

Hybrid Wireless Broadband

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Abstract

Wireless access networks are evolving rapidly and hold the promise of significantly altering the landscape for broadband competition. In a companion paper,³ we explained why wireless networks are unlikely to converge toward the sort of broadband platform network exemplified by wired Next Generation Access Networks. In this paper we present in more detail the future architecture we see most likely for wireless access networks, which we call hybrid wireless broadband.

A hybrid wireless broadband access service is a high-capacity converged service implemented via multiple overlaid wireless networks, some of which share resources with other systems. Such a service is hybrid in two senses. It integrates multiple wireless networks to serve user needs, for example a voice specific network and a data-only Internet access network. It also combines multiple spectrum access models, for example dedicated spectrum (exclusively licensed) and shared spectrum (unlicensed). The set of flexible spectrum sharing models we anticipate to appear are collectively referred to as Dynamic Spectrum Access (DSA).

In the earlier paper, we explained how the inherent scarcity of spectrum pushes wireless architectures toward specialization and away from general-purpose designs in the quest for greater spectral efficiency. In this paper, we focus on the second aspect of hybrid wireless broadband: the move toward DSA, and more explicitly, sharing across network infrastructures. We see the trend to greater sharing as both inevitable and desirable. However, the rate of increase of sharing and the eventual intensity of sharing and spectrum use depend on appropriate policy choices and research investments. We analyze three focus areas for policy development and research investment: mobile device economics, validation certification and liability assignment, and the business models for spectrum sharing.

1. Introduction

The growth in demand for wireless access from all types of wireless services (commercial and public, mobile and fixed, high and low power) coupled with the fundamental scarcity of RF spectrum will

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³ Lehr and Chapin (2009).

compel spectrum users toward greater spectral efficiency (higher utilization) and more intensive spectrum sharing (across users and uses, and across networks).

In an earlier paper,⁴ we examined the fundamental technical and economic forces that are pushing wireless access network architectures away from a common Internet-based “platform architecture.” We use this terminology, in part, to highlight how and why we believe wireless and wired access architectures are evolving differently. Whereas we see wired networks evolving toward a common general-purpose, fiber-intensive, Internet protocol-based platform, we see wireless networks as remaining more diverse, incorporating both specialized and general-purpose elements. An example of such specialization is the use of separate lower-layer networks by wireless service providers to support voice and data services. Both services are supported over a common transport layer in the wired platform networks being rapidly deployed today. Spectrum scarcity and the spectral efficiency benefits of service-specialized wireless networks are key drivers for our predictions.

In this paper, we describe the future architecture that we see as most likely for wireless networks. Under the pressure of spectrum scarcity, we believe wireless service providers will begin to rely on a mix of dedicated and shared spectrum resources, leading to what we call Hybrid Wireless Broadband services. When spectrum is shared (across location, time, users, uses, and deployed networks), the range of techniques used to make this efficient and safe are collectively referred to as Dynamic Spectrum Access (DSA).⁵ We focus our analysis on explaining the reasons why spectrum sharing among independent deployed networks will become prevalent, because we believe this is the most contentious aspect of the DSA future we envision.

Realization of the hybrid wireless broadband and DSA future we forecast will be enhanced by complementary developments in the areas of mobile device economics, techniques for validation

⁴ *Ibid.*

⁵ We define the DSA research agenda broadly. It is about sharing spectrum more intensively in every dimension and in a variety of contexts. This includes models for unlicensed or private commons access, for secondary markets, and for complementary enabling technologies, institutional reforms, and regulatory policy. For further discussion of DSA sharing see Chapin and Lehr (2007a).

certification and liability assignment, and business models for spectrum sharing. With respect to mobile device economics, we point to the need to focus initial regulatory efforts promoting shared spectrum on bands and channel types that reduce the required investment in frequency agility and waveform flexibility. Validation, certification, and liability assignment are key enabling processes both to promote the evolution of new systems and to enable more flexible modes of spectrum access included in DSA. Finally, network operators will need to evolve their business practices to make spectrum sharing, and especially sharing across wireless infrastructures, the norm. These developments are not all that is needed, but we highlight these because we believe they have not been adequately addressed in discussions of the policy agenda. For example, much of the policy discussion has focused on the need for spectrum management reform and supply-side issues (how to expand availability of spectrum supply⁶), while demand-side issues have been under-appreciated. Affordable client devices, risk reduction processes, and innovative business models supportive of DSA are also needed to take advantage of any incremental spectrum supply that is made available.

In Section 2, we explain further what we mean by Hybrid Wireless Broadband and emphasize how this contributes toward a DSA future. In Section 3, we explain how existing mobile network architectures already embody elements of the Hybrid Wireless Broadband vision and identify the reasons why we believe these elements will be reinforced and extended in the future. Specifically, we explain why we believe increased sharing across infrastructures will be necessary and pursued by mobile wireless broadband providers. In section 4, we go a step further and suggest a specific model for how we envision mobile operators implementing DSA. In Section 5, we consider some of the complementary developments that are necessary and suggest what this means for policy. Section 6 concludes.

⁶ This includes discussions of the need to redeploy spectrum to higher value uses (e.g., from government to commercial uses, from broadcast to mobile communications) and the mechanisms required to achieve this goal (e.g, spectrum auctions, spectrum clearing). Much of the academic debate over spectrum management reform has focused on how to establish appropriate property rights for access to allow market-based mechanisms for reallocating spectrum to succeed. See Lehr (2009) and sources cited there for pointers to literature on spectrum management reform.

2. The Wireless Future and Hybrid Wireless Broadband

The demand for wireless access rights is expected to grow from all sources, for communication and remote sensing applications,⁷ for low and high power networks,⁸ and for public and commercial applications.⁹ These applications are today served by a diversity of specialized networking technologies and this will continue to be the case in the future. Thus, the landscape for future wireless networking will be quite heterogeneous with respect to user needs (the ultimate motivation for providing the service), the contexts in which those needs are met (e.g., commercial vs. public sector, planned vs. ad hoc, rural vs. urban, etc.), and the solutions which evolve to address those needs (e.g., wireless infrastructures).

Mobile wireless access networks – our principal focus here – are evolving within this larger context of wireless growth and technical/business/market heterogeneity. Since the introduction of the first systems based on analog technologies offering mobile telephony in vehicles in the 1970s ("1G" or First Generation systems) through the emergence of mass market mobile telephony services based on digital technologies in the 1990s (so-called "2G" or Second Generation systems) to today's mobile systems offering broadband data services (so-called "3G" or Third Generation), we have seen continuous improvements in system capacity and capabilities,¹⁰ with an attendant expansion in mobile network traffic. Both penetration and per-user usage have expanded significantly.¹¹ In response to this, mobile

⁷ This includes passive and active imaging and measurement systems such as those used by space telescopes, ground radar, and weather telemetry systems.

⁸ Power is often used as an imperfect gauge of the geographic coverage for a wireless transmitter. RFID and sensor networks and personal area networks (e.g., Bluetooth) are expected to operate at low power and over short distances (up to a few 10s of feet); medium power systems such as WiFi are used for local area networks (up to a few 100s of feet), and higher-power systems such as microwave, satellite, or terrestrial mobile networks operate over wide coverage areas (spanning distances from several to many miles).

⁹ Public uses include public safety and military applications, both of which anticipate futures with much more intensive use of wireless in all its forms.

¹⁰ Coverage has increased to be near ubiquitous in many OECD markets, and service quality and data rates have also increased.

¹¹ See Cisco (2009).

operators have invested heavily in acquiring additional dedicated spectrum resources (via auctions, merger & acquisition activity,¹² and private contracting).

Our vision of a hybrid wireless broadband service is a high-capacity converged service implemented via multiple overlaid wireless networks, some of which share spectrum resources with other wireless networks.

- *A converged service:* A customer using the hybrid wireless broadband service receives an integrated and extensible set of services (e.g. voice, video, and data) normally delivered through a single device. The prototypical version of this device is a smart phone handset such as the iPhone that supports voice, streaming media, and broadband Internet access applications. It is intended to be portable which imposes strict form factor (size and weight) and power constraints. It is intended also to be accessible to a mass market which imposes per unit price and design constraints. Niche applications such as mobile access in vehicles or specialized commercial applications (e.g., inventory control systems such as used by UPS or repair personnel) may relax these constraints in specialized contexts.¹³
- *A high-capacity converged service:* The services the customer receives match common expectations for a broadband service, which may evolve over time. This implies a high peak data rate (relative to earlier systems) and hence a relatively large frequency bandwidth (which may or may not be contiguous).¹⁴ Growing market penetration and the growing requirements of the services offered to each user drive mobile operator demand for additional spectrum resources.

¹² Sprint's merger with Nextel and AT&T's acquisition of spectrum from Aloha Partners provide examples of how additional dedicated spectrum rights are acquired via mergers and acquisitions.

¹³ For example, mobile access from automobiles may be less constrained by form factor or power constraints, but may confront specialized constraints imposed by the need to conform with automotive deployment. Specialized commercial applications (including public safety/military) may be less susceptible to price constraints, but may confront more rigorous service requirements.

¹⁴ As we explained in Lehr and Chapin (2009b), the inference from data rate to required frequency range is approximate and changes over time as innovation increases the bits per second capacity per Hz.

- *Multiple overlaid wireless networks:* Although the customer receives a converged service through a single device, this is implemented using multiple wireless systems. The networks are specialized for different tasks or roles and are overlaid geographically. In some cases the coverage regions are similar (e.g. 3.5G data and DVB-H video) while in others they may be very different (e.g. 3.5G data and 802.11 hotspots). This means that the heterogeneity that we see as a defining and enduring feature of the wider world of wireless networking will also prevail in the architectures for mobile broadband access networks. This poses challenges (relative to a more homogeneous world) in terms of the realization of scale, scope, and learning economies; of ensuring interoperability; and for the potential for offering differentiated services based on differentiated wireless network architectures (rather than on differentiated marketing strategies).
- *Share resources with other systems:* Some of the networks providing the converged service share resources across network infrastructures. We assume it is relatively uncontentious to argue that future wireless networks will need to share spectrum resources across users and uses. This is already done today via time and frequency division multiplexing of capacity on a single wireless network (e.g., what happens in your typical 1G or 2G mobile network). We also expect to see future wireless networks dynamically reallocating network resources, including spectrum, across different applications in time (e.g., using voice channel capacity for data services when voice demand is low). What is new is our contention that different wireless networks, operated and used by non-affiliated network operators and wireless users, will share spectrum resources. Some of this sharing will take the form of mobile operators relying on wholesale services provided by third-party networks (e.g., the Qualcomm MediaFLO network which supports broadcast media distribution to wireless handsets). However, we predict that some of it will also take the form of dynamic access to shared spectrum resources such as unlicensed spectrum.

It is worth noting that current 3G networks fit the definition of a Hybrid Broadband Network, with arguably the distinction that access to shared spectrum is still nascent. For example, AT&T implicitly supports integration of WiFi access via the iPhone but limits the use of VoIP over the iPhone's

WiFi connection via Skype. Multiple mobile providers subscribe to Qualcomm's MediaFLO network. And all of today's 3G operators support voice telephony and broadband data access over separate wireless networks. What is potentially contentious is that we forecast (based on the reasoning in our earlier paper) that this state of affairs will continue. That is, future deployments by mobile wireless broadband access providers will still be Hybrid Wireless Broadband networks.

Currently, the most widely accepted architecture for the continued evolution of mobile networks to 4G (Fourth Generation) and beyond is called Long Term Evolution (LTE).¹⁵ We are innately skeptical that *any* single architecture for the evolution of 4G networks – no matter how well thought out – will uniquely prevail. Further, we doubt the likely success of the LTE vision to the extent that its proponents argue it will offer a common platform for a wide range of application services. General-purpose Internet access will certainly be well supported, but other applications (media, voice, sensors) will likely be carried dominantly by specialized networks that are closely coupled to the LTE mobile network.¹⁶ Most importantly for the discussion in this paper, it appears that the LTE vision assumes a continuation of the current model of spectrum access rights in which service providers operate networks almost entirely within dedicated spectrum resources. We forecast a major shift by service providers from entirely dedicated spectrum to a mix of dedicated and shared spectrum resources (e.g., unlicensed, spectrum accessed in real-time markets, or via some sort of closed commons).¹⁷

In the next section, we explain why our vision implies more intensive spectrum resource sharing across networks.

¹⁵ Bogineni *et al.* (2009a, 2009b).

¹⁶ Lehr and Chapin (2009b).

¹⁷ It is unclear whether LTE makes any assumptions regarding the underlying rights regime. It is conceivable that LTE could be deployed in a mixed rights regime. By this, we do not mean co-existing with other operators using shared (e.g., unlicensed) spectrum (which is certainly the case), but rather with an LTE operator provisioning its services via both dedicated and shared spectrum.

3. Resource sharing and Dynamic Spectrum Access (DSA)

Observing current deployments, there are already important cases where mobile broadband operators depend on access to shared spectrum to support core functionality (rather than as an incidental or temporary aspect of their service provisioning).¹⁸

- *WiFi roaming capability*: High-end mobile devices incorporate 802.11 WiFi chipsets, giving the user cheap internet access when in range of a hotspot. Neither the spectrum used for this service nor the infrastructure supporting it are the property of or leased by the service provider who subsidizes the user's device. While service providers may prefer that all internet access run through their private networks, they have been unable to make internet access cost-effective enough to retain customers when competitors offer devices with 802.11 capability.
- *Bluetooth for wire-free connections*: Wireless headsets using Bluetooth technology rely on shared access to the 2.4GHz unlicensed band used by WiFi, cordless phones, and other unlicensed devices. This link appears peripheral to wireless broadband but it is actually an important part of the service. Converged user devices need a large screen and full keyboard to support effective data access. The resulting device size and weight is not appropriate to hold to one's ear for a long call. Headset wires are perceived as undesirable by a significant fraction of the market. Therefore a wireless headset link is essential to convince many users to rely on the broadband device for telephony. Broadband providers promote telephony use because of the importance of voice revenues to their overall business case, and to improve their competitiveness in the no-holds-barred fight for user pocket space. If unlicensed spectrum were not available to support the wireless headset, the broadband provider would likely have to acquire dedicated spectrum for the link.

¹⁸ One might regard AT&T's current implicit support of the iPhone's WiFi access as an incidental byproduct of AT&T's negotiation with Apple for the rights to sell the iPhone for use with the AT&T network. Alternatively, a number of mobile service providers may use leased (DSA spectrum acquired in secondary market transactions) or even unlicensed spectrum (as was the case with the RIM Blackberry network) as a temporary strategy until it becomes feasible to migrate their services to dedicated (exclusively-licensed) spectrum. While such examples are common and likely to continue, these do not represent the type of enduring commitment to a mixed spectrum access model anticipated by our hybrid wireless broadband vision.

- *GPS Satellite-based Services*: Location awareness is normally provided by GPS or equivalent satellite systems, which operate in spectrum shared by all service providers. Service providers could offer better quality location awareness through private spectrum or private resources. For example terrestrial systems have been deployed that work much more reliably than satellite systems when the mobile device is inside a building, through measuring digital television signals. However the public service has proven good enough that no private services have been adopted by major broadband service providers.

Each of the examples cited above shows how today's 3G operators rely on integration of specialized wireless networks that use shared spectrum as well as their better-known dedicated (exclusively licensed) spectrum resources, and thus are Hybrid Wireless Broadband network operators.

3.1. The need for more resource sharing

The examples above demonstrate that use of spectrum access models combining dedicated and shared spectrum resources to deliver core services is already common. We expect the need for shared use to increase significantly in the future. The need for this can be traced directly to the fundamental mismatch between projected growth in demand for spectrum access rights and the fixed availability of RF spectrum.

In May 2006, an official report was published estimating spectrum requirements for the mobile wireless service through to 2020.¹⁹ The estimates include both voice telephony and broadband data services. The report comes from ITU-R Working Party 8F, drawing on substantial international participation and industry expertise. It considers a variety of factors affecting spectrum requirements, including traffic projections and requirements, service and application requirements, spectrum efficiency, radio transmission characteristics, sharing and compatibility analysis.

¹⁹ See ITU (2006).

The report developed two primary projections, derived from Low or High world economic growth through to 2020. One critical output of the report is summarized in the following table (values are in MHz).

Demand model	2020 Predicted total	Europe, Middle East, and Africa		Americas		Asia-Pacific, Iran	
		2006	Increase	2006	Increase	2006	Increase
Low	1280	693	587	723	557	749	531
High	1720	693	1027	723	997	749	971

If the recession that began in 2008 is as deep and prolonged as feared, demand growth seems likely to track the Low projection more closely than the High projection. Even so, the report estimates that mobile wireless service will need over 500 MHz of additional spectrum in each of the world's regions to meet demand. Furthermore, the report states that the spectrum allocated must be below 5 GHz for mobile wireless service to be economically and technically feasible.

In 2008 the US trade association CTIA commissioned a follow-up study looking specifically at spectrum usage by mobile devices in the US. This report agreed with the ITU study regarding the critical need for large amounts of additional spectrum to support forecast demand growth.²⁰

To put the reported spectrum requirements into perspective, 22 MHz of nationwide spectrum licenses in the USA (700 MHz band) plus a similar amount broken up into regional licenses was auctioned in 2008 for over \$19 billion. This was considered to be a large offering of spectrum. Given all the other demands on spectrum, it is hard to see how hundreds of megahertz of additional spectrum below 5 GHz can be freed up for exclusive licensing. Even if it could, prices approaching \$1 billion per MHz would make exclusive licensing of that amount of spectrum prohibitively expensive for the cellular industry.

²⁰ Rysavy Research (2008).

Given all of the contending demands for additional spectrum, we believe that the current strategy for providing mobile wireless, where all core broadband and voice services operate in exclusively licensed spectrum, will cease being viable well before 2020.

3.2. Dynamic spectrum access

If mobile operators cannot meet their need for additional spectrum from new allocations of dedicated spectrum (redeployed from arguably "lower-valued" uses such as over-the-air television broadcasting or "under-utilized" government spectrum²¹), then they have only two options: improve the spectral efficiency of the technologies using the dedicated resources they already have and expanding usage of non-dedicated, shared-use spectrum in its many multiple forms. Both strategies will likely be employed and both represent an intensification of spectrum sharing.

Dynamic Spectrum Sharing (DSA) is the umbrella term used to refer to all of the ways in which spectrum may be shared and utilized more intensively. This includes sharing across time, frequencies, space, and codes. Many DSA technologies are currently deployed and will continue to be deployed in dedicated spectrum. While this will continue, our focus is on the role of DSA in facilitating multi-user access to shared spectrum.

There is a range of models for supporting multi-user access (by unaffiliated network operators) in shared spectrum.²² These include sharing among primary users (with equal rights to spectrum access) and secondary users (whose use may be pre-empted by primary users). In Chapin and Lehr (2007), we described both non-cooperative and cooperative sharing models to enable secondary use sharing. In the non-cooperative model, secondary users may access the spectrum without the permission of the primary user. Examples of this include sharing by low-power devices such as Ultra Wideband (UWB) that operate

²¹ The broadcast industry and government users do not believe that their uses or needs reflect an inappropriate allocation of resources. There are certainly usage scenarios that suggest high-value uses for increased spectrum allocations to both types of users. We put "lower-valued" and "under-utilized" in quotes to demonstrate that these positions are contentious.

²² See Chapin and Lehr (2007b) or Lehr (2009) for further discussion of sharing models.

below the noise floor in dedicated licensed spectrum.²³ Such secondary use is a form of "underlay" easement. Such an easement is intended to allow scope for entry of new technologies in previously allocated spectrum in a way that is non-interfering and so non-infringing on the (interference-protection) rights of the primary users of that spectrum. Adopting such an approach was deemed necessary to allow technologies like UWB an opportunity in the marketplace because it would be unreasonable to expect them to negotiate cooperative sharing agreements with all of the rights holders across the wide band of spectrum that UWB technologies use (i.e., in excess of 500MHz).

A second type of non-cooperative sharing is characterized by so-called "overlay" easements whereby secondary users are allowed to operate in the licensed spectrum of primary users so long as they do not interfere with the primary rights holders. Technologies such as database look-ups (e.g., is there an active primary user in this frequency in this geographic area?) or spectrum sensing (e.g., "listen-before-talk") may be employed to allow secondary use sharing. The Television White Space rules provide an example of policies intended to promote this type of non-cooperative sharing.²⁴

Models for enabling sharing by co-primary users include real-time markets (wherein the rights to the spectrum are assigned to a single dedicated user for a period of time). Spectrum leasing markets already exist in a number of bands (e.g., to lease satellite channels) but in the future it is expected that buyers and sellers of access rights may transact on much shorter timescales than is the case today. The trading of primary spectrum rights falls under the heading of "secondary market" trading (where "secondary" in this context means the trading of rights that have previously been allocated), and is akin to secondary trading of financial securities (after their initial issuance).²⁵ It is also conceivable that markets may develop for secondary trading of secondary usage rights, and other refinements, analogous to the trading of derivative securities in financial markets.

²³ See http://www.fcc.gov/Bureaus/Engineering_Technology/News_Releases/2002/nret0203.html.

²⁴ See http://fjallfoss.fcc.gov/edocs_public/attachmatch/DOC-286566A1.pdf.

²⁵ For a recent assessment of the status and growth of secondary market trading, see Mayo & Wallsten (2009).

Dedicated unlicensed spectrum provides another example of non-cooperative sharing by devices that conform to the "unlicensed" etiquette (or Part 15 rules in the U.S.).²⁶ Such devices share the unlicensed spectrum as co-primary users (that is, no unlicensed user has rights to protection from any other unlicensed user that conforms to the spectrum access etiquette that is in force for that band). The sharing by WiFi devices in the 2.5GHz and 5GHz ISM bands represent examples of this sort of non-cooperative unlicensed sharing.

All of these models may prove useful in the future, but at this stage it is unclear which models will find the greatest success in the marketplace. We are still in the early stages of transitioning to a world of more intensive spectrum sharing, or DSA. In addition to the models cited above, we believe that there is a need for additional experimentation with models for cooperative sharing between primary and secondary users, and among co-primary users.

In the first form of cooperative sharing, primary rights holders would contract with secondary rights holders. Because of the inherent flexibility of private sector contracting, we believe such cooperative spectrum sharing is likely to play an important role in the future. In Chapin & Lehr (2007a, 2007b), we discuss technologies and policies that may help support the emergence of this type of sharing.

Another type of sharing which we believe would be helpful is a "closed commons" approach. It is analogous to unlicensed in so far as those with rights to access the spectrum are peers or co-primary users. It is different from the standard model of unlicensed in that access is restricted to a subset of potential users. As we discuss further below, this model of sharing would allow the participants in a closed common to ensure a more predictable spectrum environment (with respect to future interference and congestion management).

4. A vision of DSA based broadband service

As just discussed, there are many forms of multi-user access to shared spectrum. From the perspective of a broadband service provider, all forms of multi-user spectrum access or DSA suffer from

²⁶ See <http://www.fcc.gov/oet/info/rules/part15/part15-2-16-06.pdf>.

a common problem. The spectrum resource may not be available when required to provide service to a user.

The solution to this problem is to recognize that not all data transfers require immediate spectrum access. In this section we provide an in-depth vision of one possible use for potentially delayed spectrum access: “bulk delivery” that transfers large amounts of non-time-critical data at much lower cost than today’s “immediate delivery” services. At the end of the section we briefly survey other potential uses for unguaranteed shared spectrum.

4.1. Bulk delivery service

An operator may offer two Internet access services. One service offers the same features as current 3G networks, supporting immediate transfers and time-critical data. The other service supports “bulk” delivery, transferring large amounts of non-time-critical data at a much lower cost, which may or may not be visible to the end user in the form of lower pricing.

There is a difference between the *service* offered to the user and the *spectrum type* that supports the service. Data transfers requested as bulk may in fact be transmitted in the operator’s exclusively licensed spectrum, while immediate transfers may be transmitted in the shared spectrum if it happens to be available. The situation is analogous to the relationship between the service a package shipper selects (priority overnight, three day, or ground) and the method used by the logistics company to deliver that package (airplanes, trucks, rush vs. standard handling). The logistics company needs to exploit trucks in order to keep its average per-package costs below the price it charges, but any given package may travel by air even if ground delivery has been requested. Similarly, the wireless service provider needs to exploit shared spectrum to profitably provide sufficient overall capacity to meet user needs, but the particular spectrum used for any given transfer may vary on a case by case basis.

4.2. Consistent with heterogeneous wireless networks

Providing two Internet access services optimized for different requirements is not a technical or business stretch for service providers. It fits naturally within the hybrid wireless broadband model

described earlier. Briefly, under pressure of spectrum capacity limits, providers already operate today (and in the future will continue to operate) multiple networks specialized for different services. For example, different technical architectures and communications standards are used for voice, video, and Internet access to optimize the spectral efficiency of implementing each service. Because this is already the normal operating mode for service providers, they have operations, billing and management systems that could easily be extended to handle multiple data services.

The operation of the bulk delivery service should be largely transparent to end users. Just as a single converged end user device such as a smartphone today interacts with multiple specialized networks for voice, video, WiFi, wide-area data and other services, a future device can incorporate access to both immediate and bulk Internet access services. This may be done with two separate radio chips or with a single flexible chip; likely both approaches will be used in different mobile devices. The precise choice of data network can be hidden from the user in most cases.

Indeed, it is quite important that data transfers normally be automatically steered to one or the other service based on application requirements. This is necessary to minimize both cost and user impacts such as delay of time-sensitive data transfers. However, just as an individual sending a package has the choice of overnight or standard delivery, the choice of immediate versus bulk Internet data service should be controllable by the end user when desired, especially if the two services are billed differently.

A significant reason we predict DSA to appear in the marketplace in the form of hybrid wireless broadband systems is precisely because the hybrid approach is such a natural extension of the current business and technical practices of wireless operators. With hybrid broadband systems, in contrast to systems that operate only in shared spectrum, it is not necessary to figure out how to charge a monthly fee for unpredictable bulk delivery service or how to build applications that never need guaranteed immediate data transfers. The specific advantages offered by DSA – low-cost spectrum access – can be exploited for those applications and data transfers that can tolerate the potential delays associated with sharing spectrum, without major change to business models or customer/vendor relationships. Moreover, the new

capabilities may be added incrementally, overlaying existing operation modes, which further contributes to lowering incremental deployment costs.

4.3. Ownership of a bulk delivery network

It is important to distinguish between the range of services offered to the user and the set of networks operated by the service provider. A distinct network may be used for each Internet access service. That is, a service provider can build out and operate separate infrastructure equipment specialized for operation in shared spectrum in order to implement its bulk delivery service, in addition to the network it already operates in dedicated spectrum for immediate transfer service. However, a separate network is *not* required.

One alternative model that reduces service provider investment is to lease access to a bulk delivery network operated by a third party, just as service providers in the US offering broadcast video rely on a MediaFLO network deployed and operated by Qualcomm. This is not a “roaming” model. In roaming a mobile device is either attached to the provider’s dedicated network or it is attached to some other provider's network. In the third-party model envisioned here, a mobile device will simultaneously have access to the operator’s dedicated network for immediate data transfers, and to a third-party network that operates in low-cost shared spectrum for bulk data transfers.

It is likely that revenues from bulk data delivery will be much lower than the revenues earned from immediate transfer data service. As a result it may not be economically viable to build out a separate specialized bulk delivery network with sufficient coverage to satisfy the offload needs of a Tier-1 service provider, even if the existing sites, backhaul links, and engineering capability of an existing carrier are leveraged to minimize the incremental investment required.

A lower-cost approach – and indeed the one we expect to see prevail – is for bulk delivery service to be offered as a parallel operation mode by the same infrastructure equipment that supports immediate transfer service. That is, a future base station may transmit and receive some carriers (e.g. 10 MHz wide LTE signals) in exclusively licensed spectrum and simultaneously transmit and receive other carriers in shared spectrum. The carriers in exclusive spectrum would be “always-on” while those in shared

spectrum turn on and off or change frequency in accordance with the spectrum access etiquette and contracts governing that shared spectrum usage. This is analogous to the use of peak power units by electric utilities. However, in this case the selection of which spectrum to use is optimized based on service requirements as well as the cost of using different spectrum.

If one operator in a market chooses to install this capability when it deploys its 4G network, other operators may lease bulk-delivery capacity from it to support their users. Such wholesale leasing is a common feature of many competitive markets, including long distance telephony services. It enables even non-facilities-based service providers to offer services that compete with facilities-based providers.

4.4. Importance of SDR technology

Successfully sharing the same infrastructure equipment for immediate and bulk transfer services depends on the continued development of Software Defined Radio (SDR) technology. SDR has two components, frequency agility and waveform flexibility. Frequency agility is the capability of a device to transmit and receive across a wide range of frequencies. Clearly a shared spectrum band for bulk delivery service can only be exploited if both infrastructure and mobile devices are capable of tuning to that band. The shared spectrum band may be distant from the operator's exclusively licensed band. Indeed this is likely to be the predominant case. Most operators' licenses are adjacent to operators offering similar services, which is heavily used spectrum that is unlikely to be available for sharing.

Hybrid wireless systems therefore will likely require a higher degree of frequency agility than is currently common in systems designed to operate only in dedicated frequency bands. There are a number of technical issues that make frequency agility challenging. Examples include the poor power efficiency of tunable high-power-amplifiers for transmission and the poor selectivity of tunable filters for reception. Antennas with good gain across a wide band are a critical need. Increased investment in these technologies would substantially speed development and deployment of hybrid wireless broadband systems. However, even at the current level of investment, the technology for frequency agility is improving incrementally. As it does, the opportunities for exploiting DSA on the same hardware that also operates in exclusively licensed bands will gradually open up.

The other component of SDR is waveform flexibility, the capability of a device to transmit and receive multiple different modulation types and data encodings. Waveform flexibility is already a commercially mature technology in infrastructure systems with little impact on either cost or performance. There is thus no technical barrier preventing the development of equipment that simultaneously supports both immediate and bulk transfer services even if the two services require different air interface standards.

We think it is likely that a high degree of waveform flexibility will be required for a single infrastructure system to support both dedicated and shared spectrum operation. Flexibility is required because spectrally-efficient operation in shared spectrum will probably require a different air interface standard than the optimal standard for exclusively licensed spectrum. A standard for shared spectrum may need to operate in multiple small (1 MHz or less) contiguous frequency ranges, since small chunks of spectrum are more likely to be available than large chunks in a shared band. This is quite different from the 10 MHz or wider carriers proposed for 4G systems. An efficient standard for DSA spectrum may need to have provisions for dynamic media access at the lowest level to tolerate uncontrolled interruptions by other spectrum users, just as 802.11 dynamically shares the congested 2.4 GHz spectrum band. For the same reasons a standard for DSA spectrum may need to have rapid synchronization and other features to exploit short time windows during which transmission is possible. This is different from the pre-allocation of precise time slots and long time windows exploited to optimize efficiency in 3G and 4G cellular systems. Finally a standard for DSA spectrum may need to have periodic quiet times during which the system listens for the presence of other spectrum users. 3G and 4G systems transmit continuously. Although these aspects of a standard for DSA spectrum differ significantly from 3G and 4G standards optimized for dedicated spectrum, they are easily implemented in software on top of the same infrastructure hardware that supports 3G and 4G systems, because current generation base stations are implemented using mature flexible SDR technology.

4.5. Applications for bulk delivery

Bulk delivery service is useful in a range of applications. In this section we highlight just some of the possibilities.

Recently the storage capacity of mobile devices has exploded. Just a few years ago local storage was measured in megabytes at most; today most smartphones have tens of gigabytes available. This storage capacity permits extensive-use of “ahead-of-time” delivery. For example email attachments can be trickled down between the time they arrive and the time the user decides to read them. Heavily used websites on the user’s favorites list can be pre-fetched, such as getting today’s newspaper at 3am. With advanced web techniques, not yet widely deployed, only subsequent changes need to be retrieved when the user actually clicks on the site. Updates triggered by RSS feeds can be sent ahead and stored locally. RSS feeds are just one example of the “publish-subscribe” systems that have become widespread in enterprise data integration and processing applications. Many of these systems can exploit the ability to send information to the mobile device before the user requests it. All of these forms of “ahead-of-time” delivery are natural users of the bulk delivery service since they are not time-critical. If delivery does not complete before the user requests that particular piece of data, it can be fetched in real-time using the immediate delivery service.

Similarly, the high capacity of mobile devices creates an increased need for periodic backups. While users can do this by local means, it is a profitable service to offer over-the-air automatic backups. Today these backups consume valuable immediate transfer service spectrum resources; they would be a great fit for the non-time-critical bulk delivery service. More generally, bulk delivery effectively supports “write-behind” applications of which backup is merely one example.

Users have a strong desire to share media such as songs and videos with their friends. Similarly it is valuable to synchronize the user’s mobile device with their media collection on their laptop or home computer. In many cases users are willing to accept a moderate delay for the transfer to complete. If the option of bulk or immediate transfer is offered with different tariffs, users will find it reasonable to decide whether to pay for instant gratification.

4.6. Other uses for hybrid wireless systems

The above discussion has focused on the use of shared spectrum in a hybrid wireless system to support a bulk delivery service, for which we see the potential for strong market demand. However, we do not expect bulk delivery to be the only use of hybrid wireless broadband systems. Once hybrid systems capable of exploiting shared spectrum are widely deployed, we expect the inventive genius of markets will produce additional novel uses.

It is possible to envision a range of services for which hybrid wireless systems can reduce cost compared to current wireless broadband systems. The common thread among these services is that, in at least some of their operating modes, they can tolerate the delays associated with unguaranteed spectrum access.

- *Data retrieval and control interaction with distributed sensors.* The sensors may be deployed to assist in the control of a utility system like power or water, support environmental monitoring, or enable innovative solutions to challenging urban problems. Moving these data interactions out of dedicated mobile device spectrum and into shared spectrum frees up dedicated spectrum for higher-revenue uses. Use of shared spectrum may be essential to reduce the overall per-unit service cost to the levels necessary to deploy large numbers of sensors. Use of shared spectrum may also allow the sensor system to exploit lower frequency bands with better propagation characteristics, reducing sensor battery and size requirements. On the other hand, sometimes sensor systems require immediate transfer of critical data (“earthquake!”) so it is difficult to operate them solely in shared spectrum. A hybrid wireless system is an appropriate solution.
- *Ad hoc or mesh networking.* A network largely based in unlicensed spectrum at high frequencies with poor propagation may exploit a mix of dedicated and DSA spectrum for long-range backhaul links.²⁷ In normal operation it is desirable to run the backhaul links in dedicated spectrum, both to increase network reliability and to exploit lower frequencies with longer propagation distances or

²⁷ In this context “backhaul” includes long-distance cross-haul links that interconnect local groups of ad-hoc nodes which would otherwise be disconnected.

deployed infrastructure with broad coverage.²⁸ However, given the low revenues associated with these networks, it seems unlikely that sufficient dedicated spectrum can be acquired to provision the backhaul links for peak load. An effective solution may be to build the backhaul network as a hybrid wireless broadband system, coupling the (expensive) dedicated backhaul with surge capacity in shared spectrum when available.

Obviously, the success of any of these services will depend on many factors in addition to the maturity and availability of hybrid wireless systems incorporating DSA technology. However, we believe DSA represents an important element in a healthy future for wireless services.

5. Complementary Developments and Policy Recommendations

In the following sub-sections we focus on three areas for complementary developments that we believe will enhance the realization of the shared spectrum future our Hybrid Wireless Broadband vision predicts. This is an idiosyncratic list that is incomplete – rather than focus on everything that needs to happen, we focus on several key areas that we believe have been under-appreciated in policy debates about the wireless future. Our intent is to elevate these issues in the policy roadmap and research agenda.

5.1. Client device economics

The economics of mass-market mobile devices are a critical constraint on the evolution of wireless access networks. Without attractive devices available at a competitive price, no service can succeed. Client devices for a wireless data service include not just handsets but also internal cards for laptops, OEM units for embedding in systems like vending machines, and highly integrated chips for low-end devices like sensors or toys. Given the high feature sets and quality of current affordable mobile devices, achieving a competitive price for an attractive device requires volume manufacturing, often at

²⁸ A nascent form of this is growing in popularity already with the deployment of the Verizon MiFi and similar devices. See http://www.verizonwireless.com/b2c/mobilebroadband/?page=products_mifi.

global scale. This makes it difficult to introduce a service like hybrid wireless broadband that involves a significant change in device design or technology.

Sophisticated client devices already have multiple radios (e.g. cellular, WiFi, BlueTooth, DVB receiver). It would not be much of a technical change to add a “DSA radio” specialized for shared spectrum, making the client device capable of exploiting a hybrid wireless broadband system. Nevertheless, device manufacturers have to be convinced that adding an additional radio subsystem for exploiting spectrum sharing will provide sufficient additional market value to justify the subsystem’s cost, size, and weight.

While this is a challenge for any new wireless access network technology, it is particularly a problem for communications based in shared spectrum. The business case for adding a DSA radio is uncertain because the radio is not guaranteed the spectrum access required to achieve the promised end-user benefits and hence may not deliver the expected market value. To overcome these challenges, it is vital to minimize the incremental cost of adding DSA radio capability to existing mass-market client devices. There are several drivers for the incremental cost.

Frequency agility: Unlike traditional radios, each of which operates in a frequency band or bands specified by its communications standard, a DSA radio needs to be able to tune over a range of frequency bands. The degree of tunability is a key figure of merit for spectrum sharing devices. A greater tuning range provides a greater chance of finding the necessary spectrum for communication.

Unfortunately, a high degree of frequency agility is expensive both in component cost and in size and weight, at least with current technology. A good example is the Rockwell Collins XG 30–3000 MHz receiver, designed to minimize size, weight, and power for military applications whose cost tolerance is high.²⁹ Even in this context, designers were forced to use a bank of physically large preselector filters, one per band, since no one filter they could acquire was both tunable enough to cover the full range and selective enough to reject strong out-of-band signals.

²⁹ Newgard *et al.* (2008).

There is ongoing work on tunable radio components that fit the needs of mass market handsets³⁰, but significant research and development is still needed. Minimizing the incremental cost of adding DSA radio capability to mass-market client devices thus requires minimizing the required frequency agility.

As a result, one of the most important tools available to regulators to assist in promoting hybrid wireless broadband systems, if this goal is judged desirable, is to focus initial efforts to permit and encourage spectrum sharing on achieving a high density of potentially available spectrum. Secondary access to 100 MHz that is scattered in small chunks all over the dial is much less likely to result in service deployment than secondary access to 25 MHz which is near or collocated with the dedicated exclusive-use spectrum that is already in use by mobile operators.³¹

Another way in which regulators can reduce the frequency agility challenge is to focus secondary access on unpaired spectrum rather than on paired spectrum. This seems a likely focus in any case since paired spectrum is both harder to identify and harder to access safely on a secondary basis. However it is worth noting that achieving a high degree of tunability for the frequency diplexer component required to operate in paired spectrum is particularly problematic. This component filters out the potentially strong transmissions by other nearby client devices when the mobile device is listening to a distant, weak transmission by the base station. In TDD systems for unpaired spectrum, transmissions by clients and by the base station are segregated in time rather than in frequency, eliminating the need for the diplexer and making frequency agility easier to implement.

Additional baseband chips: Viewed at a high level, the radio in a wireless client device consists of two components, a radio front-end that handles the analog tasks (tuning, amplification, filtering) and a baseband processor that handles the digital tasks (modulation, equalization, coding). In the most integrated designs these two functions are combined into a single chip, but often they are separate since the manufacturing processes and design engineering capabilities required are quite different.

³⁰ Cafaro *et al.* (2007).

The investment required to add a DSA radio to a mobile device can be significantly reduced if one of the existing baseband chips can also support the DSA radio functions. Thus instead of adding two chips, a new radio front end and a new baseband chip, the designer can get away with adding only a new radio front end.

The challenge of sharing a baseband chip is that this significantly constrains the waveform that can be used in the shared spectrum. The situation is quite different from the infrastructure devices discussed in Section 4.4, which are implemented using highly flexible hardware components (e.g. FPGAs). Due to cost and power consumption challenges in client devices, their baseband chips combine some amount of flexible processing with fixed-function hardware circuits specialized to a particular communications standard. While a waveform for shared spectrum could be implemented entirely in the flexible processing subsystem, this approach would result in high power consumption and low performance making the DSA operating mode unattractive to users. To exploit the available hardware accelerator circuits, the shared spectrum waveform will need to draw most of its low-level design from one of the waveforms already supported by the client device.

For the reasons described in Section 4.4, an optimal shared spectrum waveform is quite different from current 3G and 4G waveforms. Yet early deployment at low incremental cost pushes for a waveform similar to current waveforms. This discrepancy suggests that regulators should consider a two-stage approach to promoting hybrid wireless broadband systems. In the first stage the shared spectrum access that is permitted or encouraged should to be focused on establishing bands or channels where current mobile-device waveforms can be used with small modifications, even though this is not optimal for spectral efficiency. After market adoption has gained momentum, further bands or channels can be opened up that require greater specialized support in the client devices.

³¹ Our choice of 25Mhz is not completely ad hoc. Less than 10MHz would not provide sufficient shared spectrum to make it useful for supporting interesting applications and more than 25MHz is unlikely to be politically feasible or economically justifiable in today's policy environment.

An important next step, beyond the scope of this paper, is to carry out a careful analysis of the implications of this recommendation. Specifically, the baseband processor implementations of mass-market mobile device waveforms (e.g. 3G, 4G, WiFi) should be studied to determine what level of altered behavior is possible within the flexibility offered by current chip architectures. This information can then be combined with analysis of potentially available spectrum (channel characteristics, other users) to determine which bands and channels offer the best prospect for early market adoption of spectrum sharing in support of hybrid broadband systems.

5.2. Verification, certification, and liability

Shared spectrum access creates new risks. A DSA radio system will likely cause interference unless its spectrum access subsystem functions correctly. This subsystem is sophisticated, including among other components sensitive sensors, advanced decision algorithms, and analog transmission chains designed to emit variable bandwidth signals with a sharp power mask edge. There is thus a greatly increased emphasis on verification techniques, certification procedures and assignment of liability for problems.

Verification of correctness of a DSA radio system is challenging in part because the device senses and reacts to its environment. It is difficult or impossible to generate conditions in the laboratory that will explore all possible states of the device's internal decision algorithms. The challenge is even greater when the spectrum sharing design involves collaboration among multiple DSA radios or between a radio and a central database or decision server. In this case the contents and timing of all information flowing in the larger distributed system affect the spectrum access decisions of the individual node.

Regulators have two levers available to reduce the barrier that the verification challenge poses to successful deployment of spectrum sharing in hybrid wireless systems. First is to select bands and access rules, at least in the early stages when market momentum is building, that simplify the sensing and decision challenges facing DSA devices. Small reductions in complexity have major benefits for verification since verification challenges grow exponentially with the amount of state in a computing device. Second is to work with government research agencies, academic researchers, and industry

participants to establish one or more test beds where prototype devices can be put through their paces in a real-world situation. Such a test bed would involve a geographic area where it is considered acceptable to cause interference, there are installations of other radio-communications systems to test against, and there is the measurement infrastructure to evaluate the exact behavior and impacts of the new radios.

Certification, in the sense used here, is approval by the regulator for a manufacturer to market a device. It draws on verification of the device's behavior but also encompasses additional issues to assure safety, for example through verifying security against hackers or requirements for professional installation. Certification of advanced mass-market radios has traditionally been challenging because the once granted, mass-market devices deployed in large numbers cannot easily be located or recalled if they cause interference. Therefore regulators have been appropriately cautious. In the context of DSA radios that are difficult to verify, this level of caution could significantly hamper deployment of useful systems. Effectiveness of the devices at detecting and exploiting spectrum sharing opportunities will likely scale directly with the level of sophistication of their control mechanisms, which in turn reduces the assurance level of verification.

To help overcome certification challenges, we have elsewhere proposed the use of Time-Limited Leases.³² Briefly, the manufacturer can build a subsystem into the device that disables its shared spectrum access capability after a preplanned duration unless a renewal certificate is received. Thus if interference problems occur in the field, the defective devices can be guaranteed to be updated or shut down within a known interval. By reducing interference risks, regulators can certify more complex devices whose upfront verification costs might otherwise be prohibitive.

Assignment of liability is another area that becomes particularly challenging with DSA radios. These devices detect transmission opportunities, exploit them temporarily, then move on to other channels and opportunities. Since they may not operate at one frequency (or even with a constant modulation) for very long, the source or sources of any interference that does occur can be hard to

³² Chapin and Lehr (2007b).

pinpoint. The traditional technique of driving around in a van with direction finding equipment is unlikely to quickly uncover interference sources, particularly if the interference problem occurs due to short transmissions accumulated from many devices distributed around a geographic region. This is exactly the type of interference problem we would expect to see if there is a subtle error in the spectrum access subsystem of a mass-market DSA radio.

Research is needed on mechanisms to more quickly and accurately assign liability for interference problems. One idea is to have DSA radio devices log their spectrum access decisions internally, then provide a mechanism for retrieving these logs when the device may possibly have caused interference.

5.3. Business models for sharing

In section 3.2 and in Chapin and Lehr (2007a), we discuss multiple models for sharing spectrum across service provider infrastructures. As we noted, there are a number of policy and industry initiatives that are actively seeking to promote many of these models.³³ In this sub-section we focus on a particular class of sharing that we believe ought to be considered more closely, a *closed commons* model. We use this to refer to shared access spectrum that is open to only a specific group of users or operators. This is to distinguish it from the more familiar model of unlicensed use or public commons in which access is open to all conforming devices.

Opponents of the unlicensed model have argued that it does not offer sufficient interference protection or predictability (regarding the future spectral environment) to be attractive to capital intensive, wide area network deployments. A closed commons could adopt a much more restrictive set of technical and economic access rules to enhance the predictability and manageability of the spectrum environment. This protects against interference and ensures predictable access during periods of congestion, making it more attractive for investment.

³³ These include underlay (e.g., FCC UWB ruling) and overlay (e.g., FCC TV white space ruling) easements, efforts to better define spectrum property rights to enable trading (e.g., Ofcom's Spectrum

We do not have precise recommendations for how such a closed commons of shared co-primary users could be structured or what policy tools should be used to encourage its development. However we believe that a closed commons would be fertile ground for the evolution and growth of shared spectrum based services with innovative business models. The successful models can then be generalized and the services extended to exploit spectrum bands that are open to all users and perhaps already occupied by a licensee who retains primary usage rights. Although we lack precise recommendations for the path forwards, we have some general ideas about useful directions for investigation.

One important area is auction frameworks that help encourage the creation of private commons shared spectrum. One potential approach is to allow consortium bidding in spectrum auctions. We could imagine a coalition of private sector users bidding collectively to create a private commons. Examples of this include mobile operators (say Verizon, AT&T, Sprint, etc.) or equipment vendors (say Microsoft, Intel, Motorola) bidding jointly for a spectrum license. The point is for such a consortium to create a pool of shared spectrum that they subsequently jointly manage and access. Setting up the right framework to allow such an outcome would be complicated. Policymakers need to ensure that this approach is not used to cartelize spectrum access. Similarly, the business models that develop to exploit the private commons will not be generalizable to other forms of spectrum sharing if the consortium members divide up the allocated spectrum on a static basis with each member guaranteed exclusive access to their share. The auction rules would therefore need to be structured to ensure that the commons is actually shared on a more dynamic basis. We are not auction design experts and are aware that arbitrary constraints on auction participation (e.g., preferences and use encumbrances) can result in significant inefficiencies (as evidenced by the failure of the 700Mhz D-block auction). However it seems clear that careful research and policy analysis focused on how auctions can be designed to encourage the creation of more shared spectrum would be beneficial.

Usage Rights consultation), efforts to improve public access to database information on spectrum rights assignments, and secondary markets proceedings.

A related issue is the potential impact of encouraging private commons on auction revenue. It seems likely that a chunk of spectrum would be worth more if dedicated exclusively to a single service provider than if shared dynamically among multiple providers. Since the latter is more desirable from an overall policy basis to promote more intensive sharing models, policy makers may need to trade off longer-term spectrum efficiency goals against short-term auction revenue. More in depth economic research of the cost-benefit analysis regarding the of creation of additional shared spectrum is clearly needed.

Finally, policymakers could help jumpstart spectrum sharing by encouraging what we believe are obvious first-adopter experiments, and by avoiding approaches that we believe falsely suggest non-shared solutions. As an example of the former, we believe a large-scale demonstration of spectrum pooling by public safety or military agencies would deliver near-term benefits and produce very valuable collective learning that would help reduce resistance to wider deployment of sharing by commercial service providers. Military users are early adopters of DSA-enabling technologies like software and cognitive radio. Their mission objectives and need for expanded wireless services of all types make them likely candidates for sharing spectrum among different military rights holders. Public safety users are in a similar position. They currently have rights to a fragmented collection of narrowband channels that could be shared more efficiently to support much needed services such as broadband access on an ad hoc basis (at the site of emergency events).³⁴ These early-adopter communities are attractive because they have an immediate pressing need and share a common set of mission goals. This is a much simpler environment than commercial deployments in which to solve the technical, economic, and political challenges of developing useful models for spectrum sharing.

As an example of what policymakers should not do, we believe that the effort to create a national broadband network in a new allocation of dedicated access spectrum is misguided. First of all, it is difficult if not impossible to allocate enough dedicated spectrum (50+ MHz) to support a service

³⁴ Lehr and Jesuale (2008) make the case for spectrum pooling by public safety users.

comparable to that of incumbent operators, so such a network would likely be sharply inferior in performance to marketplace expectations, which both reduces its social benefit and makes it hard for the licensee to raise enough capital to build out the network. Second, even if allocating enough spectrum were possible, doing so would distort existing spectrum management and auction processes as well as the economics of the current competition among operators, while doing little to stimulate solutions to the fundamental long-term problem of wireless broadband, which is that demand growth will soon outstrip the conceivable supply of dedicated access spectrum.

6. Conclusions

This paper has focused on our vision of hybrid wireless broadband service. Such services are high-capacity converged services implemented via multiple overlaid wireless networks, some of which share spectrum resources with other wireless networks. We see hybrid services emerging as the dominant future model for wireless broadband, not because providers or vendors want to grow in that direction but because they will be unable to continue growing along their current path in which all core broadband services are provided via exclusively licensed spectrum. User demand growth coupled with the lack of spectrum at useful frequencies available for reallocation to commercial broadband service ensures that the current dedicated spectrum approach will become nonviable well before 2020.

While significant growth in spectrum sharing is inevitable, there are a range of models possible and it is by no means clear what form of sharing will dominate or what business models will succeed in the marketplace. Therefore the focus of regulatory policy at this time needs to be to create the conditions for technical and market experimentation so the appropriate solutions can evolve. We have made several suggestions for ways policy makers can encourage this experimentation. Options include auction design that stimulates creation of private commons, selecting bands in which to encourage sharing that are close to existing commercial broadband spectrum and that permit use of waveforms closely related to existing commercial broadband waveforms, and creation of testbeds and certification procedures that reduce the risk of deploying innovative sharing technologies.

However it is implemented, shared spectrum will support a significantly different user quality of service than existing dedicated spectrum, since the provider cannot guarantee communications capability at any particular time. We have discussed in detail one example of what we believe may be a commercially viable service that tolerates this behavior, low-cost “bulk” delivery of non-time-sensitive data. We have identified several other applications such as sensor networks that may also be viable. In each case, we believe it will prove valuable to couple the non-time-guaranteed communications based in shared spectrum with time-guaranteed communications based in dedicated spectrum, which argues for encouraging the growth of hybrid wireless broadband systems rather than seeking to stimulate systems that operate solely in shared spectrum.

To summarize, the focus of spectrum management and regulatory policy for wireless broadband should be on transitioning to a future in which shared spectrum is a core resource exploited by the broadband services, used jointly and in close coupling with dedicated spectrum resources.

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