How I learned to stop worrying and love interference

Using well-defined radio rights to boost concurrent operation

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***Abstract*—Private and public resources are being wasted in disputes about radio operation that cannot be resolved bilaterally and have to be escalated to the regulator. This challenge becomes acute in dynamic coexistence scenarios. This paper proposes defining rights with the goal of maximizing concurrent operation, not minimizing harmful interference. It takes an explicitly probabilistic approach to rights definition; defines transmit rights in terms of transmission permissions; states the RF environment an operator can expect in terms of reception protections; and defines these parameters in terms of resulting electromagnetic energy rather than using transmitter rights and/or receiver specifications. The bottom line: the regulator should delegate interference management to the parties who are coexisting with each other.**

Keywords-radio; wireless; property rights; policy; dynamic spectrum access

I. INTRODUCTION

A. The Challenge

More and more private and public resources are being wasted in disputes about radio operation that cannot be resolved bilaterally and have to be escalated to the regulator. Recent US examples include the public safety/cellular conflict in the 800 MHz band, WCS/SDARS, and the argument over AWS-3 rules [1]. A common thread is ambiguity in the rights that govern cross-channel interference, particularly between dissimilar service types. Inter-licensee conflict is greatest across boundaries with different adjacent uses. In the absence of clear rights, "expectations to coordinate" imposed by the regulator only work effectively when participants have symmetrical or at least similar interests. Such uncertainty affects the value of radio licenses, as in the unexpected cost and complexity of protecting Broadcast Auxiliary Service (BAS) adjacent to the AWS-1 A block [2].

While the pace of auctions of new exclusively-assigned, flexible use radio licenses may be slowing, there are still auctions in the offing in the US as a result of the National Broadband Plan [3], and spectrum releases are planned in Norway, Denmark, Germany, India, the Philippines and Hong Kong [4]. The pressure to "allocate everything" continues grow as bandwidth-intensive applications like video migrate to wireless, leading to calls for converting guard bands to allocations, and increased "spectrum sharing". This increased frequency overlap between systems amounts to more intensive concurrent operation.

This challenge becomes acute in the dynamic coexistence scenarios under the rubric of "dynamic spectrum access" (DSA). DSA is premised on decentralized coordination, which requires that the regulator is decoupled from operational decisions; participants can't run back to Mommy every time there's a disagreement. Such delegation will only succeed if there are clearly defined and assigned rights that form a basis for resolving conflicts by negotiation or adjudication.

The ambiguous definition of rights has long been recognized as a problem. For example, the FCC Spectrum Policy Task Force noted a widespread sentiment that "the Commission's most difficult, controversial, and unsatisfactorily resolved cases have resulted from situations in which the extent of an incumbent's spectrum rights and interference rights, and its limitation on impacting other bands or users, were not clearly understood by the incumbent, by a new service provider, and even by this Commission" [5].

The definition of cross-channel rights and responsibilities to date has been *ad hoc*; there is no standard approach. The increasing diversity of radio uses and users is amplifying this problem, to the extent that regulators do not have the resources to continue the current practice making detailed coexistence decisions in every case, even if that were desirable. Regulators have struggled to resolve adjacent service coexistence problems even for static allocations; what chance is there for DSA conflicts?

Institutional custom and practice has also encouraged protracted, politicized proceedings. If rights were sufficiently clear and complete, then courts (either administrative law judges, or conventional courts) could resolve disputes, and incrementally assign rights regarding behaviors not defined in the initial entitlement, i.e. rights currently in the public domain. However, since the FCC can also make rules, it has a penchant for jumping to creating new rights while trying to resolve conflicts, without building up the body of case law as one would in a common law system that would allow wise evolution of rights.

B. A way forward

Most current implementations of radio regulation have two fundamental flaws: they are rooted in the concept of "harmful interference", which is so vague as to be useless for adjudicatory purposes; and the trading of rights to protection against interference is hampered because they are held by the regulator and not effectively assigned to participants.

This paper proposes defining rights with the goal of maximizing concurrent operation, not minimizing harmful interference. It explicitly takes a probabilistic approach to rights definition; defines transmit rights in terms of transmission permissions; states the RF environment an operator can expect in terms of reception protections; and defines these parameters in terms of resulting electromagnetic energy rather than using transmitter rights and receiver specifications. Quantifying and addressing harmful interference remains a very important topic, but is delegated from the regulator to operators.

The use of resulting electromagnetic energy metrics to characterize licenses is not new. Matheson proposed a regime in which all licensed signals must be less than some designated field strength at all points outside their licensed "electrospace" volume [6]. The FCC's interference temperature proceeding [7] advocated a shift from a focus on transmitter operations to an approach that is based on the actual radiofrequency environment, and such an approach was implemented by Ofcom in the L-band auction [8] [9]. This is also at the heart of Australia's space-centric approach, even though the assigned rights are expressed in terms of transmitter powers at a specific location [10].[1] The need to define maximum level of noise that a user had to accept from other RF sources has been clearly recognized for some time, e.g. in a summary of consensus on "basic spectrum rights parameters" ([11] section III. B).

This paper builds on these precedents by introducing explicitly stated reception protections, using similar parameterizations for reception and transmission levels, strictly limiting parameter changes to license renewal time, and using a registry. It emphasizes using rights to foster improved concurrent operation through wise initial assignment and bilateral negotiation, rather than the management of harmful interference by the regulator. The bottom line is simple: delegate interference management to the parties who are coexisting with each other.

C. Nomenclature

This paper focuses on concurrent operation or, equivalently, the coexistence of multiple systems. Since interactions between systems can be highly non-local in geography and frequency due to propagation and non-linear receiver effects, respectively, the notion of "neighbors" is a fuzzy one [12]; systems widely separated in space and/or frequency may affect each other's concurrent operations. Conversely, depending on system design and topography, "neighboring" systems may in fact be able to operate completely independently of each other.

Consequently, I frame interference in terms of (a failure of) concurrent operation, rather than in terms of harm. "Harmful interference" has developed unhelpful and inaccurate connotations of assigning blame to a transmitter when a receiver's poor sensitivity may be just as easily held responsible; as an example of such loaded language, one often hears about "victim receivers" but never "victim transmitters". Therefore, I will use the term "fails in concurrent operation" rather than "suffers harmful interference".

While complete engineering and business model neutrality is impossible, it remains a useful goal. This paper therefore formulates its approach in terms of transmission and reception, rather than transmitters and receivers, in order to underline that rights are intended to be independent of implementation.

This paper frequently refers to "rights". This term refers to permissions to behave in a certain way, and does not imply that there is an underlying asset to which licensees might obtain a property right; rather, it refers to an operating right. "Spectrum" is not an asset; when there is no transmission, there is literally nothing there.[2] The asset inheres in the operating permission.

D. Structure

After outlining the principles that underpin this proposal in Section II, I turn to defining operating rights with an emphasis on engineering parameters in Section III. Some legal and economic considerations are reviewed in Section IV, but a detailed treatment is deferred to a subsequent article. Section V closes with a brief discussion of implications and future work.

II. Underlying Principles

A. Aim regulation at maximizing concurrent operation, not minimizing harmful interference

Basing radio policy on preventing harmful interference is ill-advised. The FCC, for example, admits in its 2009 Notice of Inquiry on wireless innovation and investment that the application of harmful interference criteria "often devolves to a case-by-case interpretation of conflicting data" [13]. It continues in a footnote: "The definition provides no quantitative guidance on what degree of signal degradation or how many interruptions over what period of time would meet the 'harmful' threshold. Moreover, there are other factors that have a strong bearing on this determination, such as the nature and purpose of the communications (e.g., voice, video, data, entertainment, public safety, etc.) that must be taken into account."

While it is certainly a warning sign when a service that used to work suddenly fails, rules that try to prevent interference at all costs lead to over-conservative allocations that under-estimate the amount of coexistence that is possible between radio systems.

The primary goal of policy should not be to minimize interference, but to maximize concurrent operation of multiple radio systems by making it easy to assign responsibility when concurrent operation breaks down. Once the cost-bearer can be reliably (and cheaply) identified, the parties have the means and motive to resolve harmful interference.

An absence of interference conflicts, even though there is a lot of demand, is a sign of inefficient allocation. Rather than

[1] Licensed transmit power spectral density is determined for every transmitter based on its distance from a geographical boundary, a per-allocation receiver level of protection (in dBm/30 kHz), and a propagation loss calculated using a prescribed model.

[2] Other than fluctuating virtual particles that constitute the vacuum energy.

minimizing interference with the secondary requirement of maximizing concurrent operation, regulation should strive to maximize coexistence while providing ways for operators to allocate the burden of minimizing interference when it is harmful.

Concurrent operation and harmful interference are dual constructs, provided harm is defined as impairment of concurrent operation. Minimizing interference and maximizing coexistence are two ends of the same rope. Imagine metering airplanes taking off from airports: if one allows just one plane at a time to be airborne in a large region, pilots don't have to worry about looking out for other craft, but very few planes would be able to fly at any given time. Conversely, allowing everybody to take off whenever they choose even during busy times would lead to congestion and collisions. Fixating on the prevention of interference is like preventing all possible traffic problems by only allowing a few planes aloft at all times, even during rush hours.

Focusing on improving coexistence means that the regulator does not need a cast-iron (or in fact *any*) definition of harmful interference for use in rights definitions. However, understanding the mechanisms that lead to harmful interference helps in designing rights that make coexistence conflicts decidable; for example, if rights ignore out-of-band transmit power levels (as in Guatemala's TUFs [14]), there is no way to decide which party is responsible for resolving receiver overload problems. Therefore, the regulator may well take a view on harmful interference scenarios when making decisions on the parameters and parameter-values in rights definitions. However, once rights are defined and one is in the conflict resolution phase, no reference to harmful interference will be necessary.

B. Delegate management of interference to operators

The political process is designed to respond carefully and deliberatively to change, and by design lags market and technology change. Therefore, regulators should define radio operating rights so that the management of coexistence (or its conjugate, interference) is delegated to operators.

Disputes about interference are not only unavoidable but a good sign: the market is pushing to the edge of the envelope. Resolving disputes is not the rule maker's function, though; parties should be given the means to resolve disputes among themselves by a clear allocation of operating rights.[3] This works today for conflicts between operators running similar systems; most conflicts between cellular operators, say, are resolved bilaterally. It's much harder when dissimilar operations come into conflict [1]; to solve that problem requires better rights definitions.

This amounts to a shift from *ex ante* to *ex post* regulation. The regulator does not try to define harmful interference up-front, but leaves it to operators to resolve it after the fact.

[3] A regulator may have both rule making and adjudicatory responsibilities; this comment applies to the rule making side.

C. Limit regulator's remit to the physical layer

Operators are in a better position to resolve harmful interference problems since they have more flexibility in considering trade-offs beyond the physical layer. There are many smart ways to improve concurrent operation if one frames the problem in terms of the entire communications stack rather than just a radio communication in a single channel [15]: that is, if one shifts the design perspective "from link to system".[4] An operator that is not entitled to force another to mitigate interference it considers harmful can still manage collision events, switch channels, choose other bands, or adjust its application's requirements. The regulator cannot, and should not, attempt to devise such engineering solutions. It should focus on defining electromagnetic parameters in such a way that systems can make the trade-offs themselves.

D. Keep roles and stages of regulatory action distinct

Radio regulators often have multiple roles and powers, for example to create regulation, assign licenses, adjudicate disputes, and enforce rules. When these multiple roles exist in one agency, as they do at the FCC, it is difficult to avoid mixing them when trying to solve problems. The regulator tangles up issues that would be more efficiently solved by the participants, with those where its role is essential and unavoidable.

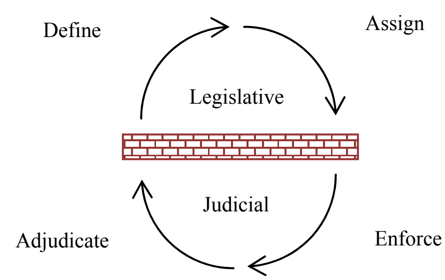

Figure 1: The Regulatory Loop for Operating Entitlements

This role mixing may have been productive in the past, when the number of participants and problem scope was relatively limited; however, it is no longer viable given the scale and complexity of contemporary markets and technologies. The regulator needs to focus its attention in areas where it plays an essential role, and stay out of the others. In broad terms, I will distinguish between defining rights (rule making and assignment) and resolving conflicts (adjudication and enforcement).

The definition of rights and the mechanisms by which they will be assigned is a legislative role, and a key responsibility of a regulator.

The definition of rights can be divided roughly into technical and economic spheres. The technical decisions concern the operating parameters of radio systems, such as reception protections and transmission permission. The

[4] Paul Kolodzy, personal communication, 5 May 2010

legal/economic ones concern how rights may be enforced, renewed and alienated. For example, if licensees can enforce their rights directly against each other, are these entitlements in property rights or damages [26]?

The resolution of conflict hinges on the adjudication and enforcement of rights. When rights are not well-defined, conflicts can often only be resolved by creating new rights, or equivalently, new rules. However, with good definition and judicious assignment, conflicts are more efficiently resolved in a decentralized way between the parties. In most cases, rights should be clear enough that parties will not have recourse to a third party. If a third party needs to be involved, it can be either the courts or a regulator with an adjudicatory function; however, if the regulator is invoked, adjudication should be separated rule creation. This is possible in theory at the FCC through the use of ALJs, but to date more honored in the breach than in the observance [16].

A regulator should not make a determination of harmful interference in its rulemaking role, but only as adjudicator. The regulator needs to have a "fire and forget" philosophy of not changing the definition and assignment of rights by rule making between renewal periods; that is, if a regulator adjudicates, it should do so without making new rules. However, adjudication (either judicial or administrative) may effectively end up shifting rights through their decisions in specific cases, particularly in common law jurisdictions.

The split responsibility of the FCC and NTIA for wireless regulation in the US creates an adjudication problem. If one assumes clearly assigned rights and low transaction costs, then it is relatively easy to assign responsibility for breakdowns in coexistence if all parties fall under the same jurisdiction. However, the lack of a venue for resolving conflicts between Federal and non-Federal users vitiates attempts to efficient sharing between such parties

III. Operating Rights

This paper proposes defining the engineering aspects of radio rights in terms of probabilistic (transmission) permissions and (reception) protections.

A. Probabilistic operating criteria

Since the radio propagation environment changes constantly, rights parameters defined probabilistically reflect reality. The determinism of rules that specify absolute transmit power is illusory; coexistence and interference only occur once the signal has propagated away from the transmitter, and most propagation mechanisms vary with time. While US radio regulators seem resistant to statistical approaches, some of the oldest radio rules are built on probability: the protection contours around television stations are defined in terms of (say) a signal level sufficiently strong to provide such a good picture at least 50% of the time, at the best 50% of receiving locations [17]. Other regulators have introduced statistical considerations into the definition of rights; Ofcom's L-band license allows the maximum aggregate power flux density to exceed its limit at 5% or fewer locations within a test area [9].

In a letter to the FCC and NTIA, the IEEE argues that FCC and NTIA should make a general policy concerning the use of probabilistic models in harmful interference determinations [18]. It notes that while the FCC has occasionally used statistical techniques in allocation design, neither the FCC nor the NTIA have a general policy on the use of such techniques; however, the UK regulator Ofcom has frequently used such techniques, and they are recommended in ITU-R M.1635. Probabilistic analyses are also used by other US government bodies such as the Nuclear Regulatory Commission and the Department of Veterans Affairs.

The rights approach advocated here would specify operating parameters at some fraction of locations and times; for example, the aggregate power spectral density might be required not to exceed -90 dBW/(m^2.MHz) at more than 95% of locations for more than 5% of the time, for a given test area and time window. The license would specify the propagation and terrain model that is to be used to test whether a given transmitter configuration meets this criterion. The model would remain unchanged for adjudication purposes for the duration of a license term; it may be changed at renewal time, or earlier with the consent of all parties. However, an aggrieved party might attempt to show that the designated model is systematically and grossly incorrect, but would bear the burden of proof.

The use of "resulting energy" rules frequently leads to a debate on the merits of measurement vs. modeling in defining rights and observing outcomes (see e.g. Section 6.4.5 in [1]). All models are imperfect, and discrepancies with measurements can always be found. However, both models and measurements make probabilistic predictions; even in the case of measurement, one has to make essentially statistical assumptions about the validity of the test points chosen. If a model agrees with measurement within the errors allowed by the operating right, the two approaches are identical for practical purposes.

B. Reception Protection

The manner and degree to which receivers are protected is an important regulatory design decision. Receiver protection in current FCC practice is broad but vague. 47 CFR § 2.102 (f) provides a blanket requirement that licensees shall choose their operating frequencies "as not to cause harmful interference to allocated services in immediately adjoining frequency bands." However, this generic protection is rarely decisive, and did not seem to play a role in public safety's conflict with Nextel over interference in the 800 MHz band. Some allocations have more specific requirements; for example, 47 CFR § 27.1133 contains the requirement that "AWS operators must protect previously licensed Broadcast Auxiliary Service (BAS) or Cable Television Radio Service (CARS) operations in the adjacent 2025-2110 MHz band," without specifying minimum performance levels for BAS/CARS receivers.

Such unconstrained obligations to protect amount to a blank check for receiver operators, and has led to frequent calls for receiver standards. However, specifying receiver standards requires a great deal of system- and scenario-specific information, and device manufacturers have successfully blocked such mandates. Receiver standards have been used by the NTIA in its role as hands-on manager of Federal systems.

One might take the position, as Ofcom has done with SURs, that defining receiver protection explicitly is not necessary since an operator can derive the signal levels their receiver has to tolerate by examining the terms of all neighboring licenses [8], [1]. Traditional licensing definitions take a similar, if somewhat less precise, approach to defining new rights: the regulator makes a judgment about the protection level that is required to maintain the value of the incumbent service, and then attempts to build that level of protection into the transmitter power levels for the new allocation. The Australian approach makes this more precise by tying transmitter licenses to locations [10]. However, these approaches provide little comfort to a licensee that has no assurances that neighboring licenses may not change in adverse ways in future; such uncertainty is at the heart of T-Mobile's objections to the rules the FCC is crafting for the AWS-3 band [19].

Conversely, one might take the position that licensees should be given explicit ceilings on the electromagnetic energy they are expected to tolerate from other operations. While this provides a great deal of certainty in planning, it can be difficult to establish which of many operations is responsible when such a ceiling is exceeded. Even if their identity can be ascertained, liability may be hard to assign. For example, imagine that two concurrent operations both deliver energy just at the allowed threshold of E_{max}, so that the receiver's ceiling is twice the protected value (E_{max} + 3dB); which one of the two would be responsible for reducing their power, and by how much?

The most challenging problem, however, is a conflict between transmission and reception rights when both have equal standing. A regulator might in good faith and best judgment assign operating rights which result in a transmitter operating within its rights violating another licensee's reception rights; concurrent operation might break down, but neither would be liable. This was arguably the stalemate in the 800 MHz band that led the FCC to award Nextel new allocations that enabled it to fund a restructuring of the band: public safety was entitled to interference protection, but Nextel was operating within its license terms.

I favor a middle path between putting reception protection on a par with transmission permissions, and providing no reception protection at all: A license should state the explicit receiver protection levels the regulator deems applicable, but these terms do not give a basis for complaint against other licensees.

These levels are an undertaking by the regulator to use its judgment – which may include choices of coexistence scenarios, measurement methods, and/or propagation models - to ensure that such reception protection will be observed (probabilistically) when making other license allocations. For example, in the course of a rule making for another allocation, a licensee may use its reception protection parameters to contest a regulator's decisions in defining rights for new allocations.

When a new allocation is being made, the regulator uses pre-existing reception protections to calculate new transmission permissions. Conversely, it takes existing transmission permissions into account when calculating the reception protections of the new allocation. These levels will most likely be derived from interference protection criteria for existing and prospective services, and a degree of technology specificity is unavoidable. However, once defined they contain no reference to interference protection of particular services, and may be changed going forward by the regulator (at license renewal time), or by operators in bilateral negotiation.

If pre-existing services do not have licenses with reception protections, e.g. they are legacy licenses with non-quantitative protections against "harmful interference", such incumbents will be issued with new licenses that replace harmful interference indemnities (if any) with reception protection ceilings. Incumbents will be able to use their new reception protections and transmission permissions in disputes with newly allocated licensees, but not against other legacy licensees. This approach limits the issue of new-form licenses only to systems which most likely to have coexistence problems (e.g. "neighbors"), and thus this new approach can be rolled out in a step-wise fashion.

Reception protections are defined as probabilistic energy levels over geography and frequency (see Table 1). The geography may be limited to the nominal area of the license, but the frequency range should extend beyond the nominal licensed channel in order to provide limits on cross-channel interference, particularly overload. However, no protection is afforded against intermodulation interference; not only does this interference mode depend on contingent behavior of other operators, but it is most cheaply avoided by the licensee themselves through suitable receiver design. Receivers themselves are not explicitly protected, nor is there a need to issue receiver standards.

The upshot of this approach is that licensees receive an assurance that no future transmission permissions will exceed objective limits; a method such as this may well have prevented the AWS-3 argument.

C. *Transmission Permissions*

Transmission permissions (for operator A, say) should be defined so that neighbors in geography, frequency and time (call them B) can determine the environment in which their receivers will have to operate. There are various ways to do this, including the Australian "space-centric" approach [10] and Ofcom's Spectrum Usage Rights [8]. These approaches implicitly or explicitly define the field strength resulting from A's operation at all locations where receivers might be found, giving operator B the information it needs to design its system. Permissions do not explicitly constrain deployment choices on transmitters, beyond those required to meet the specified levels.

Just as with reception protections, these permissions are defined probabilistically as an envelope of energy levels over the parameter spaces (see Table 1). In order to facilitate planning for concurrent operation, transmission permissions should be defined beyond the nominal geographic and frequency boundaries of the license; this will help characterize co-channel and cross-channel interference risks, respectively.

There are no obligations to prevent “harmful interference” to other concurrent operations; if a service operates so that resulting energy levels meet the requirements specified in its license, it is has no liability for harm to other operators.

D. Parameters

The parameterization of protection and permission levels needs to strike a balance between attempting to cover all possible scenarios, and providing a minimal set that minimizes information overhead and compliance costs. The interference protection criteria in Table 2-2 of NTIA Report 05-432 [20] provide a useful reference, as does Section 4.4 of the 2006 report for Ofcom on technology-neutral spectrum usage rights [21]. A parameter list is proposed in Table 1.

Energy levels are defined over all frequencies and locations, not just within the nominal boundaries of the license where energy is most concentrated. These levels may be zero, non-zero, or not specified. Electromagnetic energy is given as power spectral densities (e.g. in dBW/(m^2.MHz) or dBμV/(m.MHz)) rather than power (e.g. in dBW) since I am interested in resulting signal levels rather than power at a transmitter.

Rights not assigned are deemed to be in the public domain and can be appropriated by any licensee – but only until the next license renewal point, at which time the regulator may add rights to the licenses specifying these parameters. For example, a transmission permission may limit resulting energy at or below an altitude of 1.5 meters, but say nothing about operation at 10,000 meters; a licensee transmitting from a surveillance drone may thus be able to use significant transmit power.

TABLE 1: PARAMETERS FOR SPECIFYING PERMISSIONS, PROTECTIONS AND PROBABILITIES

Parameter	Description
Electromagnetic energy[5]	A measure of electromagnetic radiation that characterizes the result of wireless transmission. There are various options. It can be defined as an absolute value or a ratio. Choices include power density S (e.g. in units W/m^2or dBm/m^2) or equivalently electric field strength E (V/m or dBμV/m), [6] or as a spectral density, e.g. dBW/(m^2.MHz) or dBμV/(m.MHz). <u>For transmission permission</u>, specified as an absolute value. <u>For reception protection</u>, specified as absolute value, or as power density ratios e.g. interference-to-noise I/N, or carrier-to-interfering signal C/I, where C is the licensed signal, I is the aggregate signal from other operations, and N is the noise figure.
Reference Bandwidth	Bandwidth in which signal power should be calculated or measured. Typical units are kHz or MHz.
Location profile	Geographic range over which various signal parameter values apply. At minimum there are two regions: inside or outside the spatial license boundaries; there may be more. Boundaries are typically specified by coordinates in degrees latitude/longitude, and altitude in meters. Parameter values can be discrete, e. g. two values for inside and outside the licensed range, or may vary continuously.
Frequency profile	Frequency range over which various signal parameter values apply. At minimum there are two regions: inside or outside the frequency license boundaries; there may be more. Range boundaries can be given as absolute values, or off-sets from the band edge. Typical units are kHz, MHz or GHz. Parameter values can be discrete, e. g. two values for inside and outside the licensed range, or may vary continuously (aka a mask).
Percentage of Time	For each signal parameter, the percentage of time during which it should or should not be exceeded.[7]
Percentage of Locations	For each threshold, the percentage of locations at which the threshold signal level should (C/I) or should not (I or I/N) be exceeded. Used in some services to protect operations within a service area.

E. Revisit parameters at license renewal points – but only then

Technologists and entrepreneurs constantly invent new approaches that can vitiate the assumptions that underpin the calculation of permission and protection parameters. Values may be affected by a better propagation model that changes the relationship between transmission and reception parameters, or a new scenario that was not contemplated during allocation. New scenarios may also introduce completely new parameters whose values were not specified during allocation.

In order to assure an orderly process, the regulator needs to exercise restraint and not change the rules in the middle of the game. In its role as rule maker, it sets parameters at issue of a license but then leaves them unchanged. If the regulator adjudicates inter-operator conflicts, it may not use its legislative power to change rules during the term of a license.

However, the regulator should make full use of license renewal phase to add new parameters or change the model used to determine whether transmissions from deployed systems conform to operating permissions. In a world of low transaction costs it should not be necessary to change parameter values; these are adjusted by negotiation. However, in certain cases the regulator may deem it necessary to change parameter values, e.g. increasing allowed out-of-band emissions when market negotiations are unlikely to incentivize a group of operators to improve receiver performance.

[5] When considering reception protection, the signal of interest may be “interference”

[6] $S = E^2/Z_0$, where Z_0 is the impedance of the vacuum. Received power $P_r = A_e S$, where A_e is the equivalent antenna area; note that A_e depends on the direction of the incoming wave (http://www.giangrandi.ch/electronics/anttool/antenna.html)

[7] For example, for reception protection, C/I should be exceeded, while I/N should not be exceeded, for some percentage of the time

If the licensee does not like the result, it has the option of not renewing its license with no penalty, at which point it'll be re-auctioned with the new rules

F. Use a registry to record current parameter values

All the parameters associated with a license should be filed in a public registry. This will provide a clear and current inventory of the rights associated with every license. Such transparency will facilitate maximal concurrent operation, allow interested third parties to challenge changes, and remove the need for taking "spectrum inventories".

All changes to operating parameters should be filed in the registry. This includes not only bilaterally agreed parameter changes between operators, but also any rule changes or waivers that operators obtain from the regulator. In current US practice waivers attach to a license, but may be very difficult to find.

G. Enforcement

Licensees, not the regulator, bear the primary responsibility for enforcing rights. If a licensee A is suffering a break-down of operations, it can take action directly against another licensee B if it can show that B is exceeding the terms of its transmission permissions. Depending on the circumstances in a particular jurisdiction, this action may be either in a court of law or through adjudication by the regulator. In either case, the dispute should be resolved without creating new operating rules. In common law jurisdictions the decisions of the court may create new rights *de facto*, which will have to be taken into account by the regulator at license renewal; it should have the discretion to either accept or over-rule this action, but only at renewal time.

Licensee A may only take action against B if A is in fact operating a system; in other words, it cannot take action itself against B unless there is a *prima facie* case that it would suffer harm through B's operation.[8]

Following the approach laid out in Section III.B above, the reception protections in A's license do not give it grounds for action against licensee B; that is, if B is operating within the terms of its transmission permissions, A has no recourse even if A's reception protections are exceeded.

IV. ECONOMIC CONSIDERATIONS

Any choice of parameter values creates winners and losers, and thus requires reference to the economics of rights assignments [22].For example, imagine that the operator in channel A would like to operate at resulting field strength less than or equal to E_{high} in their channel, but that the operator in adjacent channel B would prefer a that field strength to be E_{low} because of the lack of sensitivity of its receivers; that is, B's system cannot operate concurrently when A is operating at E_{high}. If the regulator chooses E_{high}, B incurs the liability of either improving the sensitivity of its receivers, or paying A to reduce from E_{high} to E_{low}; conversely, a choice of E_{low} imposes the burden on A of operating at less-than-desired power, or paying for B's receivers to be upgraded.

While calculating the levels of resulting desired or undesired electromagnetic energy can be contentious given uncertainties in deployment and propagation scenarios, the consequences of an error are significantly reduced if there is a way for participants to adjust these values by transferring rights through negotiation.

A central finding in Coase [23] is that the assignment of liability to one party or another does not affect the economically optimum solution for society at large; however, the windfall gains or losses of particular parties do depend on the assignment [24], [25]. There are therefore political choices of wealth distribution that are independent of economic efficiency.

Calabresi & Melamed's seminal paper on property vs. liability rules offers a method for a preliminary analysis of some choices for the rights proposed here [26]. They recommend that entitlements are assigned in a way that takes into account one's degree of certainty has about the participants' knowledge and capabilities. For example, if the government can't make a knowledgeable trade-off between social costs and benefits, it should assign the cost to the party best placed to make a cost-benefit analysis, which in pollution contexts means the least-cost avoider; if that party can't be identified, then it should impose costs on the party that can most cheaply act in the market to correct errors in entitlements. In addition to efficiency consideration, society also has to consider that cost assignment as wealth redistribution effects.

The conventional approach of providing radio licensees with blanket protections against harmful interference presumes that the transmitter and/or new entrant is the least cost avoider; the interference protection imposes on them the cost of fixing a breakdown in concurrent operation. The introduction of frequency-agile radios, and the availability of a growing number of alternative communication paths, means that this assumption is no longer obviously true.

Once an entitlement is assigned, it still remains to be decided whether it should be protected by property rules, liability rules, or rules of inalienability. In Calabresi & Melamed's nomenclature, a property rule allows the owner to specify the amount that has to be paid to compensate a loss; a liability rule entails that a pre-determined amount has to be paid if the entitlement is destroyed; and an entitlement is inalienable to the extent that it cannot be transferred even between a willing buyer and willing seller.

Calabresi & Melamed contend that "a very common reason, perhaps the most common one, for employing a liability rule rather than a property rule to protect an entitlement is that market valuation of the entitlement is deemed inefficient." Applied to radio regulation, this suggests that licenses for which a market exists, such as transferable, flexible-use ones obtained at auction, can be given a property rule; the amount to be paid to compensate for a breakdown in coexistence will be

[8] This principle aligns more closely with a trademark metaphor for radio operations than the spectrum-as-real-estate one; the holder of a trademark can only sue from infringement if it is using a mark, and can show that its customers are being misled by an infringing mark. See Section V.C and [28] for more on trademark.

set through bilateral negotiation of the parties. However, entitlements associated with services that don't have a market price, like public safety and Federal uses, would have liability entitlements; the regulator would set the price for damage to such operations.

Inalienable entitlements may apply to situations where rights are split, as they are in broadcasting: transmission permissions and reception protections apply to different parties. One might thus argue that a TV broadcaster should not be able to alienate their transmission permissions (e.g. take a payment from a cellular operator to reduce broadcast power in order to remove interference to a broadband network) if that would impair the ability of viewers to receive a broadcast signal.

Further, the way in which rights are assigned can be just as important as the way in which they are defined. Hazlett has pointed to evidence in the law and economics literature that the configuration of radio rights would influence the efficiency with which they can be used and reconfigured [27]. When the government distributes rights to a large number of owners, it increases the number of borders where coexistence problems can arise, and the transaction costs make it difficult to reassemble rights to make efficient deals. Assignment tools, such as auctions, should be crafted so that efficient recombination is cheap and easy, for example through combinatorial auctions, or national licenses.

V. IMPLICATIONS AND FUTURE WORK

A. *No new regulatory authority required*

This approach does not require a change in the FCC's authority. Implementing it would lead to service rules being defined in different ways (e.g. using resulting field strength rather than transmitter power) and the application of previously underused license renewal powers, but does not require alterations in the FCC's authority.

However, substituting explicit energy levels for generic "no harmful interference" license conditions may require the FCC to forbear from applying sections of 47 CFR § 2.102; this requires further study.

B. *Unlicensed allocations*

The approach proposed above was framed in terms of licenses; however, it can be extended to unlicensed or licensed-by-rule operation.

Since individual devices are licensed, transmission permissions defined in terms of the resulting energy of all operations cannot be used. Just as is done today, devices would be given individual permissions to transmit on the basis of an assessment of the aggregate energy that would result when they are deployed. These permissions would be derived from the explicit protections given to primary operators.

These parameters then provide a tripwire for changing the device rules by comparing resulting electromagnetic energy delivered by unlicensed deployments with the protection level of primaries. If protections are exceeded, either by individual devices or in aggregate, then there is a *prima facie* case for a rule change to less permissive unlicensed device transmission permissions; conversely, if protections are undershot, then there is the basis for a rule change favoring more permissive transmit permissions.

This approach motivates collective action by manufacturers: the promise of more permissive rules is an explicit incentive to develop operating standards for all devices that maximize concurrent operation.

Such examinations would occur at regular intervals, just as in the case of license renewals. Every ten years, say, the regulator would have an opportunity to adjust the unlicensed rules, up to and including revoking the allocation of there is insufficient evidence of use.

C. *Alternative conceptual frameworks*

The exposition above assumed the conventional framework of real estate-like property rights in radio licenses. However, the principles also apply to non-conventional approaches, such as one based on non-spatial metaphors such as trademark [28].

In the trademark-inspired approach, property rights are obtained by registering system operating parameters like transmission and reception masks, just as a trademark registration covers a variety of brand attributes. Any set of operating parameters that can coexist with existing registrations on the basis of their declared masks is authorized. There is no need for a regulator-driven allocation process. Rights have an indefinite term, but are forfeited if not used. In general, the definition and assignment of rights is driven by operators, not regulators. The current US allocation that most closely resembles a trademark-inspired entitlement is the 3650-3700 MHz radio service (FCC R&O in docket 05-56, March 10, 2005): anyone deploying base stations must register in a central, accessible database. However, all parties have equal rights regardless of when they started operating.

The methods of defining rights outlined above goes through as before, although parameter values are determined by operators. Rights that are not appropriated (i.e. both declared and used) are in the public domain. The regulator may choose to define sets of rights and auction them, but auctions are not essential for rights assignment.

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