POLICY-BASED RADIOS

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This paper describes a new radio technology, denoted policy-based radios, which has the potential to enable greater access to the radio spectrum while enhancing and simplifying spectrum management. Spectrum management faces both challenges and opportunities in developing countries. The role for policy-base radios in this environment is described as well as key design decisions for their use.

6.1 INTRODUCTION

Broadband access is key to economic growth in the modern interconnected economy. Ironically, recent decisions by the U.S. Federal Communications Commission (FCC) [1] [2] [3] will soon yield a new commercial wireless technology that may be even more useful for the expansion of broadband access in developing countries than in the U.S. The FCC opened the door for "TV white space" devices that operate in spectrum allocated to television. These devices use geolocation technology and a database of TV transmitter locations to avoid harmful interference to TV. Several other nations led by the U.K. are also in the process of making it legal to use this technology.

TV white space devices are a special case of so-called *policy-based radios*, which are radios governed by policies that are machine-readable and easily modified. The ability to customize policies and even change them over time brings a flexibility that can greatly enhance effective

1. Federal Communications Commission, Second Report and Order and Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Nov. 14, 2008.
2. Federal Communications Commission, Second Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Sept. 23, 2010.
3. Federal Communications Commission, Third Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, April 5, 2012.

use of spectrum, especially in developing nations which have spectrum needs and resources that are somewhat different from the economies that tend to drive demand for wireless devices. Nevertheless, there are challenges to applying policy-based radio technology in order to meet the broadband needs of developing countries. There are significant differences in regulation, how the network will be used, and the underlying infrastructure that need to be addressed. Many countries have high-capacity transmission networks, but are severely limited in last-mile connections. Rwanda for instance has 2,300 kilometers of fiber optic cables connecting distant parts of this small country but limited distribution and access to the end users. Last-mile connectivity could be provided by policy-based radio devices. For instance, TV white space frequencies are better suited to provide coverage in hilly or densely foliated terrain than higher frequencies. Moreover, if there were regulatory reform, the amount of spectrum that could be available to policy-based radio devices is likely to be much greater in places in developing countries than in major U.S. and U.K. markets, because there is spectrum that remains fallow in developing countries in part because this spectrum is unavailable in the largest markets; this prevents manufacturers, standards bodies, and regulators from unleashing wireless devices in these bands that would only be useful in smaller markets.

This discussion suggests that policy-based radios will have a role to play in broadband access. This paper argues that these radios can play a significant role for spectrum regulators to manage many aspects of the radio spectrum. Though there remain challenges to the widespread use of policy-base radios, which we discuss, the technology has developed to the point where its use should be considered.

6.2 CHALLENGES TO SPECTRUM MANAGEMENT

Spectrum management faces several challenges especially in developing countries. For instance, Africa falls within the International Telecommunication Union's Region 1 for the purpose of managing the global spectrum. Region 1 also includes Europe and the Middle East and so supports diverse economies. Africa's population density is about one fifth of Western Europe's and the per capita GDP is about 22 times smaller. From these figures we can expect that the spectrum needs of Africa may differ from other parts of Region 1. Within Africa there are also many differences between countries.

Country spectrum regulators need to balance competing needs on several levels. First, they must balance allocations for individual countries versus the larger Region 1. Deviations from Region 1 band plans can lead to interference at international borders that is difficult to manage. Second, they must balance custom radio applications versus regional

and global standards. Modern radio equipment is complex. Managing and maintaining radio software and hardware leads to costly devices unless these fixed engineering costs can be spread across many units. So, spectrum managers must avoid disqualifying the use of low-cost commodity radios through non-standard allocations. Third, though a non-standard allocation today may be consistent with current uses in adjacent countries and current technologies, spectrum use evolves continuously. As countries develop, previously under-used bands in bordering countries become more used within existing allocations making cross-border interference challenges more acute. We would also expect that regional allocations will change to accommodate changing use of the radio spectrum. Even within existing allocations, new services that are socially and economically important can emerge. In short, spectrum regulators need a future-proof technology that allows them to unlock the spectrum's potential both today and in the future.

Historically, spectrum allocations have been "hardcoded" in the radio devices themselves. For instance, the allocation to broadcast radio is encoded in the tuners of the millions of consumer radios sold. This static coding in the radio devices is a drag on change and innovation. Because of this drag, allocations have tended to be static with very infrequent changes. Spectrum allocations continue long after the original utility has subsided and there is significant "friction" to changing allocations. As a result, when new spectrum needs arise spectrum is not available. This leads to spectrum hoarding and spectrum warehousing whereby spectrum licensees fight to keep their spectrum even when their spectrum use is socially suboptimal.

While spectrum is fully allocated, paradoxically, studies show that much of the valuable spectrum is underutilized for much of the time. The result is a gross under-utilization of the spectrum. Spectrum measurements even in large cities of countries such as the United States and Great Britain show that no transmissions can be detected from a fixed receiver in the vast majority of spectrum at any given time [4]. In a particular frequency band, if there are regions in which new devices can be allowed to transmit without causing harmful interference to any incumbent systems, then these regions are referred to as spectrum *white spaces*. White-space sharing occurs when devices are allowed to transmit when and only when they can determine that there is white space. Moreover, even when spectrum is in use, it may be possible for additional devices to operate without causing harmful interference under the right technical constraints. This is referred to as gray space sharing [5]. Opportunities for both white space sharing and gray space sharing are inevitable because of the relatively static way spectrum has traditionally been managed. For example, a license-holder may be given exclusive rights to transmit at all times throughout a large region, when it only wants to operate in part of the region for part of the time. Note that white space can change over time, e.g. if that license-holder decides to deploy transmitters in new locations, or if a TV broadcaster changes its antenna or transmit power.

4. Federal Communications Commission. In the matter of Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies, (ET Docket No. 03-108) and Authorization and Use of Software Defined Radios (ET Docket No. 00-47), ET Docket No 03-222 Notice of proposed rulemaking and order. Dec. 30, 2003.

5. J. M. Peha, "Spectrum Sharing in the Gray Space," Telecommunications Policy, Vol. 37 No. 2-3, March, 2013, pp. 167-77.

That is why the flexibility inherent in policy-based radios is important.

Attempts to share spectrum are common but they are not always successful. In the United States, for example, garage door opener manufacturers were allowed to operate in a radar band on a secondary basis. Eventually, these secondary users became so prevalent that the primary user was required to invest to mitigate the growing number of interference cases. It is worth noting that it was not the primary user that was suffering harmful interference but rather the garage door openers. Moreover, the interference problems were unexpected, but because the garage door openers were already widely deployed with hard-coded sharing policies, there was no easy way to change the technology so that interference would not be problematic. This cost the primary user. Thus, it is understandable that primary license holders are reluctant to share their spectrum with even the most benign of other services. More flexible technology may reduce such problems, and thereby encourage greater sharing.

Moreover, there is particularly great opportunity in developing countries for sharing. In Rwanda, for instance, there is a single TV channel in use (although there are multiple transmitters on this channel according to the DVB standard). Currently there are plans for at most two other TV transmitters. This implies that only 24 MHz is occupied out of the 320 MHz allocated to TV broadcasting. In addition to TV there are many other spectrum bands that may be unused in a developing country such as maritime bands in landlocked regions, and satellite downlink bands far from any satellite users,

Based on these arguments, it is clear that there needs to be a mechanism to reduce the friction associated with spectrum sharing, to increase the ability of countries, especially developing countries, to flexibly allocate and reallocate spectrum.

6.3 COGNITIVE AND POLICY-BASED RADIOS

A policy-based radio is a "radio in which the behavior of communications systems is governed by machine-interpretable policies that are modifiable," where a policy is a "set of rules governing radio system behavior" [6]. Policies can be relatively static to describe conventional spectrum allocations, or they can describe dynamic spectrum sharing. They can encode hardware limits, such as the allowed tuning range of the underlying frequency agile radio, as well as bands to be avoided. In this way the policy-based radio is a unified mechanism to reason about multiple facets of spectrum use.

These policies may be established by regulators, standards bodies, manufacturers, system operators, or more likely some combination thereof. Thus, it is possible to change how a policy-based radio is al-

6. SDR Forum, "Cognitive Radio Definitions and Nomenclature," SDRF-06-P-0009-V1.0.0, Sept. 10, 2008.
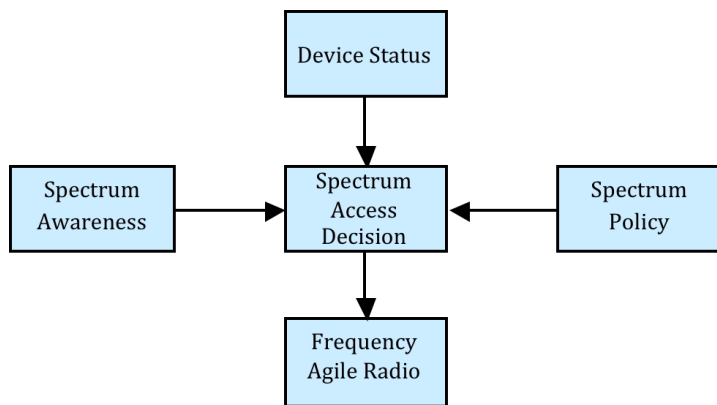
Figure 6.1: Functional blocks of a cognitive policy-based radio

lowed to access spectrum simply by modifying a few input files. This modification may happen when the device is produced, perhaps to take a mass-produced general-purpose policy-based radio and then customize it at little cost for different national markets. On the other hand, modification may occur after the system has already been deployed, perhaps to keep pace with changing regulations, or to shift out of a band after unexpected harmful interference has been observed.

The concept of a policy-based radio can be made even more powerful when combined with that of *cognitive radio*, *software-defined radio*, or both. A cognitive radio is a "radio or system that senses, and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters" [7]. One way that a radio may be reconfigured in this way is to make use of spectrum that it somehow senses is available. A software-defined radio is a radio that can be reconfigured through software, as opposed to hardware modifications. Great progress has been made in recent years on making policy-based radios, cognitive radios, and software-defined radios that are cost-effective, and although the concepts are orthogonal, they are also mutually reinforcing in the realm of spectrum access. As an example, Figure 1 shows a radio that is cognitive, since it has sensing in the form of spectrum awareness, the ability to reconfigure in the form of frequency agility that can alter frequency and modulation, and a cognitive or decision-making capability. The radio is also policy-based, since decisions are made in consideration of spectrum policies that are modifiable.

The choice of bands is a so-called *spectrum access* decision that is based on several factors. *Device status* is information such as the device location. *Spectrum awareness* is how the cognitive radio discovers what frequency bands are not being used by an incumbent user and thus potentially available. We focus here on methods that combine the device status and spectrum policies. *Spectrum policies* are machine readable

7. Radiocommunication Study Groups, "Working Document Towards A Preliminary Draft New Report: Software Defined Radio In Land Mobile Services," International Telecommunications Union Document 8A/121-E, 15 September 2004.

rules that specify in what frequency bands the radio is permitted (or prohibited) to transmit, at what locations, when they can be accessed, and under what conditions. Thus to transmit in a band requires that the band is within the capabilities of the radio, not occupied by an incumbent user, and that there is a policy stating that its use is appropriate for the application. The spectrum access decision is not an isolated and fixed decision. Both the transmitter and receiver must find and agree on a common spectrum band in a so-called rendezvous process. As conditions change such as a change in location the radios must make a handoff from one band to another in what is denoted a spectrum handoff [8].

8. I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, "NeXt generation dynamic spectrum access cognitive radio wireless networks: A survey," Computer Networks, 50(13), 2127-2159, 2006.

6.4 ADVANTAGE OF POLICY-BASED RADIOS FOR SPECTRUM SHARING

Policy-based radios present several advantages for spectrum sharing.

6.4.1 *Making more spectrum available*

The policy-based radio allows finer-grained allocations of spectrum over time, frequency, and location. A policy can be thought of as a time-limited lease that specifies a period over which a right to access the spectrum within the applicable technical constraints is valid [9]. The period can range from a short term such as a fraction of an hour to long terms that extend into months. The periods have start and stop times and may be valid starting at some future time. The policy can specify daily or weekly schedules of allowed operation. The policies can allocate large allotments of spectrum but can as well specify down to individual channels or sub-channels. The policy can specify frequency-dependent power limits. Locations can be precisely defined to protect incumbent users while maximizing the area where a band can be used.

9. J. M. Chapin, W. H. Lehr, "Time-limited leases in radio systems," IEEE Communications Magazine, vol. 45, no. 6, pp. 76-82, June 2007.

As an example, policies to operate in and near a radar band would first define areas around the radar sites where the band cannot be used, which are known as *exclusion* zones, and areas where the band can be used. If gray-space sharing [10] is supported, there will also be areas where usage is allowed, but only within specific technical constraints carefully designed to protect the radar from harmful interference [11]. Policies for allowing spectrum use directly in the band would have larger exclusion zones, while adjacent bands may have smaller exclusion zones. The policies would be valid for a month at a time and renewed at, say, weekly intervals. The result is a seamless access to the band over time. When a new radar is to be installed, the new radar site will be incorporated into new policies and the radar operator can have confidence that the old policies will expire within a month freeing up the spectrum around the new site. Similarly, if an existing radar is upgraded to a new technology,

10. J. M. Peha, "Spectrum Sharing in the Gray Space," Telecommunications Policy, Vol. 37 No. 2-3, March, 2013, pp. 167-77.

11. R. Saruthirathanaworakun, J. M. Peha, and L. M. Correia, "Opportunistic Sharing between Rotating Radar and Cellular," IEEE Journal on Selected Areas in Communications, Vol. 30, No. 10, pp. 1900-10, Nov. 2012.

this may lead to changes in the size of the exclusion zone, or changed in the policies governing gray-space sharing.

More generally, policies address the problem of static spectrum management. Fine-grained allocations foster more efficient use of the spectrum with greater communication capacity to support future growth and innovation in wireless applications. More importantly, policy-based radios can use such allocations automatically while still adhering to stakeholder requirements. This automation provides government regulatory flexibility that is not currently present and promotes better use of the spectrum. Spectrum regulators such as the FCC in the United States, recognize that policy-based radios can be applied to dynamically reuse white spaces in licensed spectrum bands, thereby efficiently utilizing under-utilized spectrum [12].

6.4.2 Making spectrum management simpler and more reliable

Spectrum does not come from a single source. The spectrum used by an end user may come directly from a top-level national spectrum regulator or it may come from spectrum assigned to intermediate spectrum brokers, frequency coordinators, or service providers. Policies can encode the delegation of spectrum management from a top-level allocation to a spectrum manager through sub-policies and sub sub-policies that further delegate spectrum management. Coordination can be delegated to the lowest level that is sufficient. A specific policy would need to have its provenance traced through parent policies back to a trusted source. Since the policies are machine readable it is easy for end-users, intermediate spectrum managers, or national spectrum regulators to automatically check them for logical consistency and to detect potentially conflicting allocations. Further, using cryptographic digital signatures, the policies can be authenticated as being valid without malicious or benign errors. This policy distribution concept has been described by Brown and Sicker[13].

6.4.3 Making spectrum regulations evolvable

Policy-based radios allow regulators to adopt spectrum policies with the expectation that those policies will evolve over time, which has great advantages. One of those advantages is the use of strategies that deliberately learn from experience. When spectrum is shared, there is often some degree of uncertainty regarding the risk of harmful interference. Since regulators are usually obligated to protect incumbent systems, this uncertainty leads to very conservative rules. Moreover, once these rules are in place, they are hard to change. Currently, spectrum technical rules are often written into federal regulations, and changes are slow and difficult, in part because transparent administrative procedures are inherently slow compared to the pace of innovation in wireless technology,

12. Federal Communications Commission, Spectrum policy task force report, (ET Docket No. 02-135), Nov. 2002. http://hraunfoss.fcc. gov/edocs_public/attachmatch/ DOC-228542A1.pdf

13. T. X Brown, D. Sicker, "Secure Distribution of Spectrum Policies to Cognitive Radios in Unmanned Aircraft Systems," Proc. AIAA Infotech Aerospace Conf., Atlanta, Apr. 20-22, 2010

and in part because some changes face stiff resistance from existing users since those changes can make radios obsolete. As a result, excessively conservative choices in rules may persist for years or decades. Policy-based radios enable spectrum managers to flexibly change rules over time to incorporate experience in the field and track new technology. For instance, the policy for secondary use in a radar band may start with policies that have large exclusion zones and low power limits. With experience these policies may be relaxed or tightened to manage the interference to the radar. Further, parallel policies can require, say, spread spectrum to promote alternate technologies.

Policy-based radios also help regulators address the challenge of usage flexibility. As discussed by Peha[14], one of the dilemmas that regulators face is how much technical flexibility to give license-holders and unlicensed spectrum-users. It is often possible to reduce the risk of harmful interference when systems must coexist, provide some degree of interoperability, or leave the door open for technologies not yet invented to share a band efficiently by imposing some technical limits on devices, but doing so also limits innovation in ways that may turn out to be significant. In the past, finding the right balance has meant predicting the future, but this is not necessary with policy-based radios. For example, perhaps a shared spectrum band was created with few constraints on devices. Over time, it is determined that devices interfere with each other in unexpected ways. This occurred in unlicensed bands when WiFi devices were found to cause harmful interference to bluetooth devices. At the time, the only option was to change the technologies, and wait for legacy devices to reach their end of life. Had these been policy-based radios, an additional option would have been available to regulators: they could have split the unlicensed band into two pieces, each with more technical constraints than were initially imposed, and one better suited for WiFi and the other better suited for bluetooth.

6.4.4   Facilitating spectrum leasing to increase efficiency

The right to access spectrum can be obtained from either of two very different sources: a regulator and a spectrum license-holder [15]. In addition to giving regulators greater ability to safely make fine-grained time-limited policies, policy-based radios bring these same capabilities to license-holders. As discussed in Section 2, some spectrum held by license-holders is typically unused, in part because of coarse spectrum allocations that cover a large region when the spectrum is needed in only part of the region, or that cover all time even though the spectrum is used only occasionally. Moreover, since spectrum is difficult to obtain, users may warehouse it for future applications, or even hoard it to prevent competition, which causes more spectrum to be unused for extended periods.

License-holders can lease their unused spectrum temporarily to other parties. Spectrum leasing became legal in the U.S. in 2003 and

14. Jon M. Peha, "Spectrum Management Policy Options," IEEE Communications Surveys, Vol. 1, No. 1, Fourth Quarter 1998.

15. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

2004 [16] [17]. Because license-holders can be paid for these arrangements, they have incentive to maximize the amount of spectrum in use. While the idea of leasing is not new, the policy-based approach gives incumbent users the ability to embed powerful and precise control over secondary users into these arrangements. Machine readable policies can precisely define lease terms in a leasing agreement, and make it easier for lessees to follow these terms strictly. Moreover, these machine-readable policies are time-limited, which limits the risk even if the terms are found later to be unfavorable to either the lessor or lessee. Thus, the policy-based approach could encourage more spectrum holders to lease their spectrum.

For instance, a spectrum holder that operates in an urban area may lease spectrum for a service in rural areas. Similar to the spectrum regulator in the previous section, the spectrum holder can start with conservative leasing terms for short trial periods that with experience evolve and extend for longer periods. If interference is found to be problematic the spectrum holder could choose to not renew the short-term lease or to appropriately modify the terms.

As a result of this greater control both before and after a lease, more spectrum will be offered up for leasing. Other users may be more willing to share spectrum such as between different government agencies. Further spectrum that has been allocated at the Region 1 level to services that are unused in individual countries can be made available in a controlled way. Spectrum that is tied up because of these inefficiencies can be unlocked by spectrum managers through policy-based radio technology.

6.5 STAKEHOLDER REQUIREMENTS

One of the many uses of policy-based radios is to allow new users to share spectrum with an existing spectrum user. In this model the existing spectrum user is denoted the *incumbent*, and the new user that is attempting to use the spectrum is denoted the *entrant*. The incumbent and the entrant as well as the regulator have requirements that a spectrum sharing approach must meet.

The incumbent is most concerned with assured coexistence and compatibility to avoid harmful interference. They are also concerned with their rights to use the spectrum or to change and upgrade incumbent operation without limitations imposed by the new entrant. They want to avoid the earlier radar band example where a change in the incumbent operation led to a complaint by the garage door opener new entrant. The sharing arrangement should be secure, trusted, and enforceable.

The new entrants also are concerned with coexistence and compatibility and to not be subjected to unreasonable interference protection criteria. Further, since they are accessing the spectrum on a secondary basis, they want assurances that the spectrum sharing scheme will con-

16. Federal Communications Commission, Report and Order and Further Notice of Proposed Rulemaking, in the matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Docket No. 00-230, Oct 2003.

17. Federal Communications Commission, Second Report and Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking, In the Matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Dkt No. 00-230, Sept. 2004.

tinue and they can design long-lived hardware and services around the scheme. They also want assurance that the scheme will produce sufficient useful spectrum.

The regulator is concerned with making sure that the spectrum sharing schemes are both flexible to allow the greatest utility in sharing but also low-cost and easy to manage by the regulator. As a principle, the regulator should avoid over specifying the technical details of sharing since best practices will evolve with experience.

6.6 SPECTRUM ACCESS THROUGH POLICY-BASED RADIOS

Spectrum access is the process by which the policy-based radios choose which frequency bands to communicate. It consists of several dimensions related to the type of spectrum, which parties control its use, and how it interacts with applications. Conceptually, spectrum access can be thought of as having an appropriate policy that permits usage of a specific band for a specified period. This section is the most detailed in order to highlight the rich set of options available to the regulator provided by policy-based radios.

6.6.1 Types of Spectrum Access

There are many different policies regarding spectrum access, any one of which can in theory be written in machine-readable form, albeit with a large number of fields. A system may be granted exclusive access, or it may share spectrum with others. If there is sharing, there are two fundamental traits that define the nature of the sharing [18]. First, there can be *primary-secondary* sharing, where primary devices are relatively unconstrained and secondary devices are prohibited from accessing the spectrum in a manner that causes harmful interference to a primary device, and there can be sharing among *equals*, where all devices have equal priority and equal responsibility to avoid interference to the others. Primary-secondary sharing is preferable when one kind of system is more important, or when one kind of system is already deployed and cannot easily be changed. Thus, we can deploy policy-based secondary devices without making any changes to the legacy primary systems. In the TV band, for example, we currently have both kinds of sharing [19]. Television broadcasters have primary rights, but secondary users must share spectrum with each other as equals, and tolerate each other's interference. Policies can specify both types of access.

For both sharing among equals and primary-secondary sharing, sharing can be based on *cooperation* or *coexistence* [20]. With cooperation, systems communicate with each other to avoid harmful interference, whereas with coexistence, devices may sense each other's presence but never explicitly communicate. Policies for this kind of sharing may

18. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

19. Federal Communications Commission, Second Report and Order and Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Nov. 14, 2008.

20. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

mandate that a specific listen-before-talk (LBT) mechanism be used in this band, for example, or that all transmissions use spread spectrum modulation. Cooperation can generally lead to higher levels of spectrum efficiency, but then devices must be required by some authority to be designed to be interoperable. Thus, for example, a policy in a band with cooperation may require devices to listen for "beacons" in a specific signalling band, and cease all transmissions in the band once a beacon is detected.

With any of the forms of sharing described above, it is possible that a band may contain only licensed devices, only unlicensed devices, or some of each. Licenses are permission from a regulator to transmit, and they usually (although not always) come with some guarantee of exclusivity. Licenses always include constraints on how the spectrum can be accessed which must be included in machine-readable policies. The level of flexibility varies considerably, from FM radio where the location, power, and modulation scheme of all transmitters is specified to the most flexible cellular licenses which allow use of almost any technology provided that interference caused to adjacent bands and adjacent regions is below given thresholds. Unlicensed devices are allowed to operate without explicit permission from a regulator, but they do so contingent on following whatever rules were established for the band. These are the rules that must be included in machine-readable policies.

6.6.2 Control of Spectrum Access

Spectrum access is controlled by policies. What are the mechanisms to distribute and manage policies that underpin the control of spectrum access? To address this question, it is necessary to examine where the policies come from, where they are ultimately used, and how the process is mediated.

Where do Policies Come From

Control over spectrum can be delegated through the leasing and sub-leasing of spectrum through policies. Policies originate from base spectrum regulatory authority. These can sublease to other agencies which in turn sublease, eventually leasing to a user.

The policies used to access spectrum must be valid in three ways. First, they must come from a source which is authorized to issue a policy. An end user needs to see not only the final policy, but also the chain of policies tracing back to a trusted root source. Because policies might be corrupted or maliciously modified in transit, the policies need to be cryptographically protected with a digital signature so that the end user can verify that each policy originated from the purported source [21]. Second, they must be consistent and not contradict other policies. The characteristics of the policies such as the spectrum bands and time period for each sub-policy must be a subset of the higher-level policies.

21. W. Stallings, Network security essential: applications and standards, Upper Saddle River, NJ : Prentice Hall, 2000.

22. IEEE 1900.5 Working Group on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications

Further, there may be other prohibitive policies that exclude use in certain bands. The end-user must validate the policy it uses against these other policies. To enable this validation and reasoning, the policies must be written in an appropriate machine readable form [22]. Third, they must apply to the situation that they are being applied. The end-user must validate that it meets the location, type of communication, and other conditions of the policy before it uses the policy.

The base authority can grant such spectrum policies to multiple sub-entities which in turn can grant them to multiple sub-sub-entities. This process produces a distributed policy tree with each node only required to a) store the chain of policies to the root of the tree that validates its authority and b) manage issuing policies to their direct child nodes. Policies can be issued with the *entire chain in every policy* so that a child policy includes the parent, grandparent, etc. policies. This simplifies the policy validation since every policy contains all the required information for the end user to validate the policy. However, in an environment where a child policy changes often, this increases the burden on the system since the entire chain has to be sent every time. An alternate approach is a web approach where the *chain must be assembled from multiple policies.* Here the challenge is that the end user needs to have access to and be able to find all the policies in the chain. This can be simplified by embedding short "resource locator" information about the needed higher level policies. In this case, the parent policies are stored and only the child policy changes. Note that the public keys required for the digital signatures can be distributed either *embedded in the policies themselves* or according to a *separate infrastructure for distribution.*

Where are Policies Used

The end user of a policy could be the radio at either side of the connection. The side receiving the policies would control the choice of frequency band. The choice could be made by *the transmitter* or *the receiver.* In using a policy, it is possible for the two policy-based radios to be widely separated. Thus, in applying the policy the end-user must consider the situation at both sides of the connection. In some cases, both sides of the connection may hold their own set of policies and neither is controlling the choice. Because they are widely separated they may hold different spectrum awareness views. In the worst case, there may be no connection and the problem is for the radios to find a common spectrum band to *rendezvous* in order to start communication [23]. Policies can also go to some other *third party* controlling entity that acts on their behalf. Some policies are *open-ended*; anyone holding the policy that meets the conditions of the policy may use the policy. Other policies are assigned to use by specific end users.

23. I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, "NeXt generationdynamic spectrum access cognitive radio wireless networks: A survey," Computer Networks, 50(13), 2127-2159, 2006.

How are Policies Mediated

In the above example, the policy's authority follows through specific organizations. More generally, these policies are mediated by a *spectrum manager*. The spectrum manager is responsible for gathering policies from appropriate agencies and distributing them to sub-lessees. A spectrum manager may be an agent within an organization or a separate designated third party.

There are several models for how spectrum policies can be distributed. In a *shared* model, a policy may give access to a set of end-users who must coordinate their access. At one extreme, the access is open-ended in terms of the number of users who are given access and as to the period that it is available. There may be operational limits to the number of users on a band (only so many radios can be at a location) or other limits (a band that is busy will simply not be used). Such shared use works better when there are rules or etiquette (e.g. listen before talk) to manage communication. To avoid channels from becoming overloaded and unusable, a *limited shared* model may be used where the set of users that have access are limited in number or time. At the other extreme is a *dedicated* model where a spectrum band may be given to only one end-user at a time. The limited and dedicated models require the spectrum manger to track which users have active policies at any given time. To better control the access, the spectrum manager may flag a policy as being *terminal*, meaning that it cannot be subleased further.

Policies can be created on an *as-needed* basis whereby the spectrum manager issues policies to the end user to fulfill specific needs. Policies can be *negotiated* whereby the end-user may make a request to a spectrum manager for a policy to fill a specific need. The spectrum manager responds with a policy that meets the request or with a message that the request cannot be met. In the latter case, the end user may make a revised request seeking to find the spectrum it needs. Policies can also be *premade* and warehoused in a database accessible to end users. Here a user visits the database, downloads suitable policies and makes its own decision about which policy to use. The premade model works best for distributing shared policies and for storing higher level policies that users can use to validate end-user policies. This section emphasizes the flexibility with which spectrum access can be managed through the use of policies. The design choices are summarized in the table below.

Table 6.1: Design Choices

Property	Design Choices
Spectrum priority	Unlicensed
	Licensed
Sharing priority	Primary-secondary
	Equals
Sharing mechanism	Cooperation
	Coexistance
Policy authentication	Entire chain in every policy
	Chain must be assembled
	from multiple policies
Public key distribution	Embedded in policies
	Separate infrastructure
Policy choice	By transmitter or receiver
	Assigned by third party
	Rendezvous
Policy assignment	Open-ended
	Specific end users
Spectrum exclusivity	Open shared (unlicensed)
	Limited shared
	Dedicated
Policy creation	As-needed
	Negotiated
	Premade

6.7 GETTING STARTED

The previous sections describe the flexibility that is possible using policy-based radios. How does a regulatory authority get started? The regulator should choose a set of bands that has suitable characteristics such as being underutilized in geographic areas of interest, relatively stable incumbent users, sufficient spectrum to be useful for entrants, and available radio equipment to operate in the spectrum. In the US and UK, they have selected TV white space access in TV bands because it provides a large amount of spectrum for broadband access in rural areas and is of sufficient interest that radio manufacturers have developed broadband access radio equipment to operate in the band.

In many countries, the users of a band are not fully documented. There may be informal agreements or simply "squatters" using the band without permission. The US, for instance, has many wireless microphones operating in the TV band. To understand the actual use may require surveys of known spectrum managers as well as field surveys with a spectrum analyzer and other measurement tools.

At this point the regulator needs to develop a regulatory framework

for entrant operation in the band. The US and the UK both have significant work in this area [24] [25]. However, experimental licenses, and test deployments may be a useful approach as is being done in many countries.

A policy database needs to be created with policies that protect the incumbent users while giving access to the entrants. The capabilities of the database depend on the expected usage. A simple web interface with downloadable lists of policies may be sufficient for a small scale or relatively static scenario. More demanding scenarios will require more powerful database mechanisms.

The regulator may wish to license outside parties to play important roles rather than play all those roles itself. In the case of TV white spaces, for example, the U.S. has certified a dozen different entities to operate the databases that a white space device must query periodically to find out which bands are available at its location [26]. While the FCC will remain involved in the data that goes into the database, the FCC can leave all interactions with end users to the operators of these databases. Since the entire system depends on correct operation of the databases, the FCC must certify database operators.

An alternative to this approach would be for a regulator to provide a spectrum license to a *band manager*, an approach that was made legal in the US in 2004 [27], and leave nearly all of the technical decisions to the band manager. This band manager may even be a profit-seeking company and may charge for access. Where there is concern that one band manager may act as a monopolist, it is possible to create multiple bands with different band managers. The band manager approach is likely to be effective in some cases, and ineffective in others depending on transaction costs relative to the value of the spectrum lease [28]. Standardized machine readable policy languages will lower transaction costs and foster competition between bands.

When there is sharing, regulators also need ways of mitigating the effects of harmful interference, both a priori and a posteriori. Beginning with the former, as with traditional radios, processes will likely be needed to certify that policy-based radios are safe. However, as discussed by Peha[29], certification is more complex with policy-based radios, in part because the behavior of these radios can change when the policy inputs change, and in part because there may be many heterogeneous devices interacting with each other. Regulators around the world are working on improving certification.

Regulators also need processes to respond to harmful interference after it has been found to occur. Given that the policy-based technology allows rapid changes in devices that have already been deployed, it would be best if the regulatory decisions that might motivate such changes could also be rapid, perhaps facilitated by forums where those operating in a given band can meet directly to discuss problems without requiring all communications to pass through the regulator [30].

24. Federal Communications Commission, Third Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, April 5, 2012.

25. Ofcom, "TV White Spaces: A consultation on White Space Device Requirements," November 22, 2012.

26. Federal Communications Commission, Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Jan. 26, 2011.

27. Federal Communications Commission, Second Report and Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking, In the Matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Dkt No. 00-230, Sept. 2004.

28. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

29. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

30. J. M. Peha, "Spectrum Sharing in the Gray Space," Telecommunications Policy, Vol. 37 No. 2-3, March, 2013, pp. 167-77.

6.8 CONCLUSIONS

Policy-based radios are a flexible technology that supports different spectrum sharing models to enable access to more spectrum. Fallow and underutilized spectrum can be used through time-limited policies so that a spectrum manager can manage when, where and how spectrum can be accessed. By resolving the static allocation issues spectrum holders would be more willing to offer up spectrum thus making more spectrum available and less spectrum left fallow. This technology is especially important in developing countries which have underutilized spectrum that can be employed for economic growth while not precluding the use of future radio advances. This paper describes the key issues for regulators to consider in the use of policy-based radios in an effort to promote how they would be used in practice.