIT/Haystack Observatory, 29 July 2021.

and the equipment manufacturers that sold to them to seek additional radio bands for these services[21]. Regulatory agencies around the world responded by making new frequencies available, but these proceedings, including the need to clear the bands, are slow compared with the rate of change of demand. So, it is not surprising that the unlicensed bands be considered for mobile services based on LTE.[68], [69]

As the proposal to use unlicensed bands for the mobile LTE service was floated, it is not surprising that existing users of unlicensed services were concerned about their ability to use these bands once LTE operated in them. After all, LTE was a rapidly growing service and the cost of using an unlicensed band was $0 (at least as far as license fees are concerned), so it was reasonable to contemplate a future where all unlicensed bands were occupied by LTE signals so that garage door openers, cordless phones, video monitors, and, of course, the all-important WiFi would no longer function properly. After a significant industry controversy[22], the FCC began authorizing the use of LTE-U devices in 2017[23]. Considered a proprietary technology, LTE-U was not ratified as a 3GPP standard; a related approach, License-Assisted Access (LAA) was adopted instead. Despite a general lack of industry news about deployments of mobile systems in the unlicensed bands, recent research indicates that there has been some deployment in at least one city in the US [70], though carrier deployments are tepid at best[24].

"Property rights" in unlicensed spectrum

It is not obvious that we could entertain a "property rights" discussion for unlicensed bands if they are an open access commons. However, for reasons noted in Section 2, the unlicensed spectrum does not have features of a pure open access commons.[25] To analyze the rules of the unlicensed band, we adopt Elinor Ostrom's perspective that "rules in use" were perhaps more important economic institutions than "rules in form" [22]. It is also worth observing that rights in unlicensed bands are often tied to the ownership of land parcels, largely because of power limitations [10]. Furthermore, following Table 1, we can proceed by eliminating alienation rights, thereby supporting five instead of six categories of users. It is the collective action rights (which include the right to exclude and the right to manage) that are most salient to this topic.

In doing so, we treat the interests for and against LTE-U/LAA as a dispute resulting from mismatched property rights. Why should these be considered mismatched rights? The premise behind LTE-U was that the unlicensed bands could be used as an integrated part of the carrier ecosystem, functionally indistinguishable from licensed bands. The structure of LTE systems puts the nexus of system (and service) control with the carrier, so that uses of these bands under LTE would be controlled by and through the carrier (under the carrier's terms of service, which could include a fee). In contrast, users' normal

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[21] Wireless service capacity can be increased by increasing the spectrum used in a service area and/or by increasing the frequency re-use by increasing the density of cells. The former requires working through the regulatory process to obtain new bands and then acquiring licenses (through auctions), while the latter requires increasing capital investments in the form of base stations and other infrastructure. The ongoing demand and willingness-to-pay for spectrum is indicative of the limits and costs increasing cell density through infrastructure investment vs. additional radio spectrum licenses.

[22] https://arstechnica.com/information-technology/2015/08/verizon-and-t-mobile-join-forces-in-fight-for-wi-fi-airwaves/ Retrieved 13 July 2021.

[23] https://www.fcc.gov/news-events/blog/2017/02/22/oet-authorizes-first-lte-u-devices Retrieved 13 July 2021.

[24] The Global Mobile Suppliers Association last reported LAA and LTE-U deployments in February 2021, with 9 deployed LAA networks and 3 deployed LTE-U networks (https://gsacom.com/paper/nts-update-february-2021-status-snapshot/, retrieved 13 July 2021). Subsequent reports do not mention LAA or LTE-U.

[25] The canonical analysis of an open access resource is Ciriacy-Wantrup and Bishop [71], and it is defined by absence of *any* property rights.

experience with unlicensed bands is built around a decentralized service environment, in which the end user controls what they wish to do and how (for better or worse). Further, LAA is typically deployed in an outdoor environment, whereas WiFi is typically used in indoor applications [70].

Rights mismatches in LTE-U/LAA

Unlicensed bands are established by the FCC using their normal rulemaking process. So, while regulations and bands can change, this occurs in decadal time frames. The debate over LTE over unlicensed (LTE-U/LAA) took place in the context of an equipment authorization action, not a spectrum allocation proceeding; that is, petitioners requested that the FCC authorize LTE-U and LAA equipment for use in the 5GHz band. These authorizations operate on a much shorter timeframe; in this case, the new equipment implied a new use for the band, which set up the conflict. Thus, new technology created a rights mismatch.

In their study of LAA deployment in downtown Chicago, Sathya et.al. [70] noted that not all LAA deployments caused potential conflicts with WiFi deployments. Thus, not all WiFi users are impacted by the LAA deployment. But this points to the spatial mismatch: LAA deployments are designed to support LTE demand whereas WiFi deployments are designed to support the local, usually indoor, demands of residences and/or businesses that deployed the access points. The Chicago data indicates that each deployment is made without regard to the others' deployment, so no mechanism exists to avoid spatial overlap.

The protocols do allow for mechanisms to alleviate temporal overlap although they may be imperfect. Differences in the channelization of LTE and WiFi also mean that temporal coordination using the Listen-Before-Talk mechanisms are more challenging. This is built into the equipment and protocols and is not subject to local negotiation. Table 3 summarizes mismatch aspects of the unlicensed spectrum.

	LOCAL USE (WIFI)	**LTE-U/LAA**
TEMPORAL	Usage requirements generally associated with household activity	Usage requirements dependent on demand and may be mobile
SPATIAL	Highly localized to household or place of business. Mostly indoor deployment. Decentralized access point deployment	Part of a metropolitan service delivery system. Mostly outdoor deployment. Base station deployment centrally planned.
QUANTITY	Any ISM band (900 MHz, 2.4 GHz, 5 GHz and recently 6 GHz). Varying channelization is possible, depending on the access point (in multiples of 20MHz)	LTE Band 47 (5 GHz). 15 MHz channelization. Traffic allocation centrally determined (by eNODE-B). Aggregation with other bands possible.
QUALITY	No guarantees, but expectations of supporting video and audio streaming, gaming, etc.	Support LTE transmission standards for throughput and latency and QoS classes.

Table 3: WiFi/LAA rights mismatch

The unlicensed band provides a property solution where individual parcels are inappropriate given the underlying demands of stakeholders. But it is not without conflict. LTE-U/LAA is, like the passive users, more of a landscape approach; WiFi is more of a parceling approach.

This mismatch was discussed through the FCC's normal process. As well, industry groups, such as the WiFi Alliance and GSMA coordinated their respective stakeholders. It is unclear that the FCC's decision to authorize LTE-U/LAA equipment considered perceived rights but rather was an application of the rules associated with the unlicensed bands that had been previously approved by the FCC.

4.3 Summary

An important technical implication is that the property dimension of importance in both cases is *received power*, frequency band, time and space. So, LAA can be cast as an overlap between outdoor and indoor usage of 5 GHz unlicensed spectrum. Following De Vries [64] on the "harm claim threshold", it is necessary to include the receiver in the interference equation. This was ultimately a key factor in the LightSquared case[26]. It is also a factor that looms large in the broader tension between active and passive uses of the radio spectrum.

5. DISCUSSION AND CONCLUSION

The property mismatch literature has some application to technology, such as telecom resources as a "long and skinny" property right regime. Such rights often do not fit well with exclusive rights as they have evolved. But there is reason to believe mismatch lies at the core of at least some spectrum coexistence challenges. Figure 1 illustrates mismatch as applied to property and the multi-dimensional analysis across time, frequency, and power.

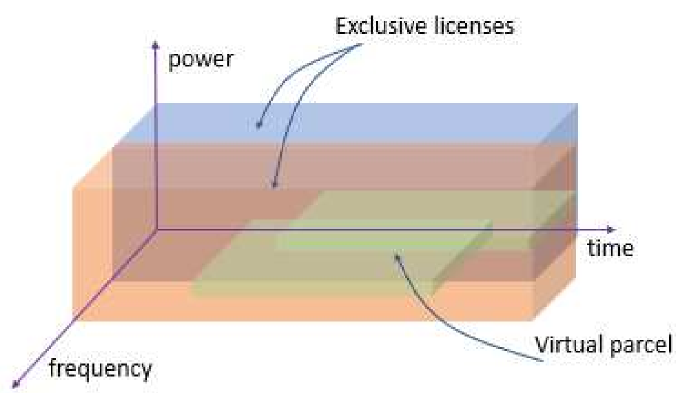

Figure 1: Virtual Parceling in Spectrum

The creation of private property rights to spectrum has some benefits, including addressing issues with congestion. But parceling the spectrum creates inefficient scales for disparate uses of spectrum

[26] GPS receivers were not very selective, so LightSquared (now Ligado) interfered with them even though they were operating in an adjacent frequency band. https://thehill.com/policy/technology/210745-fcc-moves-to-kill-lightsquared (retrieved 2 August 2021).

resources. One reason, unlike with resource commons, is that technology is always redefining what is possible in terms of performance parameters such as capacity and interference tolerance. Rather than exclusive rights, what could be more appropriate might be a property regime that can be continually adjusted.

Experience has shown that the initial spectrum property assignment has a great deal of inertia. As a manufactured resource, substantial capital investments in radios, receivers, antennas, etc, for passive and active users, are needed to utilize this resource. These investments are often highly specific, partly because of physics and partly because of technology. For example, antennas are strongly related to the frequency they are intended to transmit and receive, and technology has limited impact on this. Traditional technology has meant that many components for transmission and reception were hard wired, although this has substantially changed with the advent of digital signal processing and software radios. For passive users, the design of receivers with the necessary sensitivity is a costly and time consuming process; these users can only change slowly to the more rapidly changing noise environment in which they operate.

Let us consider the example of broadcasting. In its traditional form, a broadcast system consists of a central high powered transmission station that is purchased, maintained, and operated by the broadcaster, who must obtain a license to transmit. Broadcasters rely on investments by consumers (in the form of radios and televisions) for their business model. The broadcaster has no control over these distributed investments. This investment scenario results in very conservative approaches to spectrum rights because technological innovations on the part of a broadcaster require that consumers follow with investments of their own. Broadcasters have to assume the worst case technology for receivers (e.g., interference vulnerability), even if technology has moved on, lest they lose audience and thus advertising revenue. The use of TV White Spaces was proposed for data services in 2004[27], and the first devices were authorized in 2008, over the continuing objections of broadcasters. In essence, this was a re-parceling of rights associated with the broadcast band and was accomplished through a separate governance regime. This governance regime consisted of a system of priority that was mediated by an automatic database system. In the framework of Schlager and Ostrom, usage rights were governed by the database but collective action rights were determined by a coalition of broadcasters and technology companies, facilitated by the FCC.

The "virtual parceling" approach [53] to deal with these property rights mismatches has been proposed as a new way to think about resource commons where some resources have to be managed at a very different scale. Many are ongoing and require additional work to resolve. But with spectrum, there is already a framework that implicitly is based on the mismatch approach in many areas. The spectrum allocation table, while not a property rights regime, recognizes several possible uses of the same band, some with larger allocation, some smaller[28]. These allocations are predicates to assignments, which are rights given to specific users, to be used for the allocated purpose.

The various spectrum sharing schemes, such as secondary use, cognitive radio, secondary markets, etc., allow for the dynamic bundling and re-bundling of rights in space and frequency. Software radios

[27] https://www.federalregister.gov/documents/2004/06/18/04-13573/unlicensed-operation-in-the-tv-broadcast-bands

[28] https://www.ntia.doc.gov/legacy/osmhome/Chp04Chart.pdf

contribute to the flexibility of capital investments in radio equipment, which supports the development of virtual parceling regimes.

Though as advances in technology open new possibilities, implementation can be a challenge as a result of lack of immediate tangible economic benefits, and private issues may arise. In the LAA example, we can consider smart phones with already known usage. Mismatches may only result under certain circumstances[29]. If we aggregate this understanding across many devices, it is possible to have a crowd-sourced geospatial awareness of (under)utilization of spectrum. An interesting future challenge is how this data can be used to assess the extent of a mismatch and to suggest institutions for resolving them. Another example, not considered in detail above, involves smart TVs. Most TVs sold today are "smart TVs" that utilize an on-board operating system. This operating system can determine whether the TV is in use or is receiving an internet stream (and not a local broadcast). In aggregate, these TVs could (in principle) be used to supplement a TV Whitespaces database to gain a real time, spatio-temporal understanding of broadcast reception demand. If a database learns that no devices are receiving an over-the-air broadcast signal in a region, then it opens the possibility of using this spectrum for other purposes without interfering with the primary user.

The more general implication is that mismatches are common and the approach of exclusive rights is often an inappropriate framework to analyze these conflicts, as the resource in this case – the spectrum – is often at a different scale than the exclusive rights, there is more demand for scarce resources, etc.

What remains is additional applications. Some extensions include Fractional Frequency Reuse within 4G and 5G systems, which does the same across cells in comparison to the frequency reuse in 2G systems. 3G with cell-breathing may be an example of "nested" parceling of resources[30]. Other examples include air space above countries. Legal rules provide rights to countries, but above many countries, there is no enforcement. The solutions are ad hoc, which probably is Ostromian, but there's a mismatch – the airwaves across countries should be a regulated commons or something similar to it, but that conflicts with the de jure property rights asserted by countries. Another example is space debris. In the US, such analysis is all classified, but in Europe, it is not.[31] Space debris by its nature is a "landscape" issue, though the governance involves a potential mismatch of property rights.

The goal of this paper was to apply the theory of property rights mismatch to problems in radio spectrum management. We have shown rights mismatches in two cases to illustrate the application of this theory. Bradshaw and Leonard [53] offer a number of approaches for the construction of "virtual parcels" that resolve such mismatches.

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[29] If users are moving, WiFi is not a good choice because of the problem of handover to new base stations. If the device is already connected to WiFi, then LAA may not be necessary for that phone.

[30] The idea of nesting is to support internal sub-division of rights, as, for example, an MVNO might use a portion of the property rights of a licensed user.

[31] To date, analysis of celestial property rights has adopted a conventional law and economics approach, in particular consideration of exclusive rights [72], [73]. As exclusive rights are established, the issues of property mismatch are likely to arise – such as Nokia's contract to establish 4G on the moon.

We believe that this approach can help policymakers anticipate forthcoming challenges associated with the increasingly heterogeneous uses of radio spectrum. More importantly, recognizing use conflicts as a property rights mismatch could facilitate the design of institutions to resolve these mismatches.

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