GOVERNING THE SPECTRUM COMMONS:

A FRAMEWORK FOR RULES BASED ON PRINCIPLES OF COMMON-POOL RESOURCE MANAGEMENT

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INTRODUCTION AND OVERVIEW

THE CONFERENCE REPORT PROJECT

This is the third in a series of conference reports prepared for groups in the media reform and justice movement. This report was prepared for the Grantmakers in Film and Electronic Media (GFEM). Previous reports were prepared for the Media Resource Center of Consumers Union (www.hearusnow.org).*

The overall purpose of the project is to summarize the technical and policy implications of material from academic conferences that may not otherwise be accessible to groups pursuing media reform and justice. The rapid growth of the media reform and justice movement, in response to policy initiatives at the federal level, visible problems in the mainstream media, and dramatic technological changes in society as a whole, has created intense demand for data, academic analyses, coherent theories, and institutional models to advance the movement and ensure its effectiveness. The goal of the conference reports is to add to the resource base of the movement, not by summarizing large quantities of unrelated information, but by offering observations on how the material relates to the movement's principles, objectives and methods of organization.

This paper deals with **spectrum policy**. From the point of view of GFEM, spectrum policy is arguably the most important policy for establishing the general environment in which creative artists work and average citizens gain access to the media in the age of electronic broadcasting. By deciding who gets to broadcast over the public airwaves, spectrum policy goes a long way toward deciding whose voice can reach the public and how the public expresses itself.

Fundamental decisions made early in the last century about the use of spectrum (Radio Acts passed in 1912 and 1927 and the Communications Act of 1934) defined the entire era of electronic media. The consequence, intended or otherwise, was to establish a handful of broadcasters as gatekeepers of a powerful, one-way medium. The reform of spectrum management that is currently being discussed would change the structure of, and conditions for, creative and public expression in the 21st century as thoroughly as the decisions made almost a century ago.

BACKGROUND ON THE CURRENT SPECTRUM POLICY DEBATE

Simply put, a couple of decades after radio broadcasting first became technically feasible, commercial and non-commercial broadcasters had filled the airwaves to such an extent that they began to interfere with one another. Two broadcasters, using the same frequency at the same

*/ Earlier reports include: *Reflections Of A Media Activist On New Strategies For Justice: Linking Corporate Law With Progressive Social Movements* (May 2005) reporting on The 2005 National Conference presented by The Equal Justice Society and the Center On Corporations, Law & Society At Seattle School Of Law in collaboration with the Critical Race Studies Concentration at the UCLA School Of Law, April 7-9, 2005; and *Online Deliberation: Mapping The Field; Tapping The Potential From The Perspective Of A Media/Internet Activist (*August 2005), reporting on The *Second Annual Conference on Online**:** Design, Research, and Practice / DIAC 2005* the Symbolic Systems Program, the Center for Deliberative Democracy, the Center for the Study of Language and Information, and the Center for Internet and Society at Stanford University, May19-22, 2005.

time, could drown each other out because, given the technology of the day, when two signals overlapped the receiver produced noise.

To solve the problem and ensure that at least some broadcasts could be heard, Congress enacted legislation creating licenses for the exclusive use of the spectrum by individuals. Some look back and question the need for this public management of spectrum, while others lament that it was executed to the benefit of only a small number of corporations, but it has nonetheless lasted for generations.

The monopoly on use was granted for a specific frequency, in a specific area, for every minute of every day, for the entire length of the license. Neighboring frequencies were also kept vacant as guard bands to prevent interference. The holders of these licenses, first for radio, then for television, became gatekeepers who chose what to air. Although the licenses were for a limited term and subject to public interest obligations, they were almost never revoked, almost always renewed, and, although the type of use could not change when the license changed hands, almost perfectly transferable between individuals.

This approach resulted in a small number of licensed broadcast speakers and a lot of unused spectrum. Reflecting the technology of the times, broadcasters blasted their signals strongly so they could reach the most distant listeners in their licensed area whose receivers were very crude.

> Current regulations provide strong interference protection to broadcasters to protect the ability of the worst-case "dumb" receivers to receive the broadcast signal, while constraining the broadcast licensees ability to benefit from using the spectrum more efficiently. The architecture uses too much power for receivers that are close, and is vulnerable to even low levels of interference for receivers that are near the edge of the serving area. With smarter receivers, spectral efficiency could be enhanced significantly. Thus, broadcast networks, in contrast to communications networks, might benefit significantly if resource management responsibility were decentralized.[1]

In fact, technology has improved to make efficient use of the spectrum possible. The digital revolution has facilitated transmission and reception with the development of superior devices called **cognitive radios**. The adjectives used to describe these devices have flowed freely: agile, smart, software-defined, intelligent. Cognitive radios adjust their transmission to look in specific places in the spectrum for signals to receive. They sense how the spectrum is being used and choose to transmit according to a set of rules (non-interference) that ensure a specific quality of service. Technical jargon aside, the technology creates an opportunity for change.

> Regulation of spectrum may undergo revolutionary changes in the near future allowing less restricted and more flexible access to radio spectrum. Intelligent radios, or so-called cognitive radios, will realize the dynamic usage of frequency bands on an opportunistic basis, by identifying and using under-utilized spectrum. Such a flexible spectrum usage requires changes in regulation toward a more open spectrum. Policies that determine when spectrum is considered as opportunity and which define the possibilities of using these spectrum opportunities are needed.[2]

This paper describes the rules necessary to implement "a more open spectrum." It is based upon the proceedings of a recent, major conference – *2005 1st IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*. The above quote is the opening sentence of the Conference Record and establishes the precise context in which the current discussion is being conducted. There is no doubt that dynamic access to the spectrum – which means many more users and uses can be supported – is technologically feasible. The public policy question is what is the best approach to get it done.

While the criticism of the fixed license regime goes back almost half a century,[3] more recently a fierce public policy debate has broken out between proponents of two very different approaches to solving the problem of underutilized spectrum.

On one side are those who would turn the spectrum into **quasi-private property**. They would allow the holders of licenses to maximize its value by flexibly using (or selling) the exclusive rights to use the spectrum that they have been given, or purchased at auction. They would demand payment from those who wanted to share the spectrum and protect their own signals from interference if they choose to continue broadcasting (they can be absentee landlords). As profit maximizers, the argument goes, they would do the best economic job of utilizing the spectrum in secondary markets.

On the other side are those who argue that the spectrum should be treated as a **commons**, which would be open to all who obey a basic set of rules about how the spectrum can be used. Because they advocate doing away with licenses altogether in some parts of the spectrum, or allowing users who have no license to share the licensed areas of the spectrum, this is frequently called an unlicensed approach. From this point of view, creating exclusive use rights in the spectrum is unnecessary and counterproductive for a number of reasons. Even when rights are flexible, exclusive rights create large transaction costs or market failures (externalities and/or abuse of market power) that plague a propertized spectrum. Above all, speech is more than just an economic commodity. Granting licenses encumbers the speed rights of those who are excluded from broadcasting.

APPROACH TO THE ANALYSIS

Some have argued that the advocates of a commons approach have failed to devote enough attention to the challenge of actually implementing a commons. The criticism is important and this paper views the conference as the launch pad for a response. For two reasons, however, the criticism is also somewhat ill-targeted.

First, given the nature of the incumbent licensees and the force of inertia, it is necessary to focus on making the case that there are benefits to be reaped from change.

Second, implementation is not a problem that only confronts the commons approach. The advocates of the licensed approach have failed to address implementation problems of their own. Spectrum is dramatically different than physical property. If spectrum is to be flexibly used to capture the value of dynamically reallocating it to various uses and users on a nearly instantaneous basis, it is just as difficult to define property rights, as it is to design open access rules that avoid interference.

> Unlike real property, radio spectrum does not allow for clear boundaries, as radio waves propagate in varying ways… Second, if property rights are granted in a manner that would allow injunctions for trespass, it is quite possible that parties could take actions solely to threaten an injunction and obtain a license along the lines of the much-criticized "patent trolls." Finally, and most significantly, any workable system of property rights will need to rely on (at least to some degree) the predictive models – i.e. statistical predictions as to how often interference is likely to occur – that generally govern how spectrum is used today. Notably, any such reliance begs the question of how such models will be integrated into an enforcement system and with the reality of whether interference is actually present.[4]

Thus, the advocates of both the property and the commons approaches should be challenged to describe in detail how their models would work.

In this paper I propose a framework for a proposal to improve use of the spectrum. I approach the solution from a commons point of view, but the challenges and the framework for assessing responses are general in principle and can be applied to a flexible, quasi-property licensed approach as well.

Ironically, while advocates of open spectrum frequently talk about the spectrum as a commons, there has been little effort to draw on the large body of sociological and economic knowledge about the successful organization of commons. In this paper, I adopt the framework for the analysis of common pool resources (CPR) articulated by one of the leaders in commons thought – Elinor Ostrom, as presented in *Rules, Games and Common Pool Resources*.[5]

The analytic scheme serves three purposes.

First, it focuses attention on the key issues.

Second, it provides a framework for fairly evaluating specific proposals to implement flexible use of the spectrum. Every proposal does not address every challenge. Because the issue is complex, it is easy to unfairly accuse proposals of failing to solve problems that they are not addressing.

Third, it helps to organize a large field. Because the issue is both highly technical and politically hot, the amount of material available is staggering. The record of this single conference includes almost 100 papers running over 700 pages.

SUMMARY OF THE MATERIAL

The technological and economic basis for a new approach to spectrum management, by expanding the role of the unlicensed, commons approach is clear.

Technology has created the possibility of a major change in spectrum governance.

- The spectrum is a vast wasteland, with more than half of it lying fallow, even in urban areas.

- The technical feasibility of building cognitive radios has been proven.
- The protocols, algorithms and rules that are necessary to organize cognitive radios into mesh networks that share spectrum effectively and efficiently have been demonstrated in theory, prototype and some practice.

The economic superiority of a mixed, **licensed/unlicensed** regime is clear in three areas.

- A commons will expand **carrying capacity** and **value** more rapidly.
- **Diversity** of institutional approaches will allow for a closer fit between needs and capacity.
- A substantial unlicensed space will be a check on market failure in the licensed space, should secondary markets be allowed.

The basic principles for operational rules seem clear.

- A simple set of behavioral rules can achieve a substantial improvement in utilization of the spectrum.
- A small number of rules reduces the complexity of implementing a spectrum sharing regime.
- Keeping the rules minimal allows innovation to flourish in a rapidly emerging field.
- Allocating a substantial amount of spectrum across a range of frequencies to unlicensed uses will significantly improve the ability to exploit the spectrum.
- **Cooperation** and communications will greatly facilitate the functioning of unlicensed spectrum.

Notwithstanding the efforts of the incumbents to convince policymakers that any sharing will lead to disastrous interference, it is possible to protect primary users from harmful, reasonably defined interference while sharing the spectrum. A balanced, licensed/unlicensed regime of spectrum governance can be built on a number of principles.

- It includes both flexible licenses and unlicensed users.
- It envisions dedicated licensed spaces, shared spaces, and dedicated unlicensed spaces.
- It envisions significant quantities of spectrum at a range of frequencies available to both licensed and unlicensed users.
- It protects licensed users rights, but demands their cooperation with the sharing regime. Primary spectrum users can be required to behave in a socially responsible manner, including cooperation in the sharing regime by using reasonable levels of power and providing information on their location and usage.

- It allows unlicensed users, but disciplines them with rules for non-interference and mechanism for enforcement.

Investment in common core infrastructure to operate the sharing regime is small, relative to the value of the spectrum. It is split between shared and private costs.

- Shared costs include the costs of beacons and the maintenance of databases, which can be deployed within existing infrastructure.

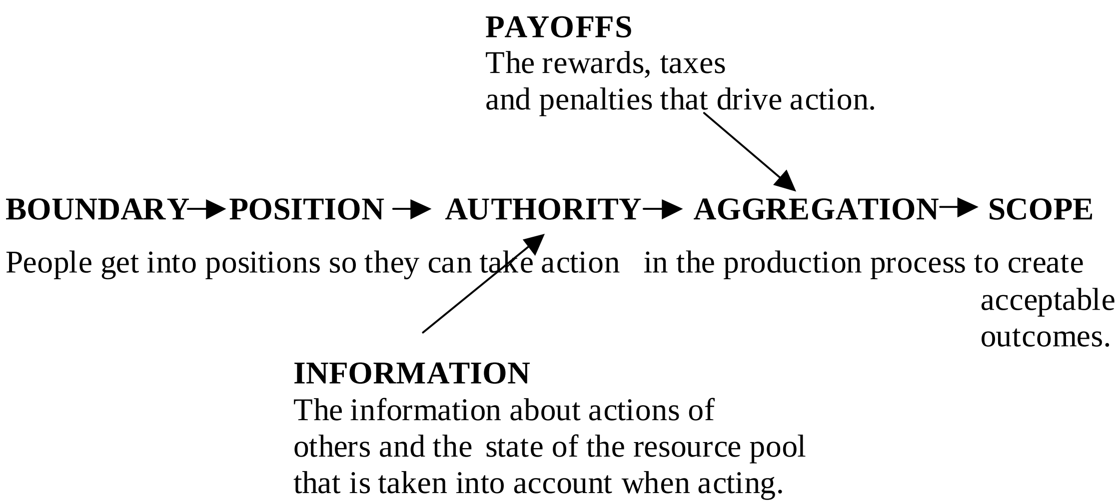
- Private investments to support cooperative use are for the hardware and software that must be embedded in the radios – e.g. sensors, protocols.

GOVERNANCE RULES

Because sharing use of the spectrum is a complex process, viewing it as a common pool resource, which it clearly is, and drawing on the rich understanding of the management of similar resources makes it easier to understand how it could be governed as such.

We can readily identify the major positions in the spectrum commons, as licensed broadcasters, unlicensed users and the regulator. We then answer the key questions about each position (see Exhibit 1). What are the boundary conditions for entering and exiting the positions? What are the actions authorized in each position and how do they add-up, aggregate to a collectively superior outcome? What are the payoffs (incentives and penalties) that motivate individuals to stay within the rules? What types of information flows are necessary between individuals to allow them to interact in a manner that sustains the commons and the production process within it?

Exhibit 1: The Flow Of Rules



The detailed rules to govern the spectrum commons that can be gleaned from the conference papers are summarized in Exhibit 2. The remainder of this paper describes how these rules and the above policy conclusions are derived.

Exhibit 2: Governance Rules For A Mixed Licensed/Unlicensed Spectrum

		POSITIONS IN A MIXED LICENSED/UNLICENSED REGIME		
		LICENSED	UNLICENSED	REGULATOR
RULE TYPE	**SUBSTANCE**			
BOUNDARY	Who	Licensee	Any certified	Issue licenses, Conduct auctions
	New entry criteria	Renewal/Auction	Certification	Hardware certification
SCOPE	Mapping outcomes	Dedicated primary	Secondary	Set Boundaries
			White spaces	
			Some dedicated	
		Avoid harmful interference	Share nicely	Define harmful interference
AUTHORITY	User	Primary	Secondary	Software evaluation
	Strength (power)	Minimum Power	Minimum power	Fairness Rules
	Time		Dynamic	
	Speed (frequency)		Dynamic	
AGGREGATION				
	Metering	Beacon	Sensor	Monitor, Central server v. Negotiated
	Usage First in	Primary, cooperative	Obey rules	Minimum operating Condition
	Announce		Look before talk	Determine behavioral rules
	Rotation		Collaborative	Group-centric collaborative
				Independent strategic
				Device centric rule-based
	Transferability	Secondary Markets	Dynamic	
PAYOFF	Taxation	Yes	Yes	
	Fines			Yes
	Incentives	Incent cooperation	Reward repeating	
INFORMATION				
	Reporting use	Location/power	Capabilities	Maintain data base
	System status	Congestion	Dynamic monitoring	Dynamic monitoring
	Monitor reports			Distributed

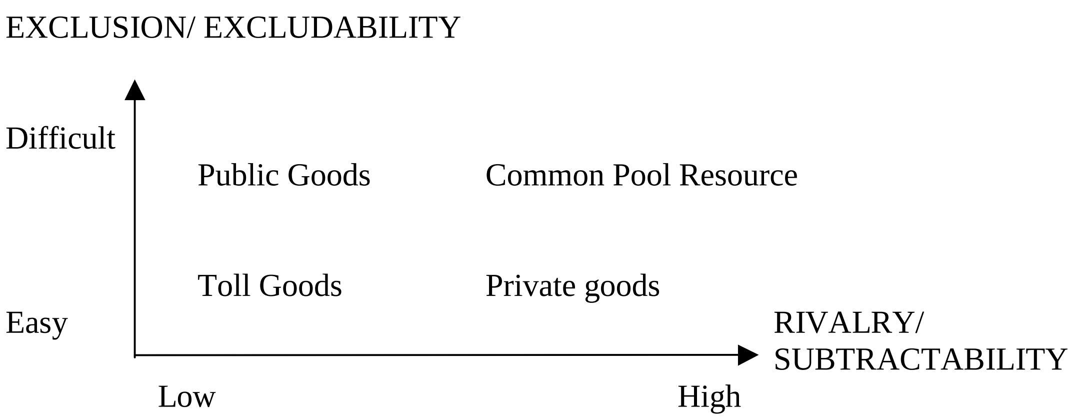
ANALYZING COMMON POOL RESOURCES

Common Pool Resources

The identification and study of common pool resources is founded on the proposition that the efficiency of governance rules for the exploitation of resources depends on the characteristics of those resources. There is a general presumption in contemporary economic thought that private property is the preferred way to organize resources, since owners have the incentive to invest in and husband those resources. Where markets work well, a property regime will maximize the value of the resources. It is also widely recognized, however, that there are circumstances under which non-property regimes work better because market failures such as externalities and public goods (as well as abuse of market power) exist.

Two attributes have been used to distinguish the situations in which different governance regimes are likely to succeed or fail. The result is to identify four types of goods (see Exhibit 3). "The two attributes are (1) the difficulty of excluding individuals from benefiting from a good and (2) the subtractability of the benefits consumed by one individual from those available to another."[6] Where **exclusion** is difficult, but the resource is **subtractable** (or subject to congestion problems), a dilemma can arise. "Individuals jointly providing and/or appropriating from CPRs are thought by many analysts to face a universally tragic situation in which their individual rationality leads to an outcome that is *not* rational from the perspective of the group. When this actually occurs, we call the behavioral result a CPR *dilemma."*[7]

Exhibit 3: Types Of Goods



The CPR dilemma is widely believed to result in the tragedy of the commons – over use and depletion of the resource. However, many CPR situations are not true CPR dilemmas because "the quantity demanded is not sufficiently large."[8] Much more importantly, "in many instances individuals jointly using a CPR communicate with one another and establish agreed upon rules and strategies that improve their joint outcomes. By devising their own rules-in-use, individuals using such CPRs have overcome the "tragedy of the commons."[9]

The purpose of studying the experience of successful common pool resource management is to learn how groups organize to solve CPR dilemmas.

> While the tragedy of the commons is real, there are many instances where institutions develop to protect against overexploitation…Forests, irrigation systems, fisheries, ground water basins, grazing lands, and the air we breath are all examples of common-pool resources (CPRs). Because no one has property rights or control over such a resource, users of CPRs are frequently assumed to be caught in an inescapable dilemma – overexploitation of the resource, or what is commonly known as the "tragedy of the commons." Many well-documented examples of overexploitation exist. The users of commonly held resources have, however, in many instances overcome incentives to destroy the resources and have developed long-enduring institutions – rules-in-use that enable them to utilize these resources more effectively. Understanding the conditions under which users of CPRs successfully develop and maintain effective institutions is critical to facilitating improved resource policies.[10]

Moreover, although the new spectrum regime will not be "self-organizing," as many common-pool resources solutions are, any set of rules applied to the spectrum will ultimately have to rely on more than just the force of law. The rule of law relies on social institutions that elicit the voluntary compliance of the vast majority of inhabitants in the space that is subject to that law. Cooperation is necessary. Common pool resource management regimes are, by their nature, institutions that elicit cooperation. The governance regime for the commons should endeavor to maximize the likelihood of such cooperation. The principles of successful self-organization to exploit common pool resources can provide useful guidance for designing the governmentally imposed rules of access to and use of the spectrum commons by pointing to ways in which cooperation and voluntary compliance can be promoted.

THE CHALLENGES OF ORGANIZING TO EXPLOIT A COMMON POOL RESOURCE

The challenge of organizing to successfully exploit a common pool resource can be framed as a series of seven practical questions.

Who gets to use the resource and who oversees it (Positions)? Position rules specify the set of *positions* and how many participants are to hold each position. Positions are placeholders to associate participants with an authorized set of actions (linked to outcomes) in a process.

How are the users awarded rights to use the pool (Boundary)? Boundary rules specify how *participants* enter or leave their positions in the commons.

How are users allowed to draw from the pool (Authority)? Authority rules specify which *sets of actions* are assigned to which position at each node of a decision tree.

How do the actions impact the pool and other users (Scope)? Scope rules specify the *set of outcomes* that may be affected, including whether outcomes are intermediate or final.

How do we measure and control the resource (Aggregation)? Aggregation rules specify the *transformation function* to be used at a particular node, to map actions into intermediate or final outcomes.

What are the incentives, taxes and fines that elicit proper behaviors (Payoffs)? Payoff rules specify how *benefits and costs* are required, permitted, or forbidden in relation to players, based on the full set of actions taken and outcomes reached.[11]

What flow of information best encourages, manages, and distributes the resources (Information)? Information rules specify the *Information* available to each position at each decision node.

Before we examine how these questions are answered, it is important to note that the institutional process of decision making itself is important. In this regard, we can distinguish three different types of decisions – Constitutional Choice, Collective Choice and Operational Rules (see Exhibit 4).

Exhibit 4: Types Of Decisions In The Governance Process

Constitutional Choice
Who participates?
What are the goals?

Collective Choice
Who participates in writing
rules to change rules?

Operational rules
Day-to-day decisions by users

Constitutional choices about who participates and what the goals of the governance regime are should be distinguished from the **collective choices** about the day-to-day **operational rules**. These constitutional choices, in turn, are different from the operational rules themselves. Thus, there is a distinction between setting the rules and living under them.

Identifying and distinguishing these choice activities is important not only because they determine the nature of the governance regime, but also because adaptation and change are important attributes of common pool resource governance. Common pool resource management is a challenging process and the regime must be adaptive. Change is a constant topic of discussion. The nature and quality of that discussion affects the legitimacy and sustainability of the entire regime.

> The capacity to change the structure of a situation is a variable in field setting, not a constant. In most enduring relationships, participants have the capability to call "time out – it's time we talked about this situation and tried to change it for the better." In many CPR situations, it is necessary to examine the process of rule change. While playing short-term games within the existing institutional and parametric structure, we often find participants engaged in a long-term process that gives us renewed hope in the sustainability of CPRs.[12]

Goal Sets

The first task is to define the **goal set** for reform of spectrum use. Three steps in that process are necessary.

- Document the inefficiency in the current approach.
- Identify benefits of alternative approaches and define a set of criteria by which alternative regimes should be evaluated.
- Demonstrate the technical feasibility of the alternative.

As part of defining the goal set one must confront the challenge of defining a workable regime that solves crucial resource problems. In the process of defining how any spectrum regime would work, be it licensed, unlicensed, or mixed, the architects must design a system that is not vulnerable to the classic problems of a commons. The governance regime must ensure provision of the resource pool and orderly appropriation therein.

Provision problems focus on the behavioral incentives for appropriators on the demand or supply sides of the resource.

- On the demand-side provision problems occur where decisions to alter appropriation activities within an existing CPR alters the productive capacity of the resources.
- On the supply-side, provision problems are the classic public goods problem where free riding can occur in decisions about whether to contribute resources for the provision or maintenance of a CPR.

Ostrom distinguishes between the **stock** and **flow** of the common pool resource, a distinction that is useful in the analysis of spectrum.

> A CPR 'facility' creates the conditions for the existence of a stock of resource units. This stock makes available a flow of resource units over time that is appropriable and subtractable in use…. This distinction between the resource stock and the flow of resource units is especially useful in connection with *renewable* resources, where one can define a regeneration rage. As long as the number of resource units appropriated from a CPR does not exceed the regeneration rate, the resources stock will not be exhausted.[13]

Spectrum is an interesting resource in the context of these characteristics. It is instantaneously **renewable** and **non-depletable**.[14] Once a transmission ceases, the frequency becomes immediately available for another transmission. It is subtractable, however, since multiple users can crowd it and destroy its value by creating interference. More importantly, spectrum is complex and **expandable**. Although the frequencies are fixed in nature, time, and space, the technology used to create the stock of opportunities is not. Different architectures of the "facility" (i.e. the network of transmitters and receivers) can support greater flows of communications.

Advocates of the unlicensed, commons approach argue that it exhibits a substantial, **positive network externality**, on both the demand side and the supply side.[15] On the demand-side, the classical network externality (also known as a demand side economy of scale) applies to communications in the spectrum. The more people who can be reached, the greater the value to the user. It also exhibits a supply side externality, at least if configured as a mesh network. When each transmitter/receiver helps to support all communications, acting as "repeaters," the carrying capacity of the spectrum expands.

Appropriation involves the manner in which individual users draw from the resource. In the case of spectrum, drawing from the resource is transmitting (occupying a frequency at a specific time and place using a specific amount of power).

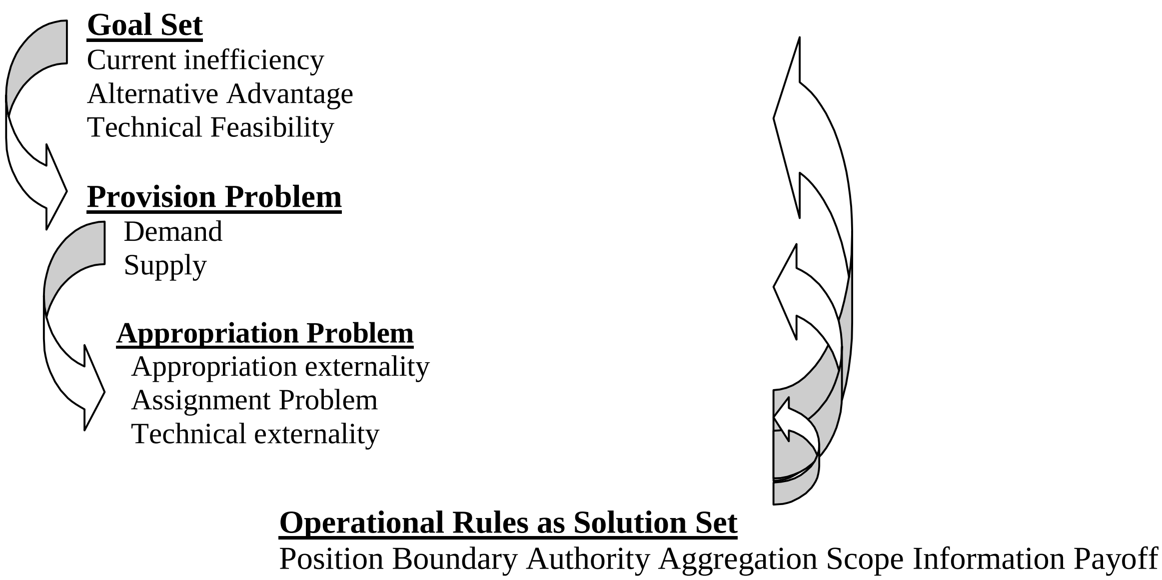
- Appropriation externalities occur when "one user's increased appropriation reduces the yield obtained by other users, for any given level of activity."
- Assignment problems occur where a heterogeneous distribution of resource units are characterized by a patchy environment in which patches may differ dramatically in yield.
- Technological externalities occur when the use of one technology increases the cost (or productivity) for the users of other technologies.

Transmitting radio waves through the spectrum exhibits all three of these characteristics. One person's signal can definitely impact the ability of receivers to usefully receive the signal of others. The spectrum is patchy. There are certainly dramatic differences in the propagation characteristics of different frequencies. Terrain and physical objects also affect the propagation characteristics of signals. Different technologies affect both the cost and productivity of users.

Thus we can conceptualize the formation of a common-pool resource management regime as a dynamic action situation in which individuals make choices and develop rules to govern their joint use of the resources The operational rules are responses to the goal set and the challenge that the common pool resource poses (see Exhibit 5).

Provision problems influence appropriation, but are distinguishable from appropriation problems. To solve these problems and achieve the goal set, governance rules must be defined to specify how the common pool resources will be managed. Common pool resources must be managed well and require rules. These rules cover the seven practical questions asked above. Ostrom notes that there is overlap between the rules.

Exhibit 5: Operational Rules Are A Solution Set To Achieve Goals And Overcome Provisioning And Appropriation Problems



Since all of these factors operate configurally, the final constellation of elements in an action situation depends on more than just one rule per element. The information available to an individual at a node, for example, is directly affected by information rules but also affected by the sequence of activities that are part of an authority rule.[16]

The role of communications and information is central to the common pool resources management regime.

> In CPR dilemmas where individual s do not know one another, cannot communicate effectively, and thus cannot develop agreements, norms, and sanctions, aggregate predictions derived from models of rational individuals in a noncooperative game receive substantial support. These are spare environments… In richer environments that vary from the institutionally sparse homeland of noncooperative game theory…. [s]imply allowing individuals to talk to one another is a sufficient change in the decision environment to make a substantial difference in behavior.[17]

The recognition of shared interest – the collective payoff – also plays a role.

> When substantial benefits can be gained by arriving at a joint plan of action for a series of future interactions, individuals may have in their repertoire of heuristics simple sharing rules to propose, backed up by the presumption that others will use something like a measured response. If in addition, individuals have learned how a monitoring and sanctioning system enhances the likelihood that agreements will be sustained, they are capable of setting up and operating their own enforcement mechanism.[18]

> Approriators of a common resource might take into account more than the individual benefits and cost they receive from following or breaking rules that coordinate resource use. If they include the opportunity costs of foregone joint benefits and the expected costs of developing new rules if detecting behavior leads to the breakdown of existing arrangements, appropriators may recognize incentives to maintain those arrangements by adopting a cooperative strategy over numerous iterations. [19]

THE GOAL SET OF THE SPECTRUM MANAGEMENT

CHOICE DECISIONS

The basic decisions about the goal set for spectrum – the constitution and collective choice decisions – were taken over by Congress early in the last century. The airwaves were deemed public and a federal agency was made the trustee. This is not likely to change, with two exceptions.

A regime that turned the spectrum into quasi-property would change the locus of the collective choice decisions. In the flexible, quasi-property, licensed approach, the holders of the licenses (quasi-owners of the spectrum) would decide who is allowed to use the rights, presumably in a market.

Interestingly, the leading advocates of the quasi-property approach envision a classically American approach to the enclosure of a commons – a land rush – for the launch of this new governance regime in the spectrum.[20] They advocate a huge **auction** of spectrum at a particular moment in time (a big bang). In their view, the land rush would lower the cost of acquiring spectrum and undercut the possibility that market power (hording) could be exercised. The winners of the land grab would then negotiate usage rights. The land grab does not solve the definitional problem of what the property right is or the technological challenges to dynamic use of the spectrum; it just assumes that economically motivated actors would defend their property and/or that the government would help sort it out.

The second area where collective choice might shift out of Congressional/FCC control is where industry **standard setting** bodies would be used to set the operational rules. The possibility of self-organizing standard setting bodies to provide an arena for choice has been furthered by the success of WiFi, which rests on a series of 802.xx standards. It seems likely that whatever the mix of the quasi-property and commons approaches is used for spectrum going forward, standard setting will play an important role.

It is useful to see the choice between a flexible, licensed regime and an unlicensed, commons regime, as well as the choice between a regulatory body and an industry standard setting body, as decisions at the collective choice level because neither solves any operational problems. These are decisions about who decides operational rules and how they are chosen, not what the content of those rules will be.

Neither the constitutional nor collective choice issues were very prominent at the conference and the property v. commons debate takes place elsewhere. However, a small number of papers were devoted to developing the pricing regime that would allocate the rights to use spectrum in **secondary markets** after it had been transformed within a flexible, quasi-property, licensed context. In contrast, a great deal of attention was focused on the goal set issue, as I have defined it.

UNDERUTILIZATION OF THE SPECTRUM

The weaknesses of the regime of service specific, exclusive licenses have been recognized for decades.[21] The assignment of licenses dedicated for specific uses of frequencies in the spectrum was always an intense political process, but the advent of multiple uses of the spectrum – one-way broadcast versus two-way communications, for example – compounded the problem. The progress of technology makes the problem more pressing by adding new uses like high-speed data and new capabilities to pursue new governance regimes. Not only is the spectrum being used for the wrong things, but also vast quantities of it are not being used at all because the licensing regime will not allow them to be. The governance regime that was the solution to the problem in the earlier age of analog technology has become the cause of the problem in the age of digital technology.

That the spectrum is **underutilized**, given the current state of technology, is quite evident. All of the studies included in Exhibit 6 rely on actual measurements of the occupancy of spectrum. Even in the most densely populated urban areas of the nation most analyses show that well over half the spectrum is not being used. These “white spaces” represent an opportunity to communicate over spectrum that is being wasted.

IMPROVING THE UTILIZATION OF THE SPECTRUM

Two avenues of reform immediately present themselves, as noted above. As we move forward in this debate, it is critically important to understand that the comparison is not between an idealized, but fictional, set of perfectly defined property rights and a historical, command and control regulator, demonized for its rigidity and disregard for economic efficiency. It is inherent in the nature of spectrum that rights of use will be muddled and complex because interference is difficult to define and measure. Property rights will be ill-defined. Opportunities to share are dynamic, complex, and valuable. The debate is between imperfect exclusion rules and imperfect inclusion rules.

Above all, it is also critical to recognize that both the licensed and unlicensed approaches to spectrum will require rules. **Rights of access**, whether they are property or commons-based, are socially defined. A rule that excludes may be simple, but it is in some sense far more heavy handed than a more complex rule that includes, subject to constraints. More importantly, radio and computer technology have developed to the point that intelligent, cognitive, smart, agile radios, make it highly likely that simplistic and broad exclusionary rules will be less efficient than well-crafted inclusionary rules.

Needless to say, simplistic, broad exclusionary rules are vastly inferior to well-crafted inclusionary rules from a **First Amendment**, free speech perspective. The aspiration for speech, laid out by the Supreme Court, is “the widest possible dissemination of information from diverse and antagonistic sources.” The traditional standard in First Amendment jurisprudence, that government use the least intrusive rules possible when regulating speech for legitimate public purposes, cuts strongly in favor of sharing.

Exhibit 6: Issue Addressed In The Dynamic Spectrum Proceedings

ISSUE AREA	PAPERS BY TRACK AND NUMBER
Constitutional Collective Choice	Property, PT2-5; Commons: PT1-1, PT1-3, Standards, PT1-3, TT3-2
Goal Set	
Current inefficiency	Empirical measurements: GS4-4, SP1-1, SP1-8, TT2-1, TT2-7, TT2-7, TT3-1, TT3-5, TT4-7, TT5-8
Alternative Advantage	GS1-2, PT1-1, PT1-3, TT1-4, SP1-6
Technical Feasibility	GS1-2, GS1-4, PT1-1, PT1-5, SP1-3, SP1-4, SP1-9, SP1-11, SP1-12, SP1-18, 1P1-19, SP1-20, SP1-27, SP1-30, TT1-5, TT22, TT2-3, TT1-4, TT2-4, TT2-5, TT2-6, TT2-7, T3-1, TT3-2, TT3-4, TT3-6, TTT3-7, TT4-1, TT4-2, TT4-3, TT5-1, TT5-2, TT5-4, TT5-6, TT5-8, Cellular/Central server: SP1-22, SP1-24, SP1-28, TT4-6, TT4-7, PT1-2
Operational Rules	
Positions/Boundary	GS2-1, PT1-3, PT3-3, TT1-6
Scope	GS1-3, GS2-1, PT1-3, PT3-1, TT1-5, Property: PT2-4, PT2-5, PT3-3, SP1-13,
Authority	PT1-3, SP1-1, SP1-3, TT4-6, TT5-3,
Aggregation	GS1-5, GS1-5, GS2-2, PT1-3, SP1-1, SP1-18, TT2-3, TT2-4, TT2-7, TT2-8, TT3-2, TT3-3, TT4-3, TT4-4, TT4-5, TT5-4
Payoff	PT1-3, Pricing: PT2-3, PT2-4, PT2-5, PT3-1, PT3-2, SP1-26 TT1-1, TT1-2, TT1-3, TT1-5, TT3-3
Information	PT1-3, SP1-13, TT1-2, TT1-3, TT1-6, TT2-4, TT2-5

References are keyed to citations in the bibliography

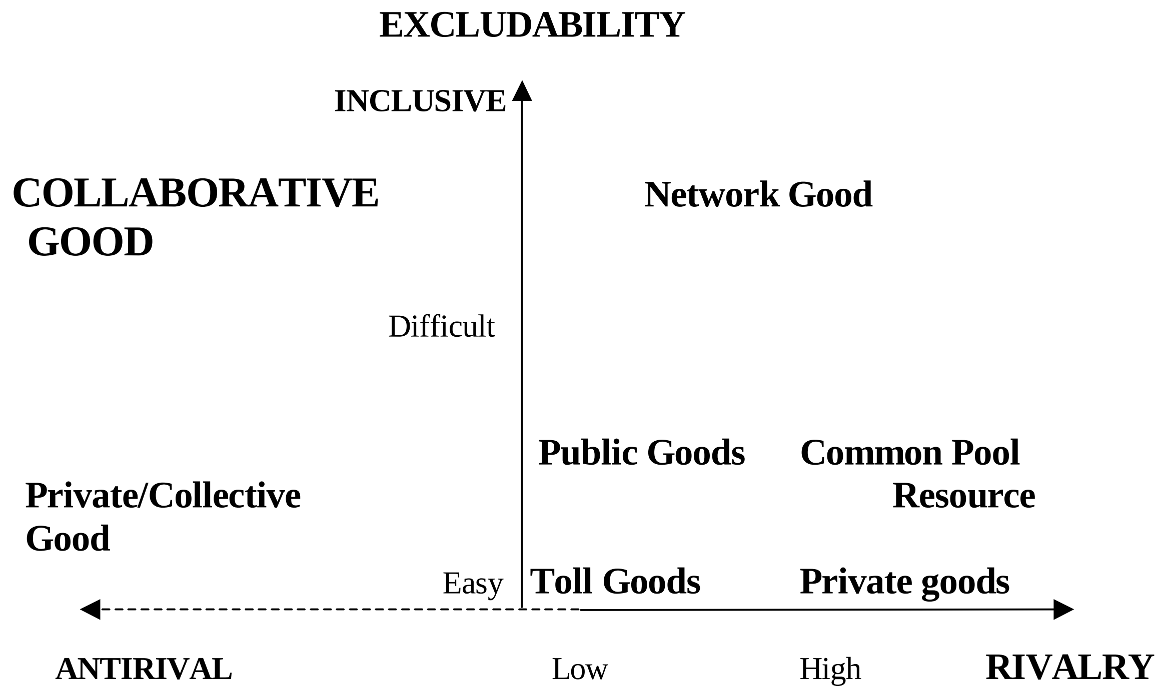
Efficiency arguments for sharing a significant part of the spectrum fall into three categories, beyond the simple fact that spectrum is underutilized today.

Many have argued,[22] as I did in my paper at the conference, that **collaborative production** of communications in the spectrum commons creates unique economic value and opportunities that cannot be achieved in a licensed approach.

> The benefits scale much more rapidly in a community. Moreover, the capacity of the system scales well. Production expands dramatically because there is greater value and more capacity. The impact of these two characteristics has a dramatic effect on the economics. Benefits that can only be captured in the collaborative approach are substantial.[23]

I have carried the argument a step further, suggesting that the spectrum is a unique resource that extends the characteristics of subtractibility and excludability to create a new type of good (see Exhibit 7).

Exhibit 7: Extending the Dimension for Defining Types Of Goods



A **collaborative good** exhibits *antirivalry* and *inclusiveness*. These increase value to the group through positive network externalities and motivate individuals, who capture non-rivalrous benefits, to voluntarily participate. In the world of collaborative goods, the challenge is to understand the willingness of producers to support or freely reveal innovations that enhance shared benefits, even though they do not appear to capture as much private value as they could by withholding.

The key is to recognize the large positive externalities associated with collaborative production. Free revealers recognize that the potential gains of opportunistic behavior will evaporate if the cooperative behavior breaks down. Cooperation becomes the rule, rather than the exception.[24]

In the digital age, as depicted in Exhibit 7, we observe new characteristics of goods that generate very high rewards for cooperation and sharing. Networks thrive when they are inclusive. Technology advances rapidly when access to ideas is facilitated. Over a significant range, participating in a common-pool resource management regime for this type of good is not a zero sum game.

The other claims of economic benefit from a substantial reliance on unlicensed spectrum are more traditional.

Having different institutional approaches allows a better fit between supply and demand.

> Spectrum used by cognitive radio networks will most likely be a combination of exclusively accessed spectrum and unlicensed/open spectrum. The exclusively used spectrum allows guaranteeing the customer a minimum level of QoS. The shared spectrum enables an extension of network capacity to provide more services and to increase the number of served customers.[25]

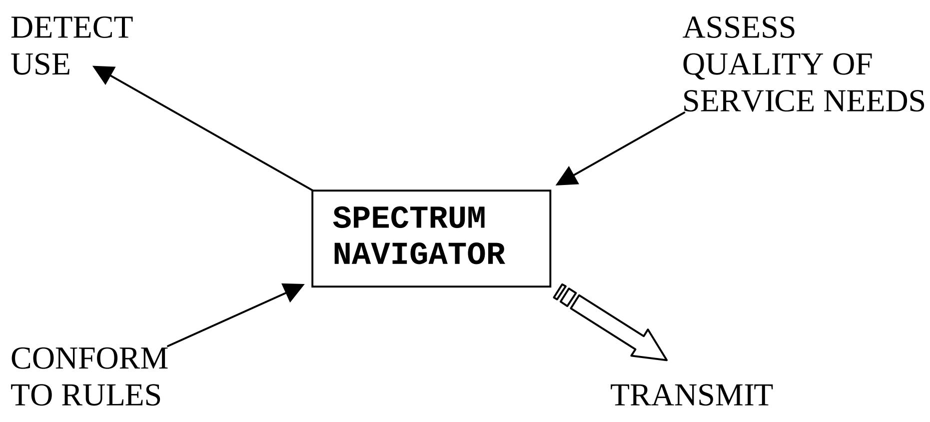
A substantial unlicensed space also provides an important check on the potential for a licensed space to fall victim to market power abuse if it is transformed into a flexible, quasi-property regime.

> If secondary markets are not efficient either because of market power or because of high transaction costs (thin markets, information asymmetries, regulatory costs), then the price for licensed spectrum may be substantially above the economic value of the spectrum. The existence of unlicensed spectrum provides a safety valve and check to help keep the prices for licensed spectrum in line with the scarcity value of spectrum.[26]

TECHNICAL FEASIBILITY

In order to exploit the opportunity of unutilized spectrum and to maximize use of the spectrum in a dynamic manner, one must build a network of smart transmitters and receivers that are agile and aware of their environment. The **nodes** in the network (transmitters and/or receivers) must be able to perform a set of functions. There are four basic functions that the radio will have to perform (see Exhibit 8).

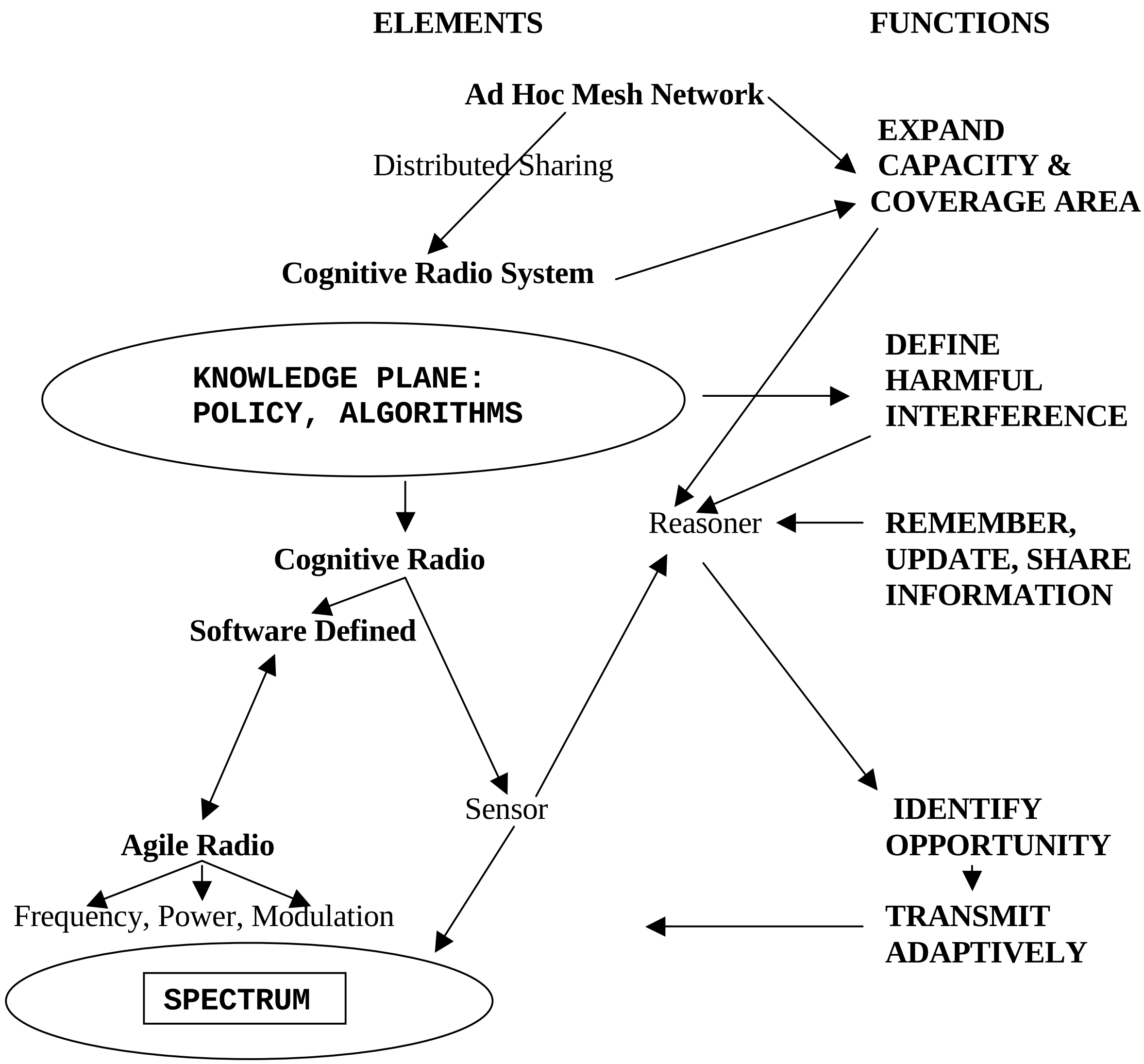
Exhibit 8: The Demands On Cognitive Radios



The radio will have to detect use of the spectrum, assess the quality of service it needs for its own transmission, and ascertain whether transmitting in the space in that manner can be accomplished in conformance with the established rules of non-interference. Simply put, the radio asks itself one question: **" is there a way (time, frequency, power) that I can transmit a signal that meets the needs of the user without interfering with other users?"** If yes, then I transmit.

The different adjectives applied to emerging radio technology can be defined in terms of those functions. "The elements that make a radio cognitive (from a spectrum utilization perspective) are the ones that identify, remember, update, share opportunity information, and exploit the opportunity information with adapted transmission to avoid causing harmful interference.[27] Exhibit 9 elaborates on Exhibit 8. Starting from the bottom left and working to the top right, each of the concepts subsumes the one below as a complex network is constructed.

Exhibit 9: Network Elements



An agile radio is a software-defined radio, one that can change its use of frequencies, power, and modulation without changing its hardware. In this sense, it is agile – as it can move around the spectrum. Frequency agile radios are a subset of the broader category, which can be agile in other dimensions (power and perhaps wave form). An agile, software defined radio is the basic building block of the new communications network.

Adding sensors and a reasoning system to an agile radio gives us a cognitive, intelligent, or smart radio.[28] Cognitive radios are aware. They sense the network and store the rules of the road. Embedded logical systems allow them to decide when to transmit without breaking the law.

Cognitive radios can be combined into systems. The cognitive system adds a layer of intelligence to the communications network by looking at the overall topography of the network.

A meshed wireless network integrates cognitive radios as access points and relay nodes (repeaters) in a unique architecture for spectrum use. It treats cognitive radios as an asset that can be used to support any communication, not just the ones in which the radio is the origin or the final destination of the message.

An ad hoc network allows radios to join and leave the network as they desire. The network is designed to adapt to the nodes that are available. The ad hoc, mesh network architecture brings new capabilities because it is not only "a form of self-configuring wireless networking in which connections are transient and formed in an ad hoc as-needed basis," but it also enables "self-healing networking in which routing continues in the face of broken nodes or connections."[29] When we rise to the level of cognitive radio systems in ad hoc mesh networks, the fundamental nature of the undertaking changes. This dynamic space bears little resemblance to the spectrum facility as it existed throughout most of the twentieth century. Several authors liken this architecture to the Internet based on an end-to-end architecture.[30] It should be recognized that this very different vision creates new challenges. Complexity increases, certification of equipment and software becomes more difficult, and monitoring behavior to enforce rules becomes harder.

It is interesting to note that one of the institutions most active in developing the intellectual basis for building these networks is none other than the Defense Advanced Research Projects Agency (**DARPA**), the same agency that took the lead role in developing the Internet protocols. This involvement follows a similar purpose as DARPA's earlier motivation. The goal is a more robust, survivable communications network. This should serve to remind us that the value of such a network can be measured in different terms than maximizing the utilization of spectrum or the revenue of service providers. Military and public safety users can value mesh networks for a different reason.

> Since both military and emergency situations are difficult to anticipate and dynamic in nature, a radio network that has the ability to design its own optimal and adaptable configuration on demand possesses clear advantages over traditional systems. In addition, cognitive radios are able to operate in and adapt to jamming and interference, ensuring quality of service is maintained…
>
> The importance of quality of service guarantees to consumer markets is undeniable, but the purpose is different. Instead of providing reliable and robust communications as

required by military and public safety users, cognitive radios allow consumers to trade resources for desired needs of their applications.[31]

OPERATIONAL RULES

It is also important to recognize that each of the elements in this complex network – agile radios, smart radios, cognitive radios, sensors and reasoners – can be combined in different architectures. Wireless providers using smart radios can improve the utilization of their licensed slice of the spectrum just as unlicensed networks can. The technical papers that dominated at the conference describe a variety of approaches to building hardware and writing the software that will constitute the new spectrum regime. This suggests that it is far too early to pick a winner. Indeed, it would probably be a grave mistake to do so at any point in time.

The goal of public policy should be to define the minimum set of rules necessary to accomplish the goal – **non-interference** – and encourage multiple approaches.

- This will have the effect of preserving the environment for **innovation**.
- It will also allow the **heterogeneity** of needs to map onto the capabilities of diverse technologies.
- It preserves the greatest **freedom** for individual action in the commons.

Exhibit 2 above summarizes my reading of the record on the "best" set of operational rules for the new spectrum governance regime. The proposal can be described as a "balanced licensed-open spectrum" approach. It is "balanced" in several respects.

- It includes both flexible licenses and unlicensed users.
- It envisions dedicated licensed spaces, shared spaces, and dedicated unlicensed spaces.
- It envisions significant quantities of spectrum at a range of frequencies available to both licensed and unlicensed users.
- It protects licensed users rights, but demands their cooperation with the sharing regime.
- It allows unlicensed users, but disciplines them with rules for non-interference and enforcement.

POSITIONS/BOUNDARIES

The discussion of the goal set identifies three positions in the new spectrum management regime – **licensed broadcasters, unlicensed users and the regulator**. Licenses will be renewed administratively or auctioned. Unlicensed hardware will be certified. While these have been traditional functions of the regulator, evaluating software functionality is a new activity and will be more difficult. The software will have to be able to demonstrate that it can comply with operational rules. Modification of software, after it is certified, is a concern, but monitoring and enforcement should catch rule violators.

A flexible license approach would allow the licensees to have flexibility in how the spectrum is used. They could do other things in the white spaces, or rent the rights to do so to others. In the commons approach, at a minimum, users would be able to fill the white spaces without permission from the licensee. In a more aggressive change, unused parts of the spectrum might be removed from the licensing regime altogether and dedicated to unlicensed users.

Scope

Given the current state of technology and policy, the licensed users will be treated as *prima donnas,* but that does not mean they are allowed to act like *prima donnas,* nor does it mean that their elevated position will be permanent. Most discussions refer to licensed users as the primary users (the Latin root *primus* for first) that define the space for unlicensed uses (which are referred to as secondary) by identifying the goal of avoiding harmful interference.

The nature of the interference that is considered harmful should be reasonably defined. The primary users should still be required to cooperate and collaborate in implementing the system that uses spectrum as efficiently as possible. The licensed *prima donnas* should certainly not be allowed to make life unnecessarily difficult for unlicensed, secondary users.

To the extent we must live in a mixed, licensed/unlicensed network, we must solve the problem of defining exclusive use rights and the problem of sharing the unlicensed spectrum, where it is feasible. The former is necessary to tell us what parts of the spectrum can be used by multiple transmitters, the latter is necessary to ensure we do a good job of exploiting the unlicensed space. Moreover, to the extent we must live in a mixed space, good rules matter a great deal because the agile radio systems perform better when more spectrum is available.[32]

It may be that certain uses will require licenses indefinitely because of quality of service needs. Such a claim will be sustainable only if the quality of service demanded exceeds what a shared, unlicensed regime can deliver and if the value of the unlicensed service exceeds the value of the licensed services that could occupy the same spectrum. Over time, we might expect the space set aside for licenses to shrink as technological progress and regulatory experience allow primary users to better accommodate sharing.

Optimizing output is more complex than just maximizing the use of spectrum. There is a trade-off between the **administrative cost** – measured in both communications and computational complexity – and the amount of spectrum available.[33] Perfect utilization is not possible, in reality, since complexity overwhelms computational rules very quickly. It turns out that a small number of simple rules can realize a great deal of efficiency improvements at what appears to be relatively low administrative cost.

The critical challenge in defining scope is to define harmful interference. The cornerstone of rights rests on the observation that "it is impossible to stop all of these unwanted signals. An absolute interference ban in a band is impossible. Therefore, wireless receivers are designed to accommodate a certain level of interference."[34] Interference must be analyzed with reference to both the licensed receiver and the unlicensed device with predictive models. If the models show interference, then the parameters can be adjusted by changing the unlicensed device rules (so they no longer interfere), redefining interference (i.e. because there will not actually be an outage), or the rules for licensed use (so they can tolerate more interference).

There are certainly challenges, and pitfalls to be avoided.

- The existence of worst –case scenarios should not be allowed to prevent the new governance regime from being implemented. "Licensed devices always have the potential of degraded performance from unlicensed devices. Yet, in practice most licensed devices work well. This suggests that the harmful interference of unlicensed devices should be measured according to their impact in practice…a receiver device interference model is inappropriate."[35]

- The existence of bad actors should not be allowed to undermine the new governance regime; "it should be emphasized, that harmful interference caused by devices that are not following the rules has a clear remedy which is for the device to cease operation."[36]

AUTHORITY

The basic definitions of authorities were specified in the positions of primary and secondary users. The authority to use the spectrum is specific to the availability of channels. To avoid interference one must only use channels that are unoccupied, or, if they are occupied, they must be used by secondary transmitters at levels of power that do not interfere with other users. Channels exist at specific frequencies, and are available in specific places at specific times. Depending on the primary users and the definition of harmful interference, power differentiation may also be used to define an available space.

> [P]rotocols for the selection, adjustment, and adaptation of transmission parameters for sessions in dynamic spectrum access networks… respond to time and frequency assignments that are provided for a session by a spectrum access system, select the modulation format and the initial code rate for the session, adjust the initial transmitter power to compensate for any errors in propagation-loss estimates, and adapt the code rate through-out the session to variations in the propagation loss.[37]
>
> In summary, distance has a significant impact on the spatial correlation on channel availability between secondary users.
>
> Temporal properties of secondaries depend on the activity pattern of primaries.[38]

There is also a set of discussions about rules that determine how quickly transmitters must respond to changes in the environment and whether certain primary users (e.g. public safety) can activate "kill codes" should the need arise to reallocate the spectrum to them. These are parameters that can be set by policy and then embedded in the rules of the road.

When considering the scope of acceptable outcomes it is important to recognize that the amount of spectrum made available for sharing is extremely important. "With more spectrum available to opportunistic sharing, wireless and ad hoc networks will perform better and become a more viable technology."[39] "Heterogeneity in channel availability and footprints are shown to be beneficial."[40]

Aggregation

Different views of the protocols to implement sharing of spectrum can be taken. The key difference in implementation methods has to do with the nature of interaction. At one end we have **group-centric** cooperation, which requires a great deal of information exchange and communication. Independent strategic games involve individual radios sensing the behavior of others and acting to maximize their utility, without exchanging information or negotiating use. **Device-centric** behavior embeds a series of rules in the devices and dictates utilization according to those rules (radios do not choose strategies).

These analyses, which are in their early phase, have successfully simulated various strategy games and policy responses (see Exhibit 10).

Exhibit 10: Coping With Strategic Actors By Imposing Behavioral Rules

Game Strategies Analyzed from Most to Least Cooperative

- Cooperate
- Forgive Occasionally
- Segregate
- Defect
- Tit-for-tat
- Exploit passives
- No regrets
- Go Nuclear

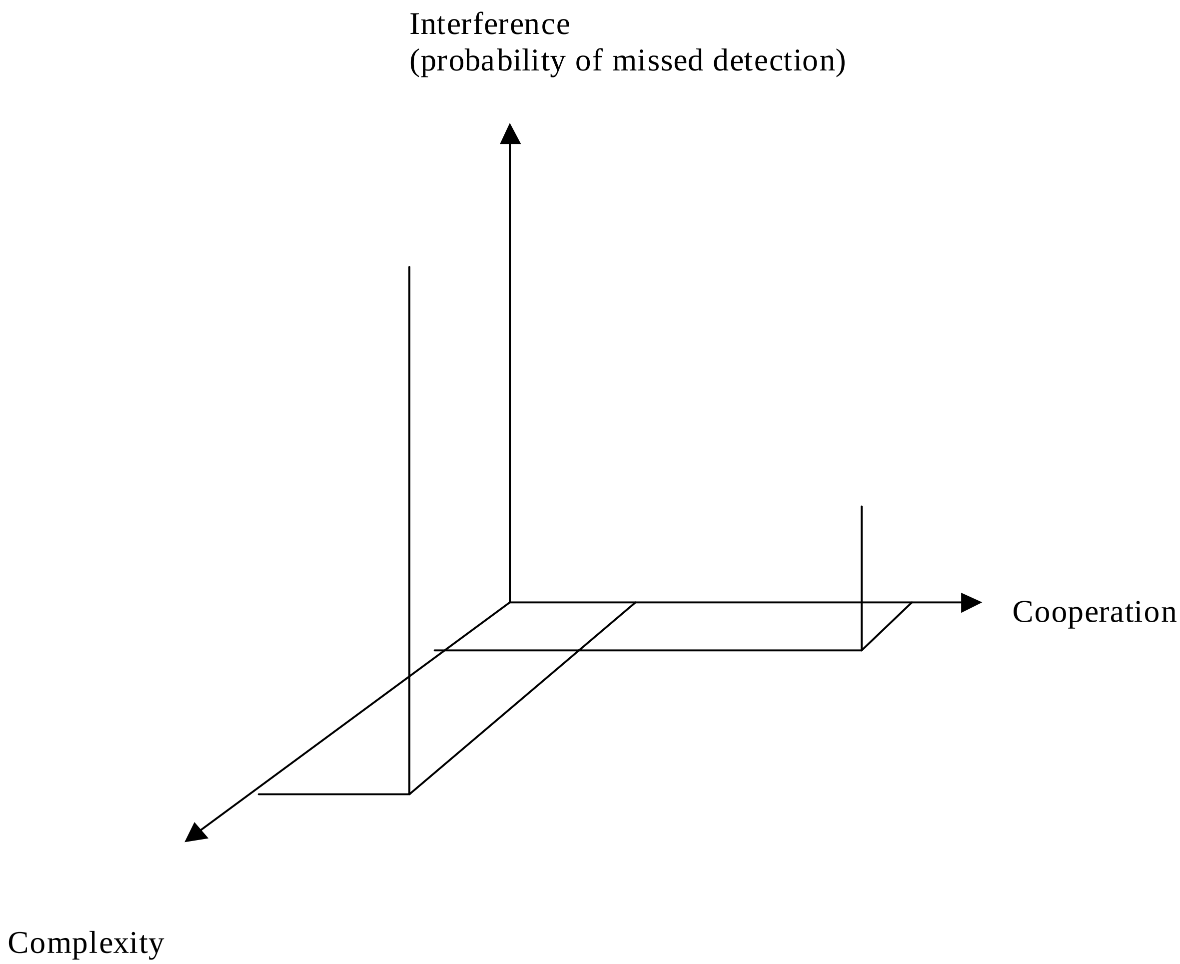
Rules from Least to Most Efficient

- Uniform use
- Uniform Idle Preference
- Minimum rate
- Proportional fairness
- Poverty line
- Poverty Guided Idle Preference
- Min-Max
- Selfish Spectrum Contention.
- Poverty Guided Selfish Spectrum Contention.

Although a few papers present solutions that assume little cooperation and information sharing,[41] the predominant opinion is that information sharing and cooperation will greatly improve the management of the spectrum commons (see Exhibit 11).

> Measured data clearly indicate the need for cooperation among cognitive radios for opportunistic spectrum usage in order to minimize both the probability of missed detection and the interference experience by non-cooperative users.[42]

Exhibit 11: Cooperation Reduces Complexity and Improves Performance



> Collaboration among nodes leads to more efficient spectrum utilization from a system-level point of view, and decreases the computational complexity of detection algorithms at the individual node-level. [43]

The key to sharing of spectrum is coordination between devices. This coordination rests on communications.

> Requiring every potential transmitter also to have a receiver capability creates the potential for a feedback control loop that would allow the transmitter's behavior to be modified. Since the transmitters are the source of the signal that created the possibility for interference, regulating their operation is an essential element in effective interference management.[44]

> Group-based coordination allows collaborations and fast information dissemination among users. In particular, it provides a simple and energy efficient procedure to broadcast route discovery message.[45]

This cooperation also generally entails some collective investment. This investment is both **centralized** – databases and beacons – and **decentralized** – sensors and software in devices – to generate, access and respond to information about the state of use of the spectrum.

> The area beacons appear to be the most reliable approach. The installation of the database and beacon transmitters would require a national investment. If these transmitters utilize existing radio towers and facilities, they will not be expensive to install and operate relative to the bandwidth resources they open up.[46]
>
> Efficient spectrum sharing among secondary users is integral to the success of open spectrum systems. Traditional approaches relying on a central server to observe and perform network-wide spectrum assignment is clearly inefficient for dynamic multi-hop networks. Instead, these network require a decentralized access model, where users access spectrum based on locally observed availability. In this model, users must coordinate amongst themselves to optimize system performance and exploit the benefit of open spectrum systems.
>
> Effective and efficient coordination depends on fast dissemination of control traffic between neighboring users. Traditional coordination uses a common control channel known to all users. However, secondary users in open spectrum systems observe *spectrum heterogeneity*, spectrum availability that fluctuates over time and location. No common channels exist … an alternative *distributed coordination* scheme addresses spectrum heterogeneity. Users in our approach self-organize into groups and coordinate using locally available common channels.[47]

In this context, there are specific lessons to be learned from the study of past common pool resource management regimes. The salutary effects of communications-rich environments in which information is freely exchanged are clear. The exchange of information facilitates the perception and understanding of shared benefits. By creating transparency of behaviors, especially in repeated interactions, the basis for reciprocity and trust can be laid. When this is reinforced with authoritative monitoring and sanctioning, a powerful force for disciplining behavior is created.

PAYOFF

Little attention was devoted to **pay-off rules**, except for a number of papers that considered how the secondary markets in the licensed space might work. Since most of the investment in an unlicensed space is made by the individuals who own the devices, as opposed to companies that operate the networks, most of the costs of meeting the requirements of a commons regime are internalized by the individual users.

Therefore, the pay-off rules must focus on the social actions that are necessary to maintain the governance regime. Incentives to cooperate and reward repeating might take a monetary form or they could take the form of preferential treatment in the rules. To the extent that there are collective investments necessary – beacons or database management – all users should contribute.

In thinking about **penalty structures** for rules violations, it is worth noting that "self-organizing" common-pool resource regimes tend to escalate sanctions slowly and rely on norms, while avoiding going nuclear.

Information

Much of the information requirement has been described in the previous discussion. Cognitive radios must keep up with the rules and ensure that they are making decisions based on the most current set of requirements. They must constantly monitor spectrum use, if they intend to transmit. They must check databases to identify the primary users. The regulator will have to maintain the database and monitor the state of the spectrum.

The schedule for updating and monitoring the status of the spectral environment will be set by the decisions about the rules of the road. The monitoring interval will have to be set to reflect the temporal needs of the most sensitive primary users, or set to respond to a situational signal that requires updating.

CONCLUSION

This analysis has endeavored to describe the nature of the potential transformation of spectrum policy made possible by the dramatic changes in technology that have taken place in the past several decades. It has used a framework for the analysis of common-pool resources to argue that an unlicensed approach will provide greater economic and political benefits. Two extremely important keys to the emergence of common-pool resource governance regimes that prevent the tragedy of the commons are communications and the flow of information. The ability of cognitive radios in ad hoc mesh networks to generate and process information and communicate it to the actors in the network is huge. The ability to embed the cognition necessary has been created by digital technology.

ENDNOTES

[1] Lehr and Cowcroft (PT1-3), p. 432.
[2] Berleman, Mangold and Walke (SG1-1), p. 1.
[3] Coase, R.H., *The Federal Communications Commission*, Journal of Law and Economics, 2: 1959.
[4] Hatfield and Weiser (GS2-1), p. 43.
[5] (Ann Arbor: University of Michigan Press, 1994).
[6] Ostrom, p. 6.
[7] Ostrom, p. 15.
[8] Ostron, p. 15.
[9] Ostrom, p. 15.
[10] Ostrom, bookjacket.
[11] Ostrom, p. 41-42.
[12] Ostrom, p. 327.
[13] Ostrom, p. 8.
[14] Stine (TT3-2), pp. 184-185:

> Spectrum is a renewable resource that is finite in any instant of time but through its different dimension of use; space, time, frequency and bandwidth, can be distributed to many users simultaneously. The process of distributing spectrum to users is spectrum management. Traditionally this function has been performed globally through international agreement and nationally by government administrations. Bands of spectrum are divided into allocations that are designated to support particular services. The allocations are subdivided to into allotments that may be used by administrations in specified geographic areas. National administrations may further allot the spectrum into channels, specify the conditions of their use and assign (a.k.a license) them to users. Historically the growth in spectrum requirements was accommodated through technology making the higher frequency band available to use. Little unassigned spectrum remains and so now spectrum management is the business of reallocating, re-allotting, and reassigning spectrum.

[15] Reed,presentation at [PT1-3).
[16] Ostrom, p. 41.
[17] Ostrom, p. 320-321.
[18] Ostrom P. 220.
[19] Ostrom, p. 296
[20] Kwerel, Evan and John Williams, *A Proposal for a Rapid Transition to Market Allocation of Spectru,* (Federal Communications Commission, OSP Working Paper Series, NO. 38, 2002).
[21] Cooper (PT1-1); Ercole (PT2-5).
[22] Reed, panel presentation
[23] Cooper (PT1-1), p. 394.
[24] Cooper (PT1-1), p. 385.
[25] Berleman (GS1-2), p. 2.
[26] Lher and Crowcroft (PT1-3), p. 423.
[27] Degroot, et al. (FT1-3), p. 556.
[28] Berlemn Mangold and Walke (SG1-1), p. 3.
Cognitive Radio Systems are a logical generalization of cognitive radios. The extension of the focue from the individual cognitive radio to a cognitive radio network aims at the improvement of spectrum utilization through spectrum reuse. Also, the coverage area can be increased through when a meshed wireless backbone of insradtructure links is established based on *Cognitive Access Points* and *Cognitive Relay Nodes*.
A cognitive radio is typically built on a software defined radio and can be defined as a wireless communications system that is aware of its environment. The reasoner makes the actual decisions on how to share spectrum. A reasoner is a software process tha uses a logical system to infer conclusions from logical assertions.
[29] Giacomoni and Sicker (PT3-3), p. 526.
[30] Berleman (GS1-2); Thomas, Dasilva and Mackenzie (TT5-6); Stine (TT3-2);

[31] Ball, Ferguson and Rondeua (PT3-2).
[32] Menon, Buehrer, and Reed. (TT1-5).
[33] Brown (GS1-3).
[34] Brown (GS1-3), p. 12.
[35] Brown (GS1-3), p. 15.
[36] Brown (Gs1-3), p. 14.
[37] Pursley, Royster and Skinner (SP1-19), p. 649.
[38] Ma, Han and Shen, (TT3-4), pp. 220-221.
[39] Ma, Han, and Shen (TT3-4), p. 203.
[40] Liu and Wang (TT3-5), p. 214.
[41] Etkin, Parekh and Tse (TT4-3).
[42] Oliveri, et al. (TT2-8), p. 178.
[43] Visotsky, Kuffner and Pterson ((TT%-4), p. 338.
[44] Lehr and Crowcroft (PT1-3), p . 434.
[45] Hao, Zheng and Yang (TT4-4), p. 267.
[46] Brown (GS1-3), p. 25.
[47] Xhao, Zheng and Yang (TT4-4), p. 259.

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GS2-1	Hatfield, D.. and P.J. Weiser	Property Rights in Spectrum: Taking the Next Steps
GS2-2	Zheng, H and L Cao,	Device-Centric Spectrum Management
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TT1-3	Huang, J., R.A. Berry and M.L Honig	Spectrum Sharing with Distributed Interference Compensation
TT1-4	Laufer, A. A. Leshem and Bar-Ilang	Distributed Coordination of Spectrum and the Prisoners Dilemma
TT1-5	Menon, R. R.M. Buehrer and J. H. Reed	Outage Probability based Comparison of Underlay and Overlay Spectrum Sharing Techniques
TT1-6	Raman, C., R.D. Yates and N.B. Mandayam	Scheduling Variable Rate Links via a Spectrum Server
TT2-1	Roger, A.E. et al.	Interference Temperature Measurement from 70 to 1500 MHz in Suburban and Rural
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TT2-3	Ghasemi, A and E.S. Sousa	Collaborative Spectrum Sensing for Opportunistic Access in Fading Environments
TT2-4	Gansen, G. and Y.G. Li	Cooperative Spectrum Sensing in Cognitive Radio Networks
TT2-5	Fehske, A.., J. D. Gaeddert and J.H. Reed	A New Approach to Signal Classification Using Spectrum Correlation and Neural Networks
TT2-6	Tang, H.	Some Physical Layer Issues of Wide-band Cognitive Radio Systems
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