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Deploying Cognitive Radio: Economic, Legal and Policy Issues

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Over the past decade, the demand by commercial, military and consumers for use of the electromagnetic spectrum has literally exploded. The most obvious examples are digital cellular telephony and WiFi, both of which have become ubiquitous in developed and less developed countries around the world within a very short time. And there is no indication that this growth in spectrum-dependent technology will abate soon. Tracking devices, machines that can "talk" to one another, exchanging information, are being deployed as we speak.

Unfortunately, the systems we use in the U.S. and worldwide to allocate and manage spectrum is bending under the strain these demands place on the system. Government allocation of spectrum, either by "beauty contests" (traditional) or auction (more recent) has failed to keep up with the growth in demand. Even worse, government allocation has led to an extraordinarily inefficient use of this valuable resource. Large swathes of spectrum are underutilized and beyond our reach even while the demand for wireless voice and data services strains existing wireless providers beyond their capacity.

Why, in fact, does the government allocate spectrum, and how does it do it? Government allocation is the 1927 solution to the problem of *interference*, instituted by the Federal Radio Act of that year, granting the Federal government the sole right to issue licenses to radio emitters. Interference can occur at a radio receiver when there is a sufficiently powerful undesired signal on or near the frequency of the signal being received. Severe interference can render the desired signal unusable.[1] The solution was to "allocate" different frequencies to different uses and impose technical rules (power limits, modulation type, etc.) designed to prevent interference. In some cases, users were required to share frequencies and to coordinate to prevent interference. A "listen before talk" etiquette is an example of such coordination.

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[1] Of course, a more sophisticated receiver can possess additional interference rejection capabilities, enabling it to sort out the desired signal from the interfering one, so interference and its mitigation is as much about receivers as it is about transmitters.

As a consequence, the Federal Communications Commission (FCC), the U.S. spectrum allocator for non-Federal uses from 1934 to the present, has tightly limited the use to which the spectrum can be put. An FM radio license cannot be used for taxi dispatch or a police radio, nor can a TV license be used for cellular telephony operation. In this way, interference has been avoided (or at least mitigated) by narrowly specifying permissible use and technology.

Over time, consumer demand has changed and technology has changed, rendering legacy allocations obsolete but difficult to change. For example, VHF TV channel allocations, originally determined in 1947, were built around the technical characteristics of TV broadcasting at that time: each channel was 6 MHz wide, and since out-of-band interference was a problem, "guard" channels were allocated between each usable channel. Today's technology of digital TV transmission is vastly more efficient in its spectrum use, so much less spectrum could carry the same information. But licensees are fiercely protective of "their" licensed spectrum.[2] So the great inefficiencies in spectrum continue to use grow as demand grows and we are unable to unlock the very substantial amount of underutilized spectrum.

The regime in which spectrum is allocated by frequency/location/power to specific users can be thought of as a *static control method* ("open loop control") for solving the interference problem. Radios for specific uses were engineered specifically for the frequency/location/power associated with the FCC licenses and so avoided interference, thanks to this static control method, but with the inefficiencies cited above.

Recent advances in radio technology, however, promise a way out. Radios that can sense their environment, including spectrum use and the presence of other such radios and then adapt their transmission/reception to avoid interference could implement a *dynamic control method* ("closed loop control") for solving the interference problem. Such radios, called *cognitive radios* by Mitola (2000), and Mitola and Maguire (1999, pp. 13-16), promise to vastly increase the efficiency of spectrum use through dynamic real-time control of interference instead of the current static licensing regime.[3] This promise is eloquently described in Rubenstein's "Radio Gets Smart" (2007, pp. 46-50).

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[2] One might think that the FCC could simply take back this spectrum at the license expiration and re-allocate it more efficiently. One might think, but one might be wrong. Any suggestion that a license might be taken away results in licensees up in arms, calling on Congress to protect "their" spectrum against meddlesome regulators. Licensees have shown themselves adept at forming effective lobbying groups to ensure their continued hold on their licenses.

[3] Virtually all engineering, law, and economic articles on cognitive radio begin exactly as this one: with a description of the huge inefficiencies of spectrum use that has resulted from FCC-allocated fixed spectrum licenses and the promise of cognitive radio to unleash underutilized spectrum. However, other means are also available to vastly increase spectrum utilization, such as the introduction of markets for licenses. This argument, with which this author agrees, is presented well in Hazlett, 2006, pp. 68-74. The two approaches (spectrum markets and cognitive radio) are not mutually exclusive.

This extraordinary potential of large increases in the efficiency of spectrum use is perhaps why *spectrum sensing cognitive radio* has been the focus of attention,[4] and will be the focus of this article as well. The FCC has issued a preliminary ruling on the use of cognitive radio and has hosted technical meetings on the topic, so apparently regulators are excited by the prospects of this technology to help. However, the deployment of cognitive radio presents some policy challenges to the current model of static allocations of spectrum frequencies. Enthusiasts claim that with the advent of cognitive radio, the entire process of licensing spectrum frequencies to specified users is now obsolete, and have proposed turning the entire radio spectrum into a commons, in which any user (with a cognitive radio) can use any part of the spectrum at any time, providing interference-avoiding protocols are observed by the cognitive transmitters/receivers. In the parlance of today's spectrum management, this proposal is tantamount to declaring all spectrum to be unlicensed, subject only to rules regarding interference-avoidance protocols. In this techno-utopian world, all radios are smart and everyone plays by the rules. The analogy to the Internet is often invoked: a standard set of protocols used by all and cooperating servers around the world that have brought so much value to us all.

An enticing vision, perhaps, but one not likely to be realized or even approximated in the foreseeable future. There are many applications for which dedicated spectrum are the perfect solution, such as airport radars and AM/FM radio broadcasting.[5] For these applications, cognitive radio is both costly and unnecessary; why require all radios in automobiles to have lots of intelligence when all the driver wants is to listen to her favorite all-news station?

It is likely that cognitive radio will have to exist in a world not unlike today's, in which there is both unlicensed and licensed spectrum, and cognitive radios will have to work within this paradigm. But to understand how cognitive radios could coexist in this mixed regime, it is necessary to understand two difficulties encountered in ensuring cognitive radios really can avoid interference: the *shadowing* problem and what I call the *power-mix* problem (Faulhaber, 2005).

Shadowing. The appealing feature of cognitive radio is that each radio is self-contained and can detect everything it needs to know to avoid interference on its own, presumably by "listening" to a frequency to determine if another transmitter is using that frequency ("listen before talk"). Unfortunately, this is not robust due to shadowing. Imagine two transmitters 1 and 2, each wishing to use the same frequency to reach a receiver A. Suppose further that the two transmitters are separated by a radio-opaque barrier, such as a mountain or large steel-framed building, so they are unable to detect the other's emissions. The potential receiver A is located at a location where it can detect transmissions from 1 and 2. If both 1 and 2 transmit on the same frequency (since they can't detect each other this may well occur) then A will be unable to separate the two signals, and simply receive noise. For obvious reasons, this is also called the *hidden terminal* (or *hidden node*) problem in the literature. The problem is well-

[4] As opposed to the more general *full cognitive radio* (Mitola radio) in which all possible environmental parameters are monitored and used.

[5] Applications which are high-powered and always-on are poor candidates for cognitive radio; it is more efficient for them to have a frequency dedicated to their use 24/7.

documented in the literature; see for example, A. Sahai, N. Hoven, and R. Tandra's, "Some fundamental limits on cognitive radio" (among many others).

This problem can be solved in several ways, each of which reduces the appeal of cognitive radio. One solution would be to maintain a ubiquitous network of detectors that can "hear" all frequencies at every location in the country (the world?); then each cognitive radio would consult the network operator to determine if transmission at a specific location on a specific frequency is non-interfering. Unfortunately, this results in the deployment of cognitive radio depending upon the prior deployment of such a network, presumably by the government or some industry body willing to accept both the cost and the risk of operating this network. Of course, spectrum resources would have to be committed to communicating with the network, somewhat vitiating the whole purpose of cognitive radio.

Another solution to shadowing would be to have nearby cognitive radios communicate with each other so that each can construct a composite view of the environment. This cooperative method avoids a ubiquitous network but requires 1) there is a sufficient density of cognitive radios in all areas that complete coverage can be assured; and 2) each cognitive radio owner is willing to use power and computational resources in her radio to facilitate other radios' connections with no direct benefit to her. Neither of these conditions is likely to be ubiquitous, indeed they may not hold at all. Cooperative solutions to the shadowing problem are problematic at best (Mishra, Sahai, & Brodersen, 2006).

Are cooperative solutions likely to be viable in practice? Cooperative networks of devices ("mesh" networks) are based upon the presence of a sufficient density of devices so that collectively they provide each other with the required information about the environment, including other transmitters that may be hidden from some devices in the network. In certain circumstances, such as urban or suburban areas, this may well be the case; in other circumstances, where the devices in question are mobile, it is certainly problematic. Even in the case where there is a sufficient density of devices to provide accurate and complete environmental sensing, devices are called upon to perform work for each other involving resource commitments of power and computation, which may not be in the short-term interest of any device owner. It is often assumed that since all device owners depend upon each other, they will have incentive to cooperate (the "golden rule" assumption). Game theory tells us that this is only true if the parties involved have long-term relationships that could be damaged by failure to cooperate. Groups of strangers who will remain anonymous and never meet again have no incentive to cooperate and are unlikely to do so absent some form of compulsion. Note, however, that device owners may be willing to supply resources to others for a payment, which is the usual form that encourages cooperation in economies. Actually levying and collecting such payments seems quite problematic for autonomous devices, however. In short, cooperative networks offer promise of helping solve the shadowing problem, but only under rather special circumstances.

Another possible solution to the shadowing problem is for the receiver who is subject to multiple signals simultaneously at the same frequency to broadcast "change frequency, please" to both transmitters, so that the transmitter required to yield in an interference situation knows to yield even if it cannot hear the hidden transmitter.

Power Mix. Many applications, particularly those using unlicensed spectrum, are inherently low power, such as WiFi, cordless telephones and baby monitors. Interference is controlled by ensuring power emission is low enough that nearby devices are unlikely to suffer interference. Cognitive radios are likely to be high powered devices;[6] can they coexist with low powered unlicensed devices such as WiFi? Again, consider the "listen before talk" protocol. A high-powered cognitive device (with a range of, say, 20 miles) listens for both high- and low-powered devices, such as WiFi (with a range of, perhaps, 100 ft.). The high-powered cognitive device certainly hears everything within a home/office, perhaps even low-powered devices in the next apartment. But it certainly doesn't hear low-powered devices a block away. This is precisely why we use low-powered devices, so we can't hear them a block away. So if the cognitive device hears nothing in, say, the 2.4 GHz band and concludes that transmitting is OK, it may interfere with a WiFi connection (or indeed several) a block or more away. It was unable to hear the low-powered devices, but those devices can surely hear a high-powered device transmitting on the 2.4 GHz frequency within 20 miles, and interference will result.

Again, the problem can be solved in several ways, each of which reduces the value of cognitive radio deployment. One solution is that the government or some other group maintains a ubiquitous sensing network which the cognitive device queries before transmission. In this case, the network must be extraordinarily ubiquitous with sensors next to every home and business so that low-powered devices everywhere can be detected,[7] a highly unlikely scenario. As above, cognitive devices could communicate among each other to enable each device to construct a map of spectrum usage in its local area, but the requirements for device density seem insuperable if all low-powered devices are to be detected. Lastly, high-powered cognitive radios could simply be forbidden to use spectrum occupied by low-powered devices. A similar alternative is to require low-power devices simply to accept whatever interference they receive from high-powered cognitive devices. Again, this removes much of the attractiveness of cognitive radio as a tool to achieve spectrum efficiency.[8]

Neither of these problems renders cognitive radio useless, but they do put significant bounds on how and when it can be effectively deployed. The initial promise that cognitive radio permits completely decentralized and local control of interference, however, is not likely to be realized. We can expect fairly significant regulation and other controls to accompany deployment of this technology in ways that severely impact the initial vision of this technology.

[6] Using only low-powered devices in certain (unlicensed) spectrum is an effective way of controlling interference. Both cordless phones and WiFi are examples of spectrum sensing cognitive radios that use low power. It appears that the main point of spectrum sensing cognitive radio is increased efficiency in high-powered applications.

[7] Mishra, Tandra and Sahai (2007) describe this problem (which they refer to as "operating at different scales") and suggest that a ubiquitous sensing network may be the only solution.

[8] A third problem could occur if a cognitive radio device correctly detects emissions on a particular frequency, does not broadcast on that frequency but does broadcast on *adjacent* frequencies. If the cognitive radio transmitter is powerful enough and close enough to a unit receiving the first signal, then the receiver may not be able to screen out the signal from the adjacent frequencies and interference will occur, particularly if the receiver is somewhat older.

How can cognitive radio be deployed in both unlicensed and licensed spectrum?

Unlicensed spectrum. The discussion above concerning the power mix problem strongly suggests that high-powered cognitive radios will most likely be excluded from unlicensed spectrum, as virtually all such spectrum is used by low-powered devices. One solution is to set aside certain unlicensed frequencies for use only by cognitive radios. To ensure interference avoidance, some party such as the FCC would mandate the protocols to be used by all cognitive radios in each band.[9] Continued regulation, even if at the protocol level, threatens to burden any cognitive radio deployment with the baggage and inefficiencies of radio regulation that we have seen in the past. This is surely not an outcome desired by the proponents of cognitive radio, but it is certainly the outcome that would occur as students of regulation can attest.[10]

An outcome now emerging in the market is to use a multiband telephone that can use a cellular service or can access a WiFi device to take advantage of a Voice over IP service associated with a broadband connection accessed by the WiFi device. In this mode, the cognitive radio scales back the power to fit the requirements of the unlicensed 2.4 GHz band while transmitting at much higher power when using a cellular band. Multiband devices may well use low-powered spectrum in other ways that augment their primary function; in the U.S., T-Mobile offers such a service, and more applications of this form are to be expected.

Licensed spectrum. There are numerous ways in which cognitive radio can use licensed spectrum, which fall into two broad categories: 1) cooperative use — use of cognitive radio by a licensee on its own frequencies or on frequencies licensed to another entity with that entity's permission, and 2) non-cooperative use – use of cognitive radio to access spectrum licensed to other unrelated entities without their permission.

Under the cooperative use approach, a licensee might sell the right to a non-interfering easement to others, just as today many licensees leases their spectrum to others, generally for months or years at a time. But why not permit licensees to lease the rights to spectrum they are not using for a mere second or minute? This would let the market determine the appropriate price; competition among licensees to attract revenue-generating cognitive devices will keep the price low, and everyone will be better off. Cooperative use could be accommodated under the rights of existing flexibly defined licenses with little additional burden on the FCC. Cooperative CR regime is likely to result in more optimum balancing of interference issues, since costs and benefits would be internalized, unlike the non-cooperative approach.

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[9] In principle, the FCC need only mandate the *functionality* of any protocol used without specifying the actual protocol. This has not been FCC practice in the past.

[10] It is often assumed by technologists that regulators will simply enact regulations that all engineers think sensible and enforce them with little or no dispute. This fails to recognize the political nature of regulation; even well-intentioned and knowledgeable staff is constrained by a regulatory process that often leads to highly inefficient outcomes. See Faulhaber, op. cit., for further explication of how regulation actually works in cases such as this.

The cooperative approach can open up applications which are of a national or global scope (such as cellular telephony). Currently such applications must use the same spectrum in every part of the country, so network operators must purchase licenses for precisely that frequency.[11] This lack of substitutable spectrum for network operators can result in spectrum hold-outs that raise the cost of acquiring spectrum or result in spectrum trades not being made even though both parties would be better off. With cognitive radio, an operator could hold licenses for many different frequency bands in different parts of the country (or the world) and cognitive devices could determine which frequency to use depending on its location. This would allow the construction of national or global voice networks to be much easier and less costly. A possible result of this would be increased competition in the wireless voice market. New entrants in the voice market could more easily become national using different licensed frequencies or perhaps even high-powered unlicensed frequencies, to achieve the coverage the market requires.

Spectrum pooling is another possible example of cooperative use of cognitive radio in licensed spectrum. The white space covered by a single license may be too small to be of much use. However, a group of licensees or their agent (broker) might aggregate white space across a much wider swath of spectrum, creating sizable virtual spectrum block that could be used (for a fee) by anyone in the group or by others. An individual member of the pooling group would receive a share the revenue based on how much (e.g., MHz-seconds-pops) of the white space use occurs within its licensed spectrum. A broker might be brought in to help organize and run such a market. Participants in a spectrum pooling group could also be expected to manage cognitive radio interference efficiently, since all of the costs and benefits would be internal to the group, unlike in the non-cooperative case described below.

The non-cooperative approach would permit cognitive radios to use spectrum licensed to others without their explicit permission. While a major part of the appeal of cognitive radio to many of its proponents, it is rather more problematic, for several reasons. First, suppose my cognitive radio used your spectrum when you were not using it. If I'm allowed to do that, then what exactly is the meaning of an exclusive license? If I possess a license to use this spectrum, then you don't have this license and I can exclude you from using it. For example, I have no right to use your home while you are on vacation, even though you are not using it and it is vacant. You would be rightly outraged if I made this argument to you to justify my breaking into your home, sleeping in your bed and otherwise taking over your domicile in your absence (even if I left no trace of my presence). Why should my use of your spectrum be any different? On the other hand, the presumption of cognitive radio advocates is "no harm, no foul." If I do you no damage, then I do nothing wrong.

The difference in law is between a *trespass* rule and a *liability* rule. In the case of real property, trespass rule governs: I can be prosecuted for trespassing on your property whether or not I caused you any damage. One's property rights to hearth and home are particularly strong, and violations do not

[11] Or frequencies. Currently, many cell phones can operate in either 800 MHz or 1900 MHz, depending on spectrum availability in different geographic areas. Cognitive radio would expand the available bands far beyond the two mentioned.

require a showing of damages but simply commission. On the other hand, legal torts are generally governed by a liability rule. If you have done something to me that has cause me damage, then I may sue you to recompense me for those damages. Otherwise, I have no cause for action. The assumption of the use of others' licensed spectrum by cognitive radios is that the appropriate rule is a liability rule.

The FCC (or indeed Congress) can, in fact, mandate that the acceptance of non-interfering uses is part of every radio license, although they have not done so generally. Such a restriction has been called a *non-interfering easement* (see Faulhaber & Farber, 2003), or in FCC-speak, an *underlay*, and they are used in certain spectrum bands today. Underlay users are required to vacate the use of a specific frequency if the primary licensee wishes to use it in a way that causes it to suffer interference from the underlay use.

An alternative model would permit licensees to sell their underlay rights to others, just as today many licensees leases their spectrum to others, generally for months or years at a time. But why not permit licensees to lease the rights to spectrum they are not using for a mere second or minute? Why should cognitive radio users get the use of the frequency band for free? Let the market determine the appropriate price; competition among licensees to attract revenue-generating cognitive devices will keep the price low, and everyone will be better off.

But should this non-interfering easement be adopted for all licensed spectrum? Adopting it would certainly favor cognitive radio, but is it in the best interest of all? It can be argued that since cognitive radio users are better off and licensees are no worse off (because they are not interfered with), then clearly we should adopt this rule.[12]

Unfortunately, life is not that simple, for two reasons: 1) the deployment of cognitive radio is likely to impose costs on others, particularly license holders, and 2) enforcement of interference protocols and rules is likely to be virtually impossible, thereby allowing "cheaters" who can take advantage the inability to enforce for their own private benefit. Primary users would be required to invest in technology that signals cognitive radios that they wish to take back their spectrum as well as technology for sensing what radios currently are broadcasting in their band. If a nationwide sensing network is deployed, primary users have the technology to consult the sensing network, as well as experience delays associated with determining whether or not their spectrum band is clear. It might be imagined that your typical FM radio station (or airport radar operators, or any number of legacy users) would wonder why it is being asked to invest in technology and tolerate delays simply because other users wish to deploy cognitive radios. For them, cognitive radio is all cost and no benefit. If, however, they are able to charge for the use of their spectrum while idle, these costs/delays may be more acceptable, certainly in comparison with a government-mandated regime.

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[12] Note that adopting a non-interfering easement requiring licenses to accept cognitive radio devices is tantamount to establishing a regulated price of zero for the resale of licensed but idle spectrum frequencies.

Further, the basic assumption is that we all play the game according to the rules, and nobody cheats. Is this a likely outcome? To determine if it is, we need to ask three questions: 1) Is it possible for an individual to cheat? 2) Does cheating pay off to the individual in the short run? And 3), Can cheating be easily detected and punished? For cognitive radio, the answers are, unfortunately, yes, yes and no.

For any software defined radio, including cognitive radio, downloading software tweaks from the Internet to modify your device for increased power or overriding the sharing protocol is likely to be relatively easy.[13] Would such modifications be in the short-term interest of users? Certainly, if one can increase your communications capability at the expense of interfering with others that you don't know, most would choose greater capabilities. But many radio issues share these features. What is it that makes cognitive radio different? It is what I call the *hit-and-run radio* problem. With static devices that are stationary in place, and frequency, a device which causes interference is relatively easy to track down (at least by a professional). The interfering device is likely to interfere multiple times in the same way, so detection and identification is relatively easy. However, a cognitive radio may be anywhere in frequency space, and if the device is mobile anywhere in geographic space. If a licensee suffers interference from a cognitive radio, it is unlikely to be able to trace the problem and detect the culprit. An owner of an illegally juiced-up cognitive radio is extremely unlikely ever to be detected and identified, particularly if the device is mobile but even if it is static. A similar problem existed in the 1970s during the popularity of CB radio. It was relatively easy to obtain overpowered CB radios which allowed the owner much greater range. Unfortunately, such devices caused interference with over-the-air TV reception as well as other CBers using close channels. Since the radios were mobile, they were nearly impossible to catch. Not only did some CBers overpower their devices (from e.g., 4W to 100W), they often broke the simple protocols about releasing channels with impunity. At their peak of popularity in the late 1970s, the FCC received 35,000-50,000 complaints per year (not counting protocol violations); enforcement efforts were completely overwhelmed. Cognitive radios add the dimension of roving over frequencies as well as geography, making the problem much worse. Cognitive radios may well be "hit-and-run" radios: renegade devices leaving a trail of interference and virtually undetectable themselves.

While policy makers can make rules forbidding such renegade devices, the ability to enforce these rules seems next to impossible. Unenforceable rules are unlikely to mean much; if it is possible to cheat, it is in the interest of parties to cheat, and cheating is undetectable, well, cheating will occur. We have witnessed exactly this phenomenon will P2P file sharing and music downloading. The Internet made it possible to download free music, it is in the interest of many to do so, and detection is essentially impossible. Copyright rules have little effect in the face of these strong incentives.

Will such cheating occur in practice? Without actual experience, it is difficult to be definitive. Related technologies, such as CB radio and P2P music downloading, suggest that with both the ability and the incentive to cheat and the inability to detect and enforce, cheating may be significant enough to degrade not only cognitive radios, but other radio users.

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[13] A technically ignorant economist found it easy to download the instructions for programming a Motorola DVR remote to activate a 30-sec. skip, to make it easier to avoid watching recording commercials.

Conclusion

Cognitive radio holds out the promise of much more efficient use of spectrum, a resource that has been sorely wasted to date. To realize this great potential, however, requires solutions to at least three policy problems: shadowing, power mix and hit-and-run radio. Without at least partial solutions to these problems, cognitive radio cannot come close to achieving its promise. A more likely outcome is that cognitive radio fills a particular niche for certain specialized applications, probably within licensed spectrum — a valuable but not revolutionary technology deployment.

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