DYNAMIC SPECTRUM POLICIES: PROMISES AND CHALLENGES

Paul J. Kolodzy, Ph.D.*

Recently, Federal Communications Commission ("FCC") Chairman Michael K. Powell indicated that the digital age, and the radical transformations that accompany it, have profoundly changed the way we use spectrum.[1] The wide development of various devices now makes it possible for "an individual [to] use a piece of spectrum in [his] home, the airport, or a store that will let [him] communicate and access information over the Internet."[2] Not surprisingly, the individual is now being viewed as the prime user of the spectrum resource, and the merging of communications and computing has made this possible.

The technologies that are being developed as part of this digital migration are rapidly changing the manner in which radios can operate. The era of devices operating in a single band for a single function is quickly disappearing. The age of wideband, flexible, and agile systems has dawned. These new capabilities have the potential to allow the spectrum resource to be accessed and used in ways and with an efficiency that is far beyond the current systems. Unfortunately, the current set of static spectrum policies does not allow system designers to tap into this potential.

This article proposes the development of dynamic spectrum policies that will open new avenues for systems and applications to access the radio frequency ("RF") spectrum. The development of dynamic spectrum policies is an evolutionary step toward more individually empowered and more efficient use of the RF spectrum.

INTRODUCTION

There has been a dramatic increase in overall demand for spectrum-based services and devices. In particular, there has been a demand for mobile spectrum-based applications. This is true for traditional, licensed services and those offered through unlicensed devices. This increased demand is propelled by a host of factors: the economy has moved towards the communications-intensive service sector; the workforce is increasingly mobile; and consumers have been quick to embrace the convenience and increased efficiency of wireless devices.

Advances in technology have significantly increased the diversity of service offerings and have also qualitatively improved existing services, thereby increasing consumer demand for spectrum-based services and devices. For example, advances in spread spectrum techniques have spawned significant consumer demand for associated applications. Spread spectrum technology, which spreads the energy of a radio signal over a bandwidth that is greater than that required to transmit a particular signal,[3] was originally devel-

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* Dr. Paul Kolodzy was appointed as director of the Center for Wireless Network Security (WiNSeC) at Stevens Institute of Technology in November 2002. WiNSeC provides leadership in advanced technology to provide secure, interoperable wireless operations for consumer, commercial, financial, defense, and public safety applications under duress and within complex environments. He also is a member of the faculty in the schools of Engineering and Technology Management.

Prior to joining WiNSeC, Dr. Kolodzy served as senior spectrum policy advisor at the Federal Communications Commission (FCC) and director of the Spectrum Policy Task Force. Kolodzy also served as program manager at the Defense Advanced Research Projects Agency (DARPA) in the Advanced Technology Office, where he managed more than $200 million worth of research and development for communications programs to develop generation-after-next capabilities.

[1] *See generally*, Michael K. Powell, Commissioner, Federal Communications Commission. The Age of Personal Communications, Remarks before The National Press Club (Jan. 14, 2004).

[2] *Id.*

[3] The FCC rules define "spread spectrum systems" as follows:

> A spread spectrum system is an information bearing communications system in which: (1) Information is conveyed by modulation of a carrier by some conven-

oped for military applications. Commercial applications of spread spectrum technology were permitted in 1985. This technology has been used for cordless telephones for some time. Still, advances in this technology, coupled with developments of industry protocols for its use—such as Bluetooth and WiFi—have contributed to the surging demand for wireless devices that enable computer and data networking through wireless local area networks ("WLANs"). Consumers are increasingly demanding wireless computer and data networking because most businesses and many homes now have multiple computers. As a result, users often find it desirable to install local area networks to share resources, such as printers, scanners, and broadband or dial-up Internet connections. Indeed, developing a local area network using wireless unlicensed devices can be a cost-attractive mobile alternative to wired networks. Thus, the technology development rush of the migration to digital has generated a great need for spectrum.

Historically, due in large part to technological limitations in radio performance, spectrum policies have parceled, or assigned, spectrum according to particular operational frequencies and geographic areas of operation. However, developments in technology have the potential to usher in a new age in RF spectrum accessibility. For instance, developments in such areas as components for wideband frequency systems,[4] systems concepts, and sensing and understanding of the RF environment are now beginning to impact the scientific community as well as the designers and products. These technologies impact how both government and commercial users access the RF spectrum.

These technological developments for radio are akin to many other historical developments that have enabled automation in many areas of manufacturing, transportation, and financial transactions. For example, the ability to accurately measure position in a milling machine has allowed the development of automated systems that translate a computer aided design ("CAD") drawing directly into a finished product. Changes in material properties and environmental conditions, such as temperature, are compensated automatically through the computer control software. In transportation, the advances in sensing exhaust and computer control have allowed systems to modify dozens of operational parameters in automotive engines to reduce particular effluents, without significant degradation in performance. Therefore, the designer need only set the desired level of effluent and the system will modify its operation to meet that requirement. The early 21st century may be marked for a similar set of advances in radio technology that will allow such dynamics to be incorporated in the United States' spectrum policy.

This new ability to allow dynamics in spectrum policy may well provide new opportunities to share and more intensively utilize the spectrum resource. As reported by the FCC Spectrum Policy Task Force ("SPTF"), the ability to opportunistically share the spectrum should be explored for a number of reasons.[5] For instance, the FCC task force explained:

> Another significant reason that spectrum may be underutilized, as noted earlier, is that the Commission's regulations do not reflect and capitalize upon the significant advancements made in spectrum-based radio technologies. Because new, smart technologies can sense the spectrum environment and because they have the agility to dynamically adapt or adjust their operations, increasing access to the spectrum for smart technologies, such as software-defined radios, can improve utilization, through more efficient access, of the radio spectrum without detriment to existing spectrum users.[6]

These new opportunities may not only allow greater opportunity for new consumer devices to access the spectrum, but may also challenge the assumption that spectrum is a scarce resource.[7]

This article will briefly review the changes that are currently underway in technology that could necessitate the need for dynamic policies. There

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tional means, (2) the bandwidth is deliberately widened by means of a spreading function over that which would be needed to transmit the information alone. (In some spread spectrum systems, a portion of the information being conveyed by the system may be contained in the spreading function.)

FCC Frequency Allocations and Radio Treaty Matters, 47 C.F.R. §2.1 (2003).

[4] *See generally,* DEPT. OF DEFENSE, DEF. SCI. BD. TASK FORCE, Wideband Radio Frequency Modulation, *at* www.acq.osd.mil/dsb/wideband.pdf (July 2003).

[5] FEDERAL COMMUNICATIONS COMMISSION, SPECTRUM POLICY TASK FORCE REPORT, ET Dkt. No. 02-135, Section IVC, *at* http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf (Nov. 15, 2002).

[6] *Id.*

[7] *See* J. Gregory Sidak, *Telecommunications in Jericho,* 81 CAL. L. REV. 1209, 1227 (1993).

are many types of dynamics that can be allowed by spectrum policies. This article will discuss seven of these dynamics and the opportunities that would be available if they are implemented. Finally, this article will review challenges in developing and implementing dynamic policies in order to better map the path forward for such a policy development.

CHANGES IN TECHNOLOGY

Technological advances are contributing to the increased diversity of spectrum-based consumer applications and, consequently, their use is resulting in greater demand for spectrum. In addition, technological advances are providing potential answers to current spectrum policy challenges. Some recent and significant technological advances include the increased use of digital technologies and the development of software-defined radios.

Growth in the use of digital technology has significant ramifications for interference management. Digital signals are inherently more robust and resistant to interference than analog signals. Moreover, digital signal processing techniques, such as coding and error correction, are more effective at rejecting interfering signals. Thus, spectrum policies can, and should, reflect this increased ability to tolerate interference. Furthermore, given the increased ability of new digital technologies to monitor their local RF environment and operate more dynamically than traditional technologies, the predictive models used by regulators can be updated, and perhaps eventually replaced, by techniques that take into account and assess actual, rather than predicted, interference.

The availability of wider band power amplifiers, synthesizers, and A/D converters is rapidly changing the capabilities of systems accessing the RF spectrum. In fact, there are four new capabilities that will help enable dynamic spectrum policies: flexibility, agility, RF sensing, and networking.

- *Flexibility* is the ability to change the waveform and the configuration of a device. That is, a cell tower that can operate in the cell band for telephony purposes but change its waveform to get telemetry from vending machines during low usage periods is an example of flexibility. The same band is used for two very different roles and the radio characteristics must reflect the different requirements such as in data rate, range, and latency.
- *Agility* is the ability to change the spectral band in which a device will operate. Cell phones have rudimentary agility since they can operate in two or more bands (e.g. 900 and 1900 MHz). Combining both agility and flexibility is the penultimate in "non-adaptive" radios since the radio can use different waveforms in different bands. It should be noted, that there are specific technology limitations as to the agility and flexibility that can be afforded by current technology.
- *Sensing* is the next step in providing dynamics. Sensing allows a radio to be self-aware and thus able to measure its environment and potentially measure its impact to its environment. Sensing is necessary if a device is to change in operation due to location or conditions.
- *Networking*, specifically wireless networking, enables "group"-wise interactions between radios. Those interactions can be useful for sensing where the combination of many measurements can provide a better understanding of the environment. It can also be for adaptation where the group can determine a more optimal use of the spectrum resource over an individual radio.

These technologies have enabled the development of two new classes of radios: software definable radios ("SDRs") and adoptive cognitive radios ("ACRs"). Although in the early stages of development, the new radio class ushers in new possibilities, as well as pitfalls for technology policy. The flexibility provided by these radio classes allow for more dynamics within radio operations.

SDRs are the first in the progression. They provide software control of a variety of modulation techniques, wide-band or narrow-band operation, communications security functions (such as hopping), and waveform requirements. In essence, components can be controlled digitally, and thus, defined by software. SDRs illustrate how technological advances can enable more intensive spectrum use. Unlike traditional radios in which technical characteristics are fixed at the time of manufacture and subsequently cannot be modified, operating parameters in SDRs, such as the operational frequency and modulation type, are determined by software. The fact that these parameters are determined by software means that a SDR can be programmed to transmit and receive on many frequencies, and to use any desired modulation or transmission format, within the limits of its hardware design. In addition, software-defined radio can be programmed to receive different types of radio signals on varying frequencies.

An ACR adds both a sensing and adaptation element to the SDR. The SDR technology provides the system developer with flexibility within the components. Cognitive radio provides both environmental sensing components, which are able to understand the environment, and the *reasoning* components, which determine what adaptations are necessary. Today, WiFi devices use media-access-and-control ("MAC") enabled radios that use carrier-sense-multiple-access ("CSMA"). They are rudimentary cognitive radios. They sense their environment and change their configuration to avoid interfering with other users. However, it is non-cooperative sensing that exploits the full promise of ACR technology.

With ACR technology, the policy makers now look at rules that have situational dependencies. That is, rules that vary due to geographic location, amount of interference, time of day, and proximity to high priority users. Two examples are increased power for unlicensed devices in low-usage/rural areas, and interruptible spectrum for public safety applications. These are discussed in the Opportunities and Challenges sections of this article.

These new technologies and radio classes, albeit in their nascent stages of development, are providing many new tools to the system developer. The tools allow for more intensive use of the spectrum. However, the fundamental aspect of each of these technologies is the ability to change configuration to meet new requirements. This capacity to change configuration and react to system dynamics will require the development of dynamic spectral policies.

DYNAMIC SPECTRUM POLICIES

Currently, the spectrum policy in the United States has dynamics with respect to frequency. That is, spectrum policies differ with regard to where a device is operating in the RF spectrum. Devices operating in the radio broadcasting bands from 88 to 108 MHz must conform to the FM broadcasting rules of Part 73.[8] Currently, new devices are being produced that can change frequency readily. These devices must incorporate aspects of the policy from each of the different spectral areas in which they operate. New devices that incorporate WiFi with cellular telephones are one example of how multiple spectrum policies are merged within a single device. However, the dynamics are quite limited in that case. This article proposes that other operational dimensions of spectrum policy will avail themselves to dynamics—specifically, time, space, and interference.

An example of using the *time dynamic* in spectrum policy was exhibited in the early days of radio. Particular stations would cease transmission late at night and resume early the next morning. Time-based dynamics can be extended significantly from this example. One extension is to include scheduled/expected interactions that are quite predictable. These may include secondary market transactions where a separate provider accesses the spectrum. These also may include the flexible access of a band by the primary user for a different application, such as reusing a cell tower to provide data telemetry from vending machines.

A further extension of this concept is more opportunistic in character. It may include using the spectrum for a short time, or within a very limited area. One example is "spot" use of micro-transactions within the secondary market. Another example could be a non-cooperative use of spectrum that is not currently in use. However, these opportunistic uses would likely exhibit quick transactions that potentially could be impractical for human intervention. Therefore, automated schemes would be used similar to those used in financial transactions on the New York Stock Exchange.

Spatial dynamics are appropriate in cases where the location of a device would determine its operational characteristics. One proposal for spatial dynamics includes allowing increased power transmission of unlicensed devices in rural environs.[9]

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[8] *See generally,* FCC Radio Broadcast Services, 47 C.F.R. §73.201 - 73.333 (2003).

[9] *In re* Facilitating The Provision of Spectrum-Based Services to Rural Areas, *Notice of Proposed Rulmaking,* 18 FCC Rcd. 20802, para. 49 (2003).

Another proposal is the use of unlicensed devices in bands where the device is sufficiently far away from a UHF TV transmitter.[10] Location sensing would be necessary for the first proposal. Signal strength sensing would be necessary for the second proposal. In either case, since the transmitters are stationary, the location information is static. Therefore, once the boundaries are determined through calculation or measurement, then these boundaries could be programmed into a device. However, extending the concept to avoid mobile transmitters creates additional complexities. The distance from mobile transmitters would be constantly changing, and therefore, more automated sensing and interference avoidance techniques would be required.

Interference dynamics is the third case to be investigated. In contrast to the spatial and temporal dynamics, this dimension would need to understand not only its environment, but also the impact of its own transmission on the surrounding environment. The capacity to accurately measure and model the environment would be needed. There has been a significant amount of research and development over the past decade to improve the fidelity of simulation and modeling of RF propagation. Companies such as Remcom distribute products that reflect these developments. Additionally, device technology has significantly reduced the cost of RF sensing, while also improving fidelity.

The following seven cases explore how more dynamics and less certainty could be incorporated into future spectrum policies. The cases begin with small changes to current policy, and then increase both in impact and potential challenges.

Case 1: Can spectrum policies be specified to location?

The density of RF emitting devices has a direct impact on potential interference between the devices. Therefore, worst-case analysis is done to limit each device's emission characteristics. However, specific regions can be selected to have either more stringent or more relaxed emission characteristics. The advent of e911-capable systems incorporating either GPS measurements, triangulation techniques between base stations, or a combination of techniques could provide the means to determine location. The recent creation of an UWB friendly zone in Singapore is a simple, static example of a location specific policy.[11] The extension of such a concept could include the ability to change the zone in time to reflect either the case of too much interference or an emergency situation.

Case 2: Can spectrum policies be limited by duration?

Could policies be incorporated into devices that have a finite lifetime? After that lifetime, the devices could either become inoperative or default to some common policy. This potentially enables more experimentation and/or quicker responses to make spectrum policy decisions in times of emergency. A device would have to obtain the timestamp from either an internal clock or an external clock transmitted on some beacon, currently done with the national time stamp system at 60 KHz.

Case 3: Can spectrum policies be specified to RF condition?

Since worst-case analysis is used to prevent interference, the average RF interference condition differs significantly from the analysis. If a device can be aware of its environment, then its emission characteristics can be altered *in situ* while still having confidence that interference will be avoided. This understanding of its environment might be done in a multitude of ways. A classic example of this is currently under discussion for rural environs. In areas where there is a distinct lack of receivers for which a 2.4 GHz WiFi transmitter could cause interference, is there an opportunity to raise the emission limits of those devices? This could be done by using a geographic delineation as described in Case 1, or it could be accom-

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[10] *In re* Additional Spectrum for Unlicensed Devices Below 900 MHz, *Notice of Inquiry,* 17 FCC Rcd. 25632, para. 8-9 (2002).

[11] This uses the entire Science Park II in Singapore as a sandbox for research and development testing. Called the UWB Friendly Zone, or UFZ, licensees are allowed full-spectrum testing of 2.2GHz to 10.6GHz up to 6dB above the general Part 15 level (–41.3dBm per MHz when over 960MHz) allowed.

plished by sensing the environment as described in this case.

Case 4: Can spectrum policies change with time?

It was discussed that spectrum policies could change with time on a periodic basis, *e.g.*, hour of the day. However, if Case 2 is acceptable, can policies be replaced on an *ad hoc* basis? One example would be using a beacon in a time of emergency—to allow all devices to switch to a different policy for enhanced public safety communications. The challenge would be ensuring the reliability of the mechanism to switch policies and creating fail-safe policies.

Case 5: Can spectrum policies be negotiated between entities?

Can entities that represent all the emitters and receivers in a local region and a specific part of the spectrum negotiate a set of policies to avoid interference? The secondary spectrum market rules[12] are a small step when there are only two entities, and only one band is within the scope of the negotiations. But, as with negotiated pollution rights,[13] can entities trade accepting interference at one time, while imposing interference at a different time? Can the regulatory agency impose an "über policy" that demarks limits for those negotiated values?

Case 6: Can spectrum policies be different based upon the impact a device has on the environment?

Currently, all signals are created equally, with respect to interference. A highly correlated signal (the easiest to remove) is considered just as harmful as an uncorrelated signal (the most difficult to remove).[14] But there are questions to consider: should higher transmission powers be allowed for easily filterable signals; should there be an implicit requirement on receivers to employ the signal processing necessary to allow such requirements; and how should those standards be developed and applied?

Case 7: Can networked devices be used for enforcement of spectrum policies?

The advent of digital systems throughout the consumer world, and the new capabilities to modify waveforms and change frequencies, will undoubtedly create the potential for serious enforcement issues (see challenges in the next section). The next generation systems are all providing some type of networking capability, either between each other or directly to the Internet. However, the proliferation of these consumer and commercial systems could also lead to the development of measurement devices for enforcement. The first requirement for these measurement devices is to monitor all of the policies that affect the spectrum. Secondly, the devices must network this information with other locally available devices to determine if there has been a breach. Finally, the device must convey this information to the appropriate regulating authority.

OPPORTUNITIES AND CHALLENGES

The incorporation of dynamic spectrum policies can provide additional capabilities to the developer, which usually translates into reduced prices and more choices for the consumer. Here, the challenge is understanding the potential of these concepts and determining the most expeditious manner to maintain the policy advantage, while limiting the challenges.

The advantages of moving toward a dynamic, device-leveled policy has been demonstrated in other areas, distinct from communications. This type of regulation is enabled by advances in: 1) knowledge of the interactions between devices and the RF propagation environment; 2) sensing techniques; and 3) control algorithms.

Regulation may be related to the engineering form of control. Control systems are developed in order to maintain the proper operation of a sys-

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[12] *See generally,* Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, *Report and Order and Further Notice of Proposed Rule Making,* 18 FCC Rcd. 20604 (2003).

[13] GEN. ACCOUNTING OFFICE, AIR POLLUTION: ALLOWANCE TRADING OFFERS AN OPPORTUNITY TO REDUCE EMISSIONS AT LESS COST 2 (1994).

[14] This phenomenon is especially true between CDMA and orthogonal CDMA, where there are losses in separating the different CDMA signals as compared to the orthogonal CDMA signals, due to selecting an appropriate signal to overlay.

tem. Proper operation can be either optimized for performance, stability/prevention of a catastrophic event, or ease of operation. In static systems, the system is developed for one operating point, irrespective of conditions, and no dynamics are present.

As systems allow for increased operational flexibility, specific control systems have been developed to transform the "fixed" systems into static "set points," or operation points that can be changed from time to time. These systems have very long time scales and thus, the dynamics are very limited. Cordless phones in the home are just one example. The consumer can select between using either a wired or wireless phone.

As systems become capable of measuring their environment, the operation points can change to address the changing conditions. These operational values become operation regions, with the operator (or regulator) determining the locally optimized operation points. For example, older cordless phones with channel selection allow a consumer to select a channel, and listen to the handset. If too much interference is present, then the consumer must select another channel to decrease interference. In this instance, the sensor is both the phone and the ear of the consumer, and the operation regions are the set of possible channels, where the consumer is the controller.

Eventually, the systems will become capable of measuring their environment with greater fidelity and with speeds quicker than that with which human intervention can adapt. At this point, the systems themselves are programmed to determine a set of locally optimized values given the state of the environment. For instance, with automated channel selections for cordless phones, the consumer is taken out of the equation and the phone can select a channel as quickly as the consumer can turn on the cordless phone.

In general, dynamics allow for greater flexibility to use a resource more efficiently and to adapt to changing conditions. The challenge is in changing "accounting-type," nationally optimized spectrum management techniques to "conditions-oriented," locally optimized spectrum management techniques. Specifically, the challenge will be to move toward technically-specified regulation. Whenever automated control mechanisms are used, specific, observable metrics are necessary for the system to function robustly.

Dynamic spectrum policies could provide many opportunities in the areas of technology development, new capabilities for the consumer, enhanced competition in the marketplace, and reduced regulation through policy-oriented management. These opportunities can usher in a new, more competitive use of the RF spectrum. Nevertheless, there are challenges in providing ubiquitous technical definitions and advanced enforcement techniques.

OPPORTUNITIES

Spectrum Access

One opportunity that dynamic spectral policies provide is the capacity to locally optimize operations so as to better utilize the RF spectrum. This optimization can be performed in space, time, and/or frequency. Two specific examples are captured by the FCC SPTF report: *opportunistic spectrum access* and *interruptible spectrum access.*[15] In the former, devices attempt to locate spectrum that lays fallow, and either cooperatively, or uncooperatively accesses that spectrum without interfering with other users that may suddenly appear. Alternatively, devices are instructed to cooperatively reduce their spectrum use, while others are allowed to increase their spectrum use. In general, interruptible spectrum is thought to be most useful for spectral bands that have low average use and high peak use.

The onset of Software Definable Radio and Adaptive Cognitive Radio technology is enabling *opportunistic spectrum access.* Opportunistic spectrum access looks for "holes" in the spectrum and then adjusts the link parameters to conform to the hole. That is, it transmits over sections of unused spectrum. However, it has the additional complexity of listening for other transmitters in order to vacate a hole when other, non-opportunistic spectrum devices are accessing it. This technology combines the flexible SDR characteristic with the sensing and adaptive characteristics of ACR technology. The potential gain is the higher utilization of infrequently used spectrum. It has

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[15] Federal Communications Commission, Spectrum Policy Task Force Report, ET Dkt. No. 02-135, *at* http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf (Nov. 15, 2002).

been estimated that on average less than five percent, and possibly as little as one percent of the spectrum, is issued. Opportunistic spectrum technology is under development by the DARPA XG program, with the goal of increasing accessible spectrum by a factor of twenty.

The availability of Software Definable Radios also allows high priority users, such as public service users, to access the radio spectrum on an "as needed" basis. This is called *interruptible spectrum access* because the normal user's spectrum access is interrupted in order to provide the spectral resource to a higher priority user. For example, in a major regional disaster, there will be a significant increase in public safety users due to the influx of responders from outside the immediate area. Such an influx of radio users would require additional spectrum to cope with the additional load. Additional spectrum could be temporarily obtained from adjacent spectral bands from the immediate area of the disaster. After the need diminished, perhaps in minutes or hours, the spectrum would be released back to the primary licensee. Mechanisms may be developed to compensate the primary licensee for their inconvenience or loss of revenue.

Spectrum Barriers

The advent of policies that change with time and space will ultimately allow for greater access to the fallow spectrum, as well as lower infrastructure costs. If policies can be malleable to the specific conditions in order to allow greater access to the RF spectrum, then the cost barriers for new entrants should be reduced. Thus, new consumer products can be developed using lower cost spectrum. The lower barriers will allow developers to use more resources in developing techniques to access the spectrum instead of investing in unused spectrum. This is similar to oil drilling. If oil exists in an area that does not allow for exploration, then the technology will not be developed to access the oil. As soon as an area becomes accessible, then cost-effective technology is developed to access the oil. Tradeoffs are made to insure that the total cost, infrastructure, and raw material are minimized.

Lower infrastructure costs are obtained through the ability to have policies change when conditions are warranted. In the example described above, for areas of low use (*e.g.*, rural), using a higher transmit power for unlicensed devices would reduce the number of access points that are needed to service an area. The optimal density of access points is related to the number of users within the footprint of the access point. Essentially, a provider wants a specific number of users per access point. Therefore, current rules have a highly suboptimal number of users per access point in low usage areas and a highly suboptimal number of access points per users in high usage areas. The current set of rules allows the area covered by the access point to be reduced, but it does not allow the increase of power. Dynamic policies associated with the state of the RF environment could allow a more optimal design, and thus lower infrastructure cost.

In congested urban areas, where high transmitter power levels on one frequency can often adversely impact the use of other frequencies, the dynamic policies could enable the use of low power transmissions. For example, the SPTF suggested that high power digital television broadcasters could be permitted to operate single frequency low power distributed transmission systems within their present service areas. Other site-licensed services could be provided similar flexibility. The SPTF also suggested considering whether it should offer incentives for reducing transmitter power, such as an increased interference protection, that could be possible with dynamic policies.[16]

Design Dynamics

Dynamic policies will alter the manner in which developers make design decisions. Devices allowing dynamic policies will be more complex and thus more expensive than static policy devices. However, these policies need to be offset with the additional advantages of spectrum availability, less infrastructure, and locally optimized performance. Previously, the design criterion was optimizing cost-performance ratio for a specific policy in a particular band. The number of design parameters was smaller. Since the cost of the infrastructure could be amortized over large number of consumer devices, the primary focus was reducing the cost of those consumer devices.

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[16] *Id.* at 54-60.

In the case where dynamic policies overlay current static policies, the choice for the designer is whether to provide those new capabilities, at additional cost for each device. An example of this is the question of whether to use licensed spectrum, secondary market spectrum, or unlicensed devices. Licensed spectrum has an assured quality of spectrum access and interference with higher spectrum costs. Each of the other choices has less assurance of quality but at lower spectrum costs.

Secondary market spectrum has a negotiated level of quality of spectrum access with a negotiated cost. The quality and costs are variable and would depict the value of the spectrum at that time and place, and the sacrifices the secondary user would be willing to accept. The designer could put in the capacity to move to a small number of different spectral bands in order to provide more flexibility, with the negotiation process. The tradeoff will be the extra expense for the flexibility with the potential reduced cost of the secondary license.

The use of opportunistic unlicensed devices does not have any explicit associated costs for spectrum access. The device would have to accept short range transmission due to limitations in the Part 15 rules; or it would need to develop a trust relationship with many other unlicensed devices to create an *ad hoc* network to extend its range; or it would need sophisticated sensing and adaptation devices over a wide frequency range in order to operate in a higher power, opportunistic mode.

It is easy to expect that with dynamic policies an explosion of new sensing devices and cooperative networks will be developed. These will be aimed at providing cost-effective solutions for both licensed and unlicensed uses. The incorporation of more processing capacity within licensed and unlicensed devices will ultimately give system developers a large number of choices in order to provide new, variable quality services to the consumer.

Secondary Markets

Although the current instantiation of secondary markets is envisioned for static use of a primary licensee's access to the spectrum, there are additional possibilities. Secondary markets can be involved with the trading and selling of time-space-frequency parcels. However, the advanced technologies that were listed above can provide a new means in which a potential secondary market user can obtain spectrum. The user can search for available spectrum and then ensure that the secondary use devices conform to the specific time-space-frequency policy. Therefore, the device would be malleable to a variety of policies. That type of flexibility can provide the basis for additional dynamics within spectrum policy because the technology will exist to employ sophisticated policy mechanisms. The advantage of these policies to secondary markets is an even higher utilization of the spectrum resource, advanced techniques for micro-transactions, and the potential development of multiple policy devices.

Policy-oriented Regulation

Spectrum policy is currently instantiated in a series of specific rules for each application. Four of the applications are: telephony/common carrier; radio/TV broadcasting; Cable/DBS; and private/commercial radio. The rules cross the boundaries from the content to the application services to the logical and then to the physical layer. When these applications were initially deployed, there were significant differences in each of the layers to warrant such cross-layer vertical silos. Bandwidths, power levels, propagation environments, transmitter-receiver geometries, and interference susceptibility of each application were unique. Therefore, spectrum was allocated according to services. In fact, terms such as "broadcast spectrum" are used instead of a more accurate expression, such as "spectrum allocated for broadcast services."

Much is changing. The common media for all services is spectrum. Spectrum is available in the air, as well as in coaxial copper cable, twisted pair cable, fiber optic cable, and now, power lines. Each of these applications has specific attributes, such as how well an RF band will propagate through the particular media. Each application also has a finite capacity to transmit information and that capacity is always related to distance. They each can use any, or all of the media. In fact, many of them do exactly that. For example, broadcast signals are transmitted through the air; through coaxial copper cable via cable TV; through twisted pair via CAT5 computer cable; through fiber optic computer cable; and through home power lines used for computer networking.

In essence, spectrum is used in many types of media to transmit information.

With the advent of digital migration, all digits are created equally. The only difference between the various applications is how many digits they need to transmit, and how far they need to transmit them. Depending on the amount of infrastructure and complexity of the transmission system, the spectrum is becoming a "common carrier" of information.

The "common carrier" view of spectrum leads to a fundamentally distinct way to regulate spectrum in the dynamic policy era. The focus should move away from spectrum rules for an application and toward spectrum access policy, with the flexibility to be dynamic by incorporating new technologies and socio-economic needs. The focus should be on applying uniform rules based upon clearly articulated rights and responsibilities for access to the spectrum. Those rules employ specific, unambiguous definitions. Therefore, regulation based on a finite set of specific engineering terms would allow greater flexibility for the regulators to provide a richer source of possibilities for consumers and industry.

CHALLENGES

The challenges associated with moving toward dynamic policies will be: 1) clearly defining the technical regimes in which dynamic policies will operate; 2) providing sufficient safeguards and incentives for incumbent license holders; and 3) developing new techniques for enforcement that will address the complex interactions between devices employing dynamic policies. Each of these is a complex challenge that will require a significant investment. The purpose of this article is to outline the basic issues and potential solutions.

Defining and Using Dynamic Policies

The first challenge requires the development of metrics. The policy goal of preventing interference is generally recalculated as to the parameters for the transmitter (*e.g.*, center frequency, bandwidth, power spectral density, antenna gain). This represents a static policy. If the metric for interference was well defined, then the policy could be to operate under a much broader set of transmitter parameters, with the explicit goal of preventing interference up a particular level within the radius of the transmitter. The interference metric could also be contextually sensitive with respect to location, time, or condition of the RF environment.

Therefore, the means to regulate a dynamic policy requires a measurable parameter of which to control and the set-point for that parameter. As with the example above, most aspects of radio regulation are to prevent interference between disparate systems. The SPTF also acknowledges that a better ubiquitous definition of interference[17] needs to be developed, stating that, "Quantitative standards reflecting real-time spectrum use would provide users with more certainty and, at the same time, would facilitate enforcement."[18]

The SPTF went on to propose one such definition, the interference temperature, as the interference metric. The rationale for this metric is to define the thresholds of harm to a radio system. However, the same metric can provide a means to dynamically change operating points in a consistent manner across the spectrum, and across disparate applications. However, this does not mean that the same value of the metric is used across all applications. The metric provides a means for licensed and unlicensed devices to operate together.

The first challenge in developing dynamic policy is defining the appropriate metrics. The next challenge is determining the means by which the metric can be applied. The interference metric must be indicative of the impact of the transmitter on the surrounding region. In a static and well-defined geometry, a measurement at the transmitter provides sufficient information from which to extrapolate the value of the interference metric

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[17] 47 C.F.R. §2.1(c) (2003) (according to the FCC rules, "interference" is defined as follows: "The effect of unwanted energy due to one or a combination of emissions, radiations, or inductions upon reception in a radio-communication system, manifested by any performance degradation, misinterpretation, or loss of information which could be extracted in the absence of such unwanted energy."). "Harmful interference" is defined by the FCC as: "Interference which endangers the functioning of a radionavigation service or other safety services or seriously degrades, obstructs, or repeatedly interrupts a radiocommunication service operating in accordance with these [international] Radio Regulations." *Id.*

[18] FEDERAL COMMUNICATIONS COMMISSION, SPECTRUM POLICY TASK FORCE REPORT, ET Dkt. No. 02-135, *at* http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf (Nov. 15, 2002).

across a wide area. However, the highest density of use of the RF spectrum is in areas with complex geometry, large number of users, and where most of them are mobile. The technology for propagation models, inclusive of complex environments, is improving and can provide qualitative results for extrapolation. But, they are insufficient for quantitative analysis. Therefore, multiple measurements distributed across the operational area are needed to accurately measure the interference metric.

The next challenge is developing the mechanism to obtain those multiple measurements. One possible mechanism to obtain multiple measurements would be to develop monitoring stations such as pollution monitoring devices. The first obstacle is to determine who would appropriate the funds to develop and deploy such a system. If it is a federally funded system, should the system be managed by the FCC, the National Telecommunications and Information Administration, or another government entity? Other questions include: who would ensure the accuracy of the measurements and who could challenge the accuracy of the devices? Another challenge is the dissemination of the results of the measurements—would there be an interface to all service providers and users who could obtain the data on a near real-time basis? Also, would the data be broadcast to all devices, or should it be available by request?

Finally, determining the ramifications of non-compliance with the policy must be considered. For instance, the need for reliable communications, free from interference, is a paramount requirement for public safety communications. Therefore, mechanisms for obtaining and releasing spectrum need to be highly predictable. "Beaconing" is one such mechanism. The question then arises as to how beaconing should be used. Should the public safety user beacon in order to announce that the spectrum is being usurped? Or should the public safety user beacon to announce that the spectrum is being released? Propagation challenges may create shadow zones that could prevent a non-public safety user from hearing the beacon. So, the technical challenge is to create the proper signaling technique, while the policy challenges involve assuring the public that the system will work; determining who is liable if it does not work; and, determining what type of compensation may be allowed between the public safety user and the primary licensee.

Safeguards and Incentives for Incumbent Users

The presumption that dynamic policies are desired is in the eye of the beholder. Incumbent license holders that are currently using all of their rights to access the spectrum may initially see no value in having dynamic policies. They use market mechanisms to balance the desire to increase efficiency versus obtaining additional licensed spectrum. Therefore, a policy that allows others access to the spectrum for which they have a license is not desired. In fact, it should be actively avoided due to the potential to seriously impact their business model if capacity is reduced due to new sources of interference. The desired impact of dynamic policies is to improve spectrum utilization and thus provide more competition and products to the market. The difficulty is to determine how such impacts can be obtained while at the same time providing assurances to current license holders and incentives for increased utilization through dynamics.

Enforcement of Dynamic Policies

Enforcement for static systems is already a problem due to the amount of resources necessary to authorize equipment; the requirement of obtaining proof that violations have occurred; and, the determination of the violators' identities. As the systems become more and more dynamic, there is an increase in the number of potential interactions that can lead to a violation. Additionally, this leads to a decrease of the time and spatial scales of these interactions. Both of these changes will amplify enforcement obstacle.

Equipment Authorization

Initial equipment authorizations have two components that increase in complexity with the onset of dynamic policies—evaluation criteria and security certification. The capacities to modify waveforms, change operating conditions, and change transmission frequencies all contribute to an exponential growth in adverse interactions between systems. Exhaustive testing becomes unattainable because of the sheer number of combinations. Therefore, the challenge will be developing practical test plans for certification.

Software security must also be considered. Software can be modified in order to allow policies to change on periodic and a-periodic cycles. The security of the software is critical to insure that rogue behavior is not programmed into the device. If the consumer can access the device's software, then the consumer can instruct the radio to perform outside of the permitted operational parameters. Issues that must be addressed include: how is software protected to insure that this abhorrent behavior does not occur; how much protection is necessary; how is it tested to insure that it is sufficiently secure; and who is liable if it is not secure.

Monitoring Mechanisms

The next challenge for using dynamic policies is finding mechanisms to observe violations. Since the number of combinations of interactions is high, and the mobility and agility of future systems is great, then how should enforcement systems be developed to observe all of these new capabilities? Three possible mechanisms are suggested: authority-based, network-based, and infrastructure-based mechanisms. The greatest challenges for development of such monitoring mechanisms are the costs of equipment and analysis, and the concerns over civil liberties.

The authority-based system is for a regulatory agency to deploy a national monitoring system. The cost would be significant, and it would put a strain on the regulatory agency to analyze such large amounts of data. In addition, there could be civil liberty challenges to a regulatory agency having compiled such a database.

The network-based system would use the variety of user devices already available to monitor the activity of the RF spectrum. Small modifications, and thus an increase in cost, would be necessary for each device to expand its spectral range of operation. The challenges would be to: 1) provide sufficient confidence in the accuracy of the measurements; 2) obtain sufficient geolocation information to make the information valuable; and 3) collect and disseminate the information to enforcement organizations within the regulatory community.

The infrastructure-based system is a combination of authority-based and network-based systems. The goal would be to use pre-existing infrastructure such as cell towers and Federal Aviation Administration towers. The network is already in place and could probably be changed to incorporate a receive-only sensor without any significant degradation to operations. The challenge would be to obtain the authority to equip each site, and to have priority access to the network from each site.

Identity Management

The third challenge is to obtain the identity of the potential violator. Currently, there is only one specific mechanism to accomplish this—using geolocation. Geolocation by itself is not sufficient for identity, but it is currently the only assured technique that is available. Network-based monitoring systems, as described above, could provide a potential system for making geolocation measurements. Again, this could cause potential civil liberties concerns.

Another concept is to require a unique RF signature for each device. This RF signature could be akin to an Internet Protocol (IP) address that each computing device has when connected to the Internet.[19] This was explored during the workshops held for the FCC SPTF. However, concerns about anonymity were raised. Yet, even with a unique identifier, the association of that identifier with a person and a place are necessary for enforcement.

SUMMARY

Communications has entered the digital era. The merging of communications and computing is opening an array of new possibilities to use the RF spectrum. Dynamic spectrum policies offer the potential benefits of greater diversity of policies to match the needs of the consumer who are demanding new ways to be informed while mobile. Those needs change with application, location, and time, as well as with the overall condi-

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[19] Currently, there are insufficient addresses to have a unique address for each device. However, there are extensions currently being deployed to allow trillions (10^{12}) of unique addresses.

tion of the RF environment. By allowing dynamics, there is a greater potential for higher utilization and more ingenious uses of the spectrum. Although the potential benefits are great, the challenges can be just as great. No longer can subjective terms such as "harmful" be used in automated dynamic systems. New, highly encompassing metrics need to be developed. Additionally, the complexity for enforcing new dynamic policies is significantly greater than for static policies. New techniques for enforcement that can address these complexities are needed; otherwise, incumbent users will be wary of any changes to the status quo.