The Path to Market Success for Dynamic Spectrum Access Technology

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ABSTRACT

Rapid progress is being made in the technology for dynamic spectrum access (DSA) radio systems. However, the structure and dynamics of the wireless services market must also evolve for DSA to succeed. This article examines the interlinked technical and economic issues associated with markets for DSA-based wireless services. We use this analysis to make technical and policy recommendations supporting the commercial success of DSA technology.

INTRODUCTION

Dynamic spectrum access (DSA) radio technology promises to increase spectrum sharing and thus help overcome the lack of available spectrum for new communication services. Currently, spectrum sharing is limited to simple approaches such as low-power unlicensed devices. New types of spectrum sharing enabled by DSA include higher-power transmission at times when the primary users of a band are inactive, real-time trading of spectrum access rights, and collaboration among unlicensed users to more efficiently share spectrum resources.

DSA will provide significant economic and social benefits only if it becomes widely available and utilized — that is, if wireless services based on DSA are commercially successful. For this to occur, the wireless services market itself must evolve. New value chains, market incentives, and ways of managing risk must develop around the new features of DSA radios. Product features and technical capabilities that support the necessary changes in the market are just as important as the core spectrum access features of DSA radios.

In this article we analyze the interactions between DSA technology and the wireless services market. We make recommendations for how the technology, markets, and regulations ought to co-evolve to overcome potential barriers to the success of DSA.

Our recommendations fit within current regulatory and policy frameworks, making them realistic short-term steps. There also are fundamental policy reforms that can accelerate and help maximize the benefits of DSA. We briefly discuss some of the long-term possibilities in the final section.

DEFINITIONS

Before proceeding, we define the key terms used in our discussion.

A *band* is a contiguous range of frequencies subject to the same regulatory treatment. Traditionally, most commercial bands were allocated via static spectrum licenses, which specify a band and grant the licensee protection against in-band interference from third parties. For example, both over-the-air broadcasters and commercial cellular service providers operate in specified bands under restricted-use licenses administered by the government.

DSA is defined in draft standard IEEE 1900.1 as: "a technique by which a radio system dynamically adapts to select operating spectrum to use available (in local time-frequency space) spectrum holes with limited spectrum use rights." Thus, DSA technology encompasses a wide range of radio system capabilities. A DSA radio may be *agile* — able to operate in many different bands, and may be *flexible* — capable of supporting many different transmission standards or waveforms. However, neither of these features is required for DSA. Many DSA devices support only one waveform and operate in a single band.

DSA technology includes cognitive radio (CR) technology, which may be used to control DSA. IEEE 1900.1 defines CR as: "a radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives." Some cognitive radios use artificial intelligence techniques, and others use simpler control mechanisms.

There is a hierarchy of spectrum access rights. A *primary rights holder* (or *primary user*) is an entity who holds a spectrum access right that is protected from interference. Most commonly, these rights are assigned to a single entity, although there are *co-primary users* in some bands who must coordinate with each other. A

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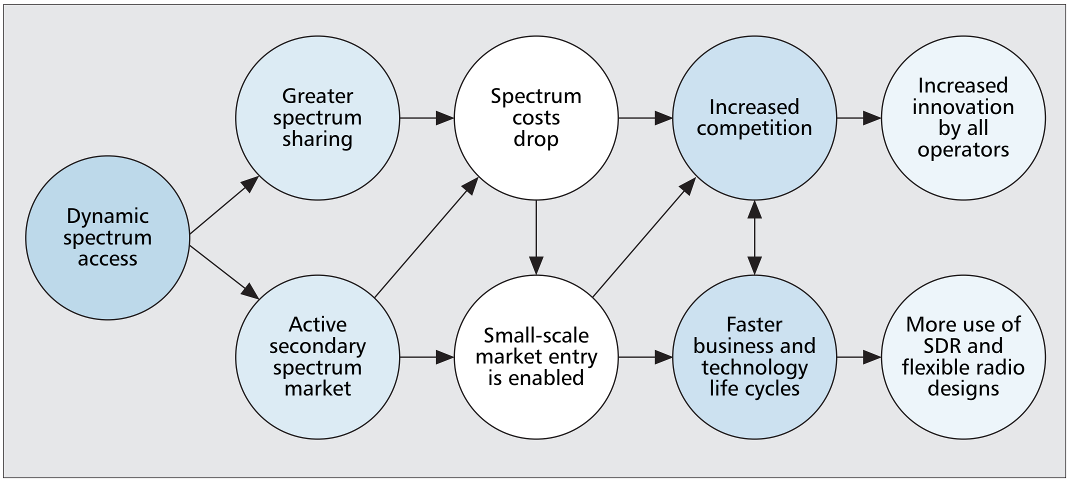


Figure 1. *Market dynamics expected to result from wide use of dynamic spectrum access technology.*

The effects of DSA as described will occur only if there is sufficient liquidity in the spectrum market to enable the deployment of DSA-based services. There are three enablers for market liquidity: available spectrum, customer demand, and low transaction costs.

secondary user is an entity accessing a band that must avoid causing interference to its primary users. There are often multiple secondary users contending for access to a single band.

There are two main frameworks for sharing spectrum between primary and secondary users: *cooperative* DSA and *noncooperative* DSA. In cooperative DSA, a secondary user may use a band only with the permission of the primary rights holder of that band. Usually, the parties enter into a contract involving payment for access rights. In noncooperative DSA, the secondary user does not require permission from the primary rights holder. By analogy to property law, *easements* created by regulatory authorities specify the conditions and requirements for noncooperative spectrum access in a given band. Low power ultra-wide-band (UWB) devices are an example of non-cooperative spectrum sharing via an easement.

Spectrum access rights are traded in a *secondary spectrum market*. What is traded may include primary (exclusive use) rights; "secondary" in this context refers to trading subsequent to the initial assignment of rights by regulators. In noncooperative DSA, secondary access opportunities are discovered and exploited rather than traded, but it still is useful to consider it as a spectrum market subject to supply and demand behaviors.

In any DSA context, whether cooperative or noncooperative, a policy or procedure called a *spectrum etiquette* controls secondary access to each shared band. This may specify only low-level transmission features such as output power, as in the case of current unlicensed bands, or it may require higher level behaviors such as listen-before-talk. The etiquette in force in a given band may be established by industry standards, by regulators, or by cooperative DSA contract.

Market Dynamics

DSA significantly increases opportunities for spectrum sharing. One way it does this is to stimulate trading in the spectrum market, because the primary rights holder need not vacate a band before offering access rights to someone else. Sharing also is increased by the coexistence of secondary users with (noncooperative) primary rights holders and by the increased number of situations where spectrum managers can safely allocate co-primary licenses.

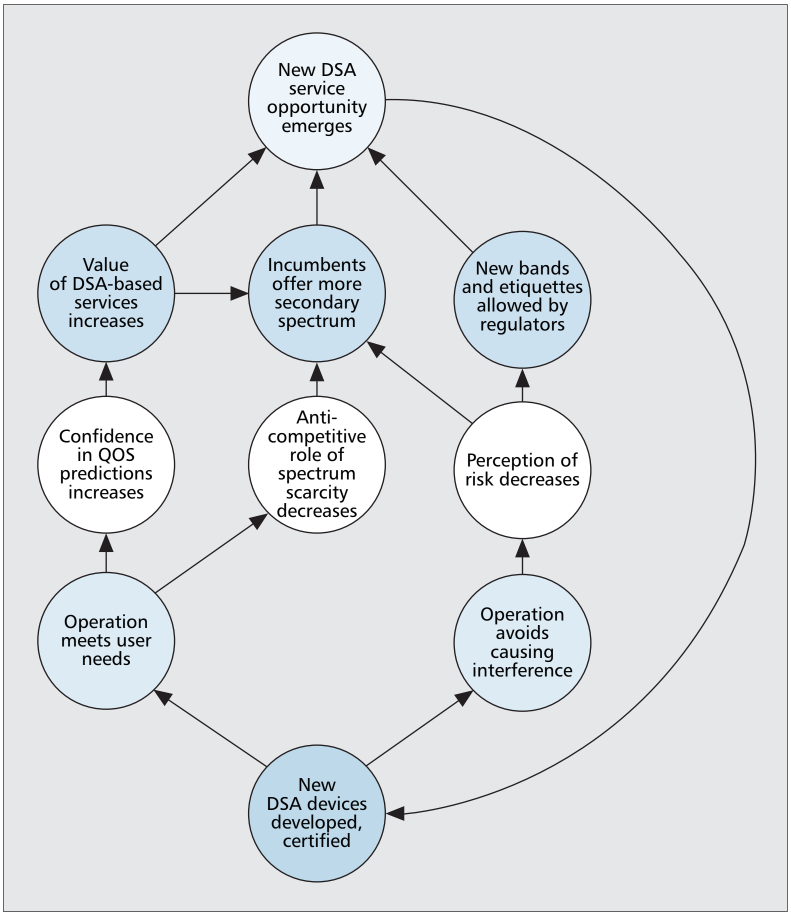
An obvious result of greater trading and more spectrum sharing is that spectrum access gets cheaper. This is, of course, the major driver for the wide interest in DSA. What is not so widely discussed is that cheaper spectrum and an active secondary spectrum market will reshape the radio services market and industry value chain (Fig. 1).

Smaller scale, lower cost entry becomes feasible, which enhances competition in data communication services, driving down service prices. As a result, incumbent business models built around spectrum scarcity will be less viable. Incumbents will be required to introduce more value-differentiated services to justify price margins. Thus, DSA will stimulate innovation in wireless communications even from operators who do not exploit it.

Lower entry costs will increase the pace of product and business model lifecycles, through faster entry and exit in the marketplace. DSA enables new services to replace legacy services more gracefully. A new entrant can begin with inexpensive, limited spectrum access rights, then scale its usage rights to match its capacity requirements as business grows.

Finally, increased lifecycle speed makes it more challenging to recover the fixed costs associated with introducing new technologies, services, or business models. It also increases the likelihood that successive generations of technologies will overlap. Both effects raise the importance of radio design techniques that reuse hardware designs across multiple waveforms, such as device modularity and software radio.

The effects of DSA just described, will occur only if there is sufficient liquidity in the spectrum market to enable the deployment of DSA-based services. There are three enablers for market liquidity: available spectrum, customer demand, and low transaction costs. The following sections describe mechanisms that enable progress in each of these areas. These mechanisms are summarized in Fig. 2.



■ **Figure 2.** *Feedback loops for growth in use of dynamic spectrum access. The multiple cause/effect chains shown here can proceed independently.*

AVAILABLE SPECTRUM

The first enabler for success of DSA-based wireless services is that sufficient spectrum must become available for secondary access. It appears likely that the supply of spectrum will increase in a stepwise, iterative manner over time, due to the various processes that will occur to make it available. The processes and conditions required are roughly the same whether DSA is cooperative or noncooperative.

MARKET PROCESSES

The perceived risk of interference due to DSA radio operation must be reduced to an acceptably low level. This can best be achieved through demonstrated safe operation with initial deployments in simpler bands. A simpler band is one where the spectrum access etiquette required for non-interfering operation is less complex, due to characteristics of the incumbent services. The level of risk that is acceptably low also varies by band, according to the function and users of that band.

The value of services based on DSA radios must be established to support the pricing of leases in the secondary spectrum market and/or provide economic justification for regulatory creation of easements. Initially, the perceived value is likely to be lower than its eventual equilibrium level, due to concerns about the quality of service that can be delivered without guaranteed spectrum rights. The ways of overcoming this concern are discussed later.

Incumbent service providers must be weaned from reliance on spectrum scarcity as a barrier against competition. Ideally, this will occur naturally over time as DSA proves viable and new entrants begin to exploit it in limited bands. Other market developments may reduce incentives to hoard spectrum naturally, such as including the growth of inter-modal competition (wired vs. wireless) and the growth of spectrum available for primary users and/or re-purposed from legacy inefficient allocations through ongoing regulatory processes.

REGULATORY ACTIONS

If the amount of available spectrum remains artificially limited by incumbent hoarding after market processes overcome the other barriers of risk and value, regulators may be required to jumpstart the market. This can be accomplished through offering secondary access to a significant amount of spectrum. This step will create the expectation of future competition in communication services and convince incumbents that a spectrum-hoarding strategy is no longer effective. Spectrum availability will then rise to equilibrium levels: in the cooperative DSA case, because primary rights holders seek to earn a share of the access revenues; in the noncooperative case, because they spend less political capital fighting the creation of new easements.

Existing allocations must be clarified to minimize uncertainty over who has the authority to offer secondary access to particular bands. For example, in the United States, much of the spectrum is already shared between federal and non-federal users. Complicating matters, the federal and non-federal uses are administered by different regulators, the NTIA (National Telecommunications and Information Administration) and FCC (Federal Communications Commission). If one of the entities with rights to a given band offers access in the secondary market, or equivalently, if one of the regulators establishes an easement, usage patterns may change significantly in a way that makes the band unusable for the other authorized users. In some cases, it even can be difficult to identify the authorized users. Case law and standard procedures must be established to clarify rights and allocate responsibilities for secondary spectrum transactions among the multiple rights holders. This should start with the simpler bands and cases and progress to the more challenging ones.

No regulatory action is required in the short term. In the United States, some spectrum is already available for DSA from a regulatory perspective, enabling the cycle of risk reduction and value development to begin immediately. For cooperative DSA, the flexible-use licenses adopted by the FCC in recent years, combined with a proceeding that has clarified secondary markets issues, give wide latitude to the primary user to trade spectrum rights. Examples of such licenses include 1.9 GHz PCS, 1.7 GHz, and 2.1 GHz AWS. Similarly, government users such as the armed forces may elect to use DSA techniques to share spectrum, thereby increasing their collective spectrum use efficiency and overall mission-effectiveness. This strategy is being explored by the DARPA XG (Defense Advanced Research Projects Agency) project.

For noncooperative DSA, the unlicensed bands provide ample opportunity for deployment. Normally devices in those bands operate without DSA techniques, but one can easily imagine products that would benefit from applying them. For example, a home WLAN system could gain sales if it advertises that it does not interfere with the consumer's 2.4 GHz cordless telephone. Furthermore, listen-before-talk DSA was recently mandated in the 5 GHz unlicensed band extension to protect incumbent military radar from interference. This offers an excellent test case. Market success in that band, and evidence that interference risks were successfully mitigated, will likely stimulate the creation of additional spectrum access opportunities using similar techniques.

CUSTOMER DEMAND

The second enabler for success of DSA-based wireless services is sufficient customer demand in the secondary access spectrum market. The notion of customers applies to both cooperative and noncooperative DSA. In the cooperative case, the market requires players who will pay for secondary spectrum access. In the noncooperative case, the market requires players who back the creation of easements and who will use those easements for sufficiently valuable purposes to justify regulatory action.

The initial customers in the secondary spectrum market are the companies whose products depend on DSA, whether equipment vendors (e.g., manufacturers of WiFi access points) or service providers (e.g., cellular carriers). Over time, as DSA-enabled devices become more successful, we expect end-users to begin acquiring spectrum access directly. For example, a hotel might expand the capacity of its wireless network when hosting a convention, through temporarily acquiring secondary access to additional spectrum, or a community of users might acquire spectrum as needed to support a broadband local access mesh.

The level of demand by customers in the secondary spectrum market is highly dependent on the quality of service (QoS) vs. price trade-off achievable with DSA. That is, a communications service with lower QoS may still generate significant end-user demand if it is cheap enough. Such price/QoS trade-off is a hallmark of competitive markets.

NEW APPLICATIONS

At first glance, it appears that DSA-based services would have a strictly lower QoS than radio services that enjoy guaranteed spectrum access. However, it is better to say that DSA-based services will offer a different QoS, one that is more desirable for some applications, in the same way that the Internet offers a different QoS from traditional telephone networks. The QoS challenge is as much about finding the right, novel applications as it is about improving the communications capability of DSA radio technology itself.

To illustrate, consider that DSA can be used to build networks that communicate more effectively through building walls than WiFi. This is possible because a DSA network can exploit VHF frequencies that have better propagation characteristics than the 2.4 GHz and 5 GHz unlicensed bands. As another example, consider a service that keeps the entertainment system in a user's car automatically updated as new media is loaded on the user's home PC. An occasional delay in updating due to spectrum access limitations is acceptable for this application, especially if the user earns significant savings compared to using cellular network services for the high volume of data that is transferred.

As with many prior innovations, the "killer app" for DSA is likely to be unforeseen. The chance that one or more will emerge is enhanced by the lower entry cost that is enabled by DSA for new service providers.

LEGACY APPLICATIONS

For legacy applications, the perceived reduction in QoS associated with DSA may impede commercial success. To address this concern, it may make sense to deploy DSA systems initially in bands where the primary usage is so low that secondary access rights are tantamount to guaranteed access to spectrum. For example, there are 6-MHz wide UHF TV channels in large urban areas in the United States where the license holder has not transmitted for years. Making such spectrum available for DSA-based wireless services will require regulatory action to create easements or to encourage secondary access contracts.

In the longer term, even desirable bands like vacant UHF TV channels may suffer from QoS challenges for legacy applications due to competition among multiple secondary users. Techniques to improve QoS for DSA systems therefore are an active and important area for research. This includes such techniques as running etiquettes simultaneously on multiple bands, coordinating independent secondary users geographically to support the QoS requirements of each, and bringing spectrum availability information into network level decisions to route around congested areas.

There are also non-technical ways to improve QoS for legacy applications. Creating a derivative securities market (e.g., options and futures contracts for spectrum access rights) will enable operators to hedge the risk of losing spectrum access. Alternatively, service providers may choose to bundle a DSA-based service together with one that has guaranteed spectrum access, perhaps as two operating modes of a single end-user device, so legacy application requirements are met despite the QoS limitations of DSA.

LOW TRANSACTION COSTS AND RISKS

Assuming we have a willing spectrum provider and customer, the final requirement for the success of DSA-based wireless services is acceptably low transaction costs and risks in the secondary spectrum market. There are obvious transaction

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costs, such as searching for an opportunity and satisfying government red tape. These costs can be reduced by spectrum brokers, who will evolve naturally as the DSA market begins to operate. Regulatory reforms to streamline procedures for transferring rights also will help. There is no fundamental reason why it should not be efficient to trade spectrum rights for short time blocks (minutes) and small bands under either cooperative or noncooperative DSA regimes.

In addition to the obvious transaction costs, there are also less obvious costs due to risks encountered by providers and customers. The risks are different for cooperative and noncooperative DSA regimes.

COOPERATIVE DSA

The provider counts the risk of reducing the value of their spectrum access rights as a transaction cost. There are three main ways the primary rights holder could be harmed.

First, there is the risk of interference caused by the secondary user. The main way to reduce this risk, of course, is to test DSA devices, either as specified by regulatory mandate or contractual agreement. However, at least in the early stages of DSA deployment, testing likely would address this risk only imperfectly. Mechanisms are required to reduce the cost of resolving interference when it does occur. One approach would be a requirement that all DSA devices transmit their make/model/software version on (authenticated) demand. Also, DSA devices could be required to keep a log of the bands where they have recently operated, similar in function to an airplane "black box," permitting post-interference analysis.

In cases where the secondary user deploys a large number of devices, perhaps distributed to consumers, there is the risk that devices will remain in the field after the access contract expires, continuing to exploit the band without authorization. This risk can be addressed through a time limit on operation that is enforced by a trusted subsystem in each device. These time limits are called *leases*. The straightforward technical implementation of leases is to use cryptographically signed certificates to send lease extensions to the device. Failure to receive a lease extension causes the device to cease operating in that band after the specified deadline.

Finally, there is the risk that authorities will retract some of the rights assigned to the primary user. Sharing with secondary users offers evidence that the primary user does not require all of the existing spectrum allocation. To reduce this risk, policymakers must make credible commitments to procedures that protect primary rights holders from subsequent loss of rights on the basis of their activity in the secondary spectrum market.

There also is risk for the customer in a cooperative DSA arrangement, which must be mitigated for the transaction to be worthwhile. The primary user may seek to expropriate the value of the secondary user's business after its viability was demonstrated. For example, the primary user can threaten to modify its usage patterns in a way that reduces the secondary user's access below the level required for acceptable end-user QoS, and thereby force the secondary user into unfavorable additional contracts. Creative contractual arrangements must be developed to protect the rights of both parties to cooperative DSA transactions, for example, including limits on the primary user's access patterns.

NONCOOPERATIVE DSA

In noncooperative DSA, the secondary user must characterize the primary user's spectrum use well enough to avoid causing interference. There are direct costs associated with doing this — monitoring, analysis, and communicating data among multiple secondary nodes — as well as risks of making a mistake and incurring legal liability. Due to both the cost of the characterization task and the associated risk, secondary users are motivated to be conservative. The simple etiquettes that secondary users decide to implement are likely to achieve a lower level of spectrum utilization than is technically possible in a band.

The cost and risk of characterizing spectrum use can be reduced through establishing an information registry, which could be governmental or private, for authoritative data about primary users. For example, posted information could include: geographic locations of transmitters and receivers; waveform characteristics, such as modulation and bandwidth; or times of day when the system does not operate. This type of information enables secondary users to execute more aggressive spectrum access algorithms at acceptably low risk. Notification of secondary users when registry data is updated would assure quick response to changes in primary user behavior. One of the primary challenges of a registry is to assure that the information posted is correct; both regulatory and market mechanisms that assist this are worth exploring.

An effective registry mechanism can reduce the interference risk of noncooperative DSA, compared to a regime where secondary users operate without external information. As a result, regulatory authorities can establish more liberal easements. This effect is synergistic with the benefits of a registry: both lead to higher spectrum utilization. The policy and technical issues associated with the registry approach are a valuable area for further investigation.

INDUSTRY STRUCTURE

The traditional model of static spectrum access supports an industry structure in which wireless services are segregated into distinct, well-defined value chain silos. Each service is provided by purpose-built networks, employing equipment dedicated to that narrow class of applications, and operating in dedicated spectrum bands. The result is a number of distinct radio system architectures. Thus, over-the-air broadcasters, mobile system operators, and end-user-deployed wireless LAN (WiFi) are based on distinct and incompatible radio system architectures, service/business models, and spectrum management regimes.

DSA technology promotes both the *vertical disintegration* and *horizontal integration* of the

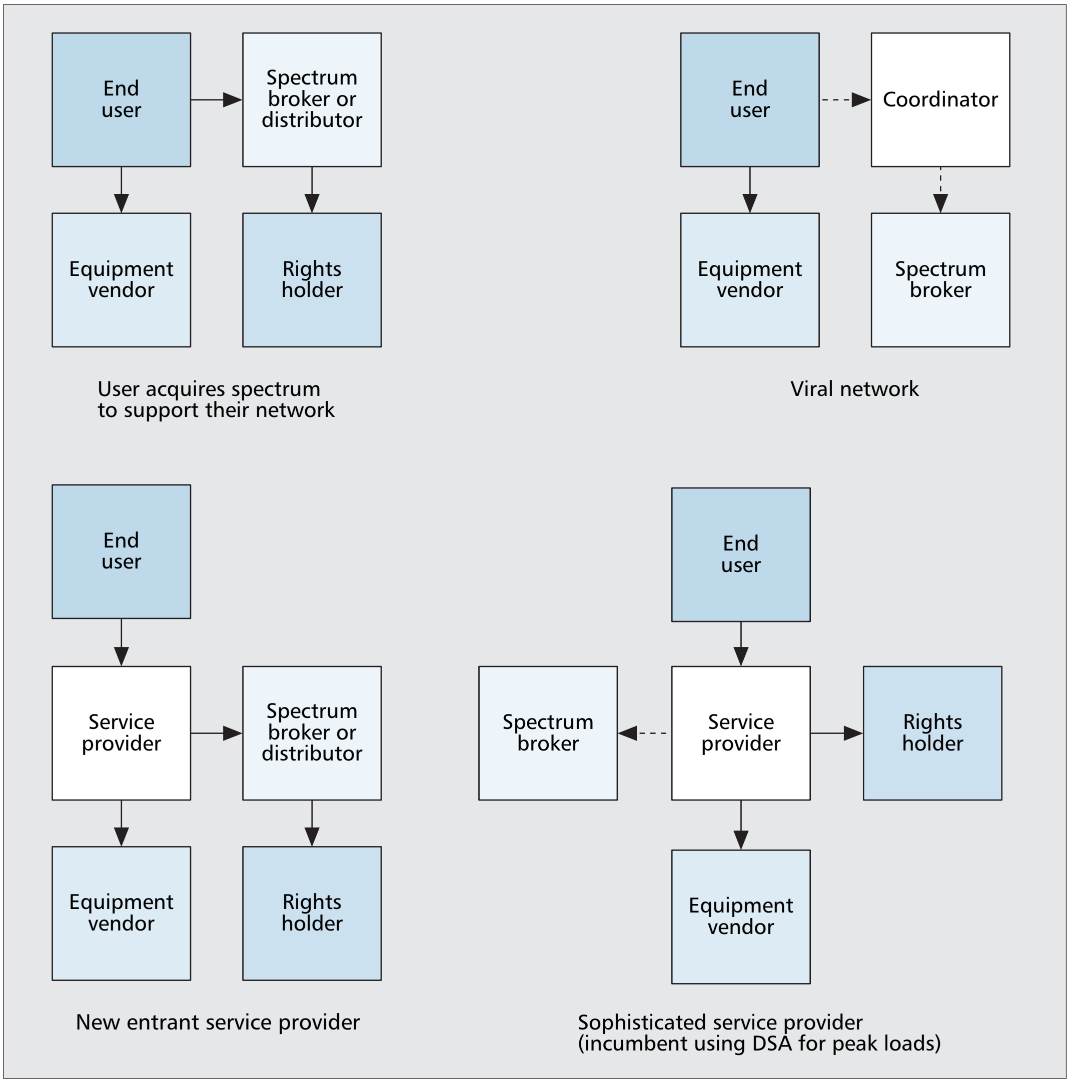


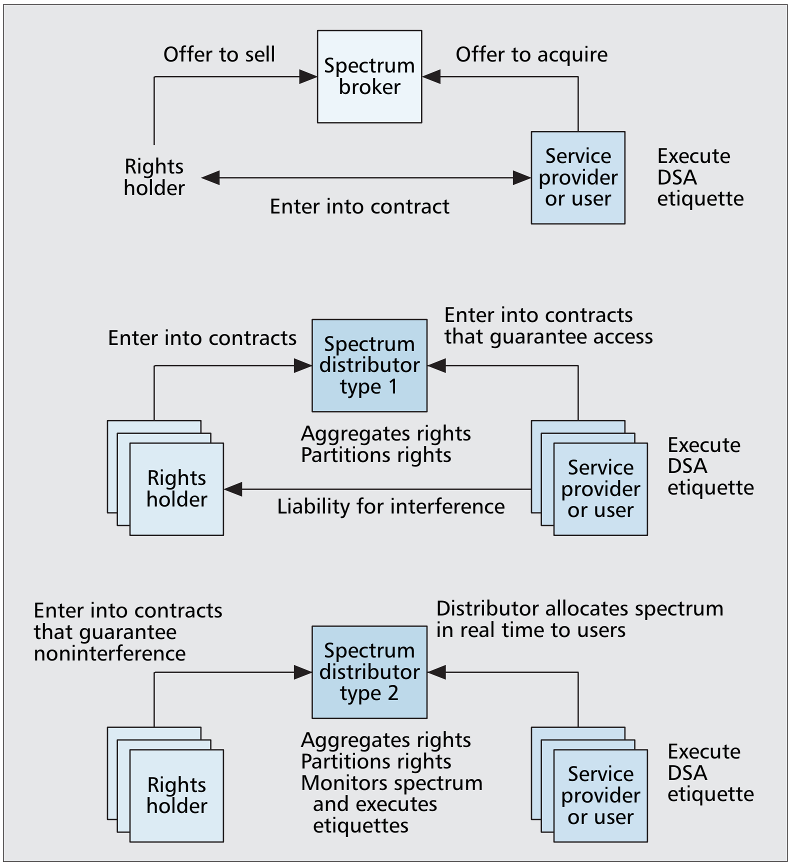
Figure 3. *Potential value chains for DSA-based wireless services. In the case of noncooperative DSA, the rights holder is removed but the rest of the chain is unchanged. Dotted arrows indicate small revenue flows.*

The spectrum access algorithms or etiquettes used to implement DSA are expected to be complex, difficult to get right, and even more difficult to have certified by regulatory authorities. There will be strong incentives for device manufacturers to acquire and reuse etiquette implementations.

existing wireless service market silos, driving the same sort of platform convergence that has been occurring in wired communication services. DSA facilitates vertical disintegration by enabling new types of business models and wireless architectures for delivering services (Fig. 3). For example, under the traditional operator/subscriber model for cellular telephone services, there is a mobile network operator that makes the capital investment in network equipment and spectrum rights, then sells services to end-customers who pay monthly recurring fees for usage. DSA makes it possible to unbundle the investment in spectrum rights, the operation of a mobile network, and the offering of mobile services. New types of intermediaries may emerge to exploit these opportunities, including: a mobile virtual network operator (MVNO) that operates a service in multiple bands; spectrum brokers that specialize in managing the transference of access rights in secondary markets; or vendors of customer equipment that support the viral deployment of end-user provisioned ad hoc or cooperative mesh networks.

Horizontal integration occurs when a single product competes across silos and thereby breaks down the barriers between sub-markets. With DSA, a radio device or system can scale its spectrum use to reflect changing application requirements and local network conditions. As a result, if QoS challenges can be overcome, it may support more effectively a larger range of end-user applications than devices based on static spectrum access. Manufacturers and service providers exploiting these more flexible system architectures will be more resilient against setbacks in any particular sub-market, making them competitive against silo incumbents.

The spectrum access algorithms or etiquettes used to implement DSA are expected to be complex, difficult to get right, and even more difficult to have certified by regulatory authorities. There will be strong incentives for device manufacturers to acquire and reuse etiquette implementations. This will promote the componentization or modularization of radio system design. Software radio technology, which is distinct from DSA but is likely to be used to support DSA systems, also promotes the vertical disintegration of traditional vertically integrated



■ **Figure 4.** *Potential role of the spectrum broker and spectrum distributor entities in an emerging DSA marketplace.*

equipment manufacturers. For example, third-party software providers may provide customizable baseband processing software that could run on common hardware and can be sold to diverse network operators.

New and particularly interesting intermediaries created by DSA are firms that specialize in spectrum trading, seeking to ensure adequate market liquidity and low transaction costs (Fig. 4). The most basic is a simple spectrum broker matching buyers and sellers. A more sophisticated variant is a spectrum distributor that adds value by aggregating and partitioning spectrum access rights. What we call a spectrum distributor type 1, contracts with end-users to deliver QoS-differentiated spectrum access, while acquiring the spectrum rights through contracts with primary rights holders or through exploiting easements.

There also is a larger potential role, what we call a spectrum distributor type 2. The type 2 distributor takes responsibility for the safety of secondary spectrum access, interposing itself as a trusted third party between primary and secondary users. A distributor filling this role might install and operate the monitoring and analysis systems required to determine when secondary operation in a given band at a given location is safe. The distributor would receive access requests in real time from secondary users, execute the appropriate etiquettes, and determine where and when each user should operate. Given its legal liability, such a distributor probably also would set and enforce standards for secondary user devices. This could be a profitable business and at the same time reduce the cost of end-user devices, the risk of interference to primary rights holders, and the degree of regulatory control required for DSA.

It is not clear what business models will prove most valuable in a DSA-enabled market. There are end-user equipment models in which end-users purchase devices and then assemble mesh networks that scale using DSA-enabled spectrum to form provider-less networks. There are disaggregated radio equipment manufacturing models offering separate hardware and software components. There are also new types of MVNO models that unbundle retail services, network ownership, and spectrum rights. The market must experiment to determine the arrangements of the value chain and new intermediaries that make the most sense. Regulatory policy must allow such experimentation to occur and should not artificially bias the market toward choosing one value chain structure over another.

Conclusion

We described a number of wireless communication-service market developments that are linked to DSA, either as required enablers or as potential effects. The underlying enablers are those regulatory steps and technical innovations that improve liquidity in the secondary spectrum access market: by boosting spectrum availability; by increasing achievable QoS and hence, customer demand; and by reducing transaction costs and risks. We identified a virtuous cycle of innovation leading to widespread use of DSA-based services. Once DSA technology is widespread, we can expect reduced entry costs for new service providers to speed up product and business lifecycles. The technology also will enable new value chains and business models for providing communication services.

The market developments analyzed in this article can occur within existing regulatory frameworks. However, proactive regulatory reform could accelerate the evolution of the market. The desirable fundamental policy reforms shift away from traditional command and control mechanisms toward more market-based mechanisms. This means increased reliance on market-based contracting to address interference concerns, industry-driven rather than government-mandated standardization, and lightweight regulatory rules that clearly specify the property rights of primary and secondary users. Current regulatory trends toward further deregulation, technology-neutral rules, and further reforms to enable secondary market trading are all encouraging. Progress will depend on demonstrating the safety and market value of DSA-based services and the new architecture DSA enables. In the early years, regulatory structures must be flexible to adapt to the lessons learned as the technology matures.

We identified a set of potential new entities, such as spectrum use registries and spectrum distributors, as well as product features such as black boxes and leases that may play important roles in facilitating the growth of the market for dynamic spectrum access-based wireless services. Research on how these entities and features can work is just as important as research on basic questions of safety in dynamic spectrum access for the technology to fulfill its promise of significant increases in overall spectrum-use efficiency and thereby deliver its full potential for social and economic benefits.

BIBLIOGRAPHY

[1] Y. Benkler, "Some Economics of Wireless Communications," *Harvard J. Law and Tech. 16*, 2002, pp. 25–83.

[2] J. Chapin and W. Lehr, "Time-Limited Leases for Innovative Radios," *IEEE DySPAN 2007*.

[3] J. Chapin and W. Lehr, "Time-Limited Leases in Radio Systems," to appear, *IEEE Commun. Mag.*, June 2007 (rev. of [2]).

[4] G. R Faulhaber and D. Farber, "Spectrum Management: Property Rights, Markets, and the Commons," AEI-Brookings Joint Center Working Paper 02-12, Dec. 2002.

[5] J. Hoffmeyer, "Draft Standard Definitions and Concepts for Spectrum Management and Advanced Radio System Technologies," IEEE Stds. Ass'n. Proj. 1900.1, Oct. 2006; http://www.ieeep1900.org/

[6] P. Kolodzy, "Spectrum Policy Task Force Report," Office of Eng. & Tech., U.S. FCC, ET Docket No. 02-135, Nov. 2002; http://www.fcc.gov/sptf/reports.html

[7] OFCOM, "Spectrum Framework Review: A Consultation on OFCOM's Views as to How Radio Spectrum Should Be Managed," U.K. Commun. Regulatory Authority, Nov. 2004; http://www.ofcom.org.uk/consult/condocs/sfr/

[8] K. Werbach, "Radio Revolution: The Coming Age of Unlicensed Wireless," New America Foundation Working Paper, Dec. 2003; http://www.newamerica.net/publications/policy/radio_revolution

BIOGRAPHIES

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