Mobile Broadband Growth, Spectrum Scarcity, and Sustainable Competition

John M. Chapin[1] & William H. Lehr[2]
Massachusetts Institute of Technology

Abstract: The explosive growth in mobile broadband traffic, driven by smart phones and tablets that significantly increase traffic per subscriber, has accentuated the spectrum shortage for Commercial Mobile Radio Services (CMRS). The spectrum shortage is driving up the costs of deploying competitive 4G mobile broadband networks and is fueling pressure for industry consolidation, and thus poses a threat to competition. The simple solution of allocating sufficient spectrum to maintain the current level of competition appears infeasible due to the high amount of spectrum required and competing political/economic claims on that spectrum.

This paper considers how to sustain competition in mobile broadband services under conditions of spectrum scarcity. We observe that the key leverage available at the system architecture level is to reduce cell size. Smaller cells increase capacity in a given amount of available spectrum, enable use of higher frequencies where new allocations are easier to provide, and for technical reasons explained in the paper, enable increased spectrum sharing which is critical for higher efficiency. The primary barriers to reducing cell size are economic. We examine how to foster inter-provider infrastructure sharing for cost sharing while mitigating the risk of cartelization. A novel feature of our analysis is that we consider spectrum congestion and economic barriers to cell-size reduction as two aspects of a single challenge. We identify several complementary approaches that simultaneously address the technical, economic and policy issues associated with this challenge.

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1   Introduction

Traffic volume on mobile broadband networks is growing rapidly. This is well documented so we review the trends only briefly. The growth is fueled by the mutually reinforcing deployment of higher rate services and more capable devices.[3] Prominent high-rate media and interactive services include streaming media, rich media gaming and video conferencing. The devices that exploit these services include smartphones, tablets and netbooks.[4] Penetration of the services and more capable devices is growing across the user base. Per-user usage appears to be increasing for all classes of users.[5] In addition to the increase in per-subscriber data usage, per user peak and aggregate data rates are increasing, and traffic is potentially becoming burstier.[6] The expansion of wireless services of all kinds brings us closer to the world of pervasive computing and the "Internet of Things" with 24/7 interactions of sensors and embedded processors.[7] Sensors and control systems directly

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[3] The drivers for increased traffic volume are similar to those fifteen years ago in the switch from dial-up to first generation broadband connections. In the initial wave of mass-market Internet adoption, content demand was dampened by the low speed of dial-up Internet connections which limited the quality of the user experience. Once the available rate increased, suppliers had an incentive to offer enhanced quality (higher bit rate) content and applications. Increased supply fueled increasing demand in a virtuous cycle. Additionally, the new broadband connections and faster desktop computers substantially raised the potential peak rate that could be exploited by an individual subscriber, and the traffic distribution became more heavy-tailed (see for example, Leland et al., 1994; Clark and Lehr, 1999; Bauer, Clark and Lehr, 2009).

[4] On July 1, 2011, research firm NetApplications reported "Mobile and tablet platforms now account for over 5% of all browsing on the internet and over 8.2% in the United States." http://www.netmarketshare.com/2011/07/01/Mobile--Tablet-Crosses-5-percent-of-All-Browsing-Globally.

[5] For example, in 2010, mobile data usage per laptop was 1.7GB/month, 405MB/month per tablet, and 79MB/month per smartphone – and smartphone usage is already more than 24 times the usage of the typical handset. Moreover, smartphones represented only 13% of the handsets in service, and the penetration of both tablets and handsets is growing (see, Cisco Visual Networking Index Global Mobile Data Traffic Forecast Update, February 1, 2011, available at: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html.)

[6] Increasing peak and per-user data rates increases capacity requirements in radio access networks and the networks that connect them to the Internet. With the rise of streaming video, it is unclear whether the traffic is becoming more bursty or not (i.e., peak to average rate increases). Bursty traffic poses additional provisioning problems because it is harder to predict peak capacity needs, and more difficult to offer acceptable service quality at high-levels of utilization. Lower effective utilization increases capacity costs. For further discussion, see sources discussing heavy-tailed distributions in note 3 *supra*.

[7] For example, see http://www.internet-of-things-research.eu/, or "Internet of Things – An Action Plan for Europe," Commission of the European Communities, 18 June 2009, COM(2009) 278, available at: http://ec.europa.eu/information_society/policy/rfid/documents/commiot2009.pdf.

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generate only low amounts of traffic. However, pervasive computing is likely to indirectly induce significant amounts of traffic as applications process real-time information flows from the environment and seek to make appropriate decisions on behalf of users.

Rapidly increasing wireless data traffic that is potentially more bursty and uncertain, from a growing number of nodes, creates critical stress on scarce spectrum resources. A number of studies (e.g. Rysavy Research 2011, ITU 2006) have forecast significant increases in the demand for RF spectrum, especially in the beachfront spectrum below 3GHz.

The strong demand for additional spectrum interacts with the competitive structure of the mobile broadband industry. Today, in many markets there are four or more operators offering comparable high-grade service to mass-market consumers. We call the top tier of the mass-market *high-grade* mobile broadband service. A high-grade service in a specific market is one that provides speed, functionality, and coverage in that market comparable to or better than that of the widely used offering from the leading national operator active in that market. We focus on competition among infrastructure-based providers of high-grade services. Competitors providing lower-grade services, and competitors without their own infrastructure (i.e. Mobile Virtual Network Operators), play a secondary role in driving the capacity increases needed to meet user demand growth.

In the current industry structure, infrastructure-based providers of high-grade services operate those services almost entirely in exclusively licensed spectrum.[8] In this paper, we start from the hypothesis that it will prove impossible to allocate sufficient additional spectrum to maintain the current level of competition under the current industry structure. Without significant new spectrum allocations, providers who wish to offer high grade services will need to invest substantially more per subscriber in infrastructure in order to shrink cell sizes to remain competitive. Unless the mobile network architectures and business models change, the level of competition will inevitably be reduced. In some markets, only a single high-grade mobile operator may remain viable.

The core of this paper is an articulation of an alternative trajectory for wireless broadband competition and the technical/business architecture that sustains it. The goal is to achieve appropriate and limited sharing of spectrum and infrastructure between leading operators in their primary markets so that (a) available spectrum supports sufficient competition, and (b) available economic resources support the highest possible reduction in cell size. One major concern addressed in the analysis is the risk that control of a shared spectrum or infrastructure resource may be used to enforce cartelization.

In Section 2, we paint what we believe is a plausible scenario for where the status quo architecture of silo-networks may take us. It is a vision with a fewer number of facilities-based operators, each with exclusive control of a larger share of the available spectrum, and operating higher-capacity networks (e.g. LTE). Dense antenna architectures will be deployed in urban markets, but less capable networks and less extensive coverage will be

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[8] AT&T's use of WiFi offload in urban cores is an interesting and telling counterexample. We discuss this in detail later in the paper.

available in secondary urban, suburban and rural markets. While such an outcome may prove satisfactory to many, we believe a better alternative exists.

In Section 3, we sketch our vision of a future with more infrastructure and spectrum sharing. We believe this alternative offers more hope of sustaining competition and wireless innovation, while helping to assure advanced mobile broadband services are available to all.

In Section 4 and 5 we analyze infrastructure sharing and spectrum sharing policy options in detail and show how they are tightly coupled. Section 6 discusses how to mitigate the risk of cartelization created by the more intensive sharing we recommend. Section 7 concludes and provides suggestions for future work.

2   A status quo vision of the broadband future

The policy response to growth in mobile data traffic over the past decades has been to increase the supply of spectrum available for commercial mobile radio services (CMRS). This policy is strongly supported by operators; according to one analysis in early 2010, increasing capacity by lighting up a new channel at an existing site is five times cheaper than establishing a new site, if the cost of spectrum is excluded.[9] The current National Broadband Plan and recent White House policy statements call for an additional 500 MHz of spectrum to be made available for commercial mobile broadband services.[10] Moving towards this goal, the FCC has targeted specific bands that it believes may be auctioned as exclusive-use CMRS licenses.[11]

How successful the FCC will be in meeting its 500 MHz goal, and how much of this will be in the form of spectrum to be auctioned for exclusive licenses, remains to be seen. While we do expect a significant amount of additional spectrum will be auctioned, we do not think that there will be enough in major markets for four or more, perhaps not even three, service providers to end up 10 years from now with CMRS spectrum rights comparable to those controlled by the two leading national operators (AT&T and Verizon Wireless). Industry behavior suggests agreement with this view. For example, AT&T and T-Mobile argue that an important motivation for their merger is to allow them to combine their spectrum resources to enable them to better offer mobile broadband services.[12] The heavily-capitalized startup

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[9] Rysavy Research (2010a).

[10] For the National Broadband Plan (NBP) see http://www.broadband.gov/ (released March 2010). The Presidential memorandum released June 2010 calling for 500MHz of additional spectrum for commercial broadband services is available at http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution.

[11] The NBP calls for the FCC auctioning 120MHz of television spectrum via an incentive-auction, as well as in other bands such as AWS 2/3, WCS, and MSS (see National Broadband Plan, Chapter 5).

[12] See "Acquisition of T-Mobile USA, Inc. by AT&T Inc.: Description of Transaction, Public Interest Showing and Related Demonstrations, Filed with the Federal Communications Commission, April 21, 2011 (redacted for public release), available at: http://fjallfoss.fcc.gov/ecfs/document/view?id=7021240421.

Lightsquared is trying to enter the mobile broadband market through a risky play involving spectrum previously allocated for mobile satellite services (MSS) rather than bidding in CMRS spectrum auctions.[13]

To understand why CMRS spectrum limitations threaten the viability of facilities-based competition, we need to flesh out the status quo story a bit further. When traffic increases but additional spectrum is not available, there are two primary strategies a network operator may employ. It can upgrade to a newer radio technology, or it can split cells.

Replacing radios with newer technology normally increases the bits per second that can be transmitted over a fixed amount of spectrum at the same distance from base station to mobile device.[14] However, technology upgrade is not an effective strategy for a smaller provider seeking to overcome a disadvantage in spectrum holdings compared to a large competitor. Unilateral technology upgrade by a small competitor will result in low-volume mobile device sales and corresponding high mobile device costs and limited selection, rendering the service offering less attractive to consumers. Smaller competitors therefore need to stay within the technology range established by the current high-volume offerings of the major international players.[15] Even large players can afford to upgrade technology only rarely and at great expense.

The primary competitive strategy to cope with insufficient spectrum holdings is thus to split cells, which means building new cell sites that infill existing covered areas. This improves the spatial reuse of existing spectrum allocations and increases capacity. Unfortunately this strategy increases infrastructure cost per square kilometer covered. Another effect increasing infrastructure costs is the high backhaul requirements of the base stations for high-grade mobile broadband services. In most markets, fiber optic backhaul is required to provide the envisioned mobile broadband quality of service.[16] Thus there will need to be significant investment in fiber plants supporting the base stations.

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[13] For more information, see http://www.lightsquared.com/uncategorized/the-spectrum-story/.

[14] For example, an Ofcom study of realistic performance increases associated with LTE deployments estimated that a typical 4G LTE deployment will be 3.3 times more spectrally efficient than a standard current 3G deployment, and that the improvement could exceed 5.5 times by 2020 (see, "Report for Ofcom: 4G Capacity Gains," Issued January 27, 2011, available at: http://stakeholders.ofcom.org.uk/market-data-research/technology-research/2011/4G-Capacity-Gains/). See, also, Rysavy (2010).

[15] This does not preclude to potential of niche entry or via a radically different business model than that associated with traditional CMRS mobile operators (e.g., one that might depend on user-deployed infrastructure).

[16] Copper lines have limited capacity and are normally leased at prices reflecting their historic value in the voice telephone system, which makes them far too expensive for the contemporary per-byte value of broadband backhaul traffic. Wireless backhaul certainly has a role to play but seems unlikely to meet the needs of high-density 4G networks. Wireless backhaul is limited by spectrum congestion and normally operates at high frequencies where an dish antenna is required. Dish antennas create

As coverage costs increase along with spectrum costs, and under the assumption that potential revenue growth per user is limited, a provider has to capture a larger share in each market in order for operation in that area to be economically viable. Moreover, the cost of providing excess capacity that is under-utilized increases, so a larger number of users per sector are required to average out each user's burstiness.

For these reasons the smaller competitors will weaken over time, leading to a reduction in the number of infrastructure-based providers able to offer high-grade mobile broadband services. We foresee two surviving 4G network operators in major markets, and one or zero in many of the smaller markets. The other mobile operators will either exit the market or be reduced to niche competitors that offer lower-quality discount services. While this surviving competition may limit the market power that the leading operators would otherwise have, it is a very different type of competition than exists in mobile broadband today, where there are multiple competitive high-grade providers.

To summarize: if nothing changes in the market structure, we expect at best duopoly competition in advanced mobile broadband services in urban markets. As one moves toward less dense markets, including many suburban markets that today are reasonably well-served by three or more 3G network operators, even duopoly competition will be hard to achieve due to the high cost of fiber infrastructure.[17] 4G class services will appear slowly if at all in rural areas. This condition will be sustained because the spectrum requirements and coverage cost of providing high-grade service will make new entry into the market even more difficult than it is today.

3   An alternative broadband future

We now turn to the question of how to establish an alternative trajectory that more effectively sustains competition in mobile broadband services than the status quo trajectory described above. This section summarizes our recommendations, which are explained in more detail in subsequent sections.

In our view, the key steps in a successful strategy to sustain competition are: (1) infrastructure sharing, leading to (2) cell size reduction, which provides (3) growth of total broadband capacity and enables (4) spectrum sharing among CMRS providers and with non-CMRS licensees. These steps are mutually complementary; progress along one will ease the path for others.

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high social impacts and excessive cost when attached to the small scale base stations used in high density 4G class networks.

[17] As required cell sizes shrink, the backhaul fiber plant for mobile broadband service begins to approximate a wired broadband system. At that cost, the infrastructure is close to a natural monopoly. For example, the National Broadband Plan assessment is that 75% of the US population will only have access to one wired broadband offering (page 42, available at: http://www.broadband.gov/plan/).

Infrastructure sharing is an essential part of the strategy because coverage costs are the primary driver of the competition problems identified above. Infrastructure sharing enables amortizing high infrastructure costs across the revenue streams of multiple competing service providers. As a result, sharing enables cell size reduction beyond that possible if each provider funds dedicated infrastructure. We recommend sharing be pursued in a way that enables technical differentiation and innovation, for example by using a Distributed Antenna System that supports multiple radio access technologies. Furthermore, operators with business models premised on sharing of infrastructure are more likely to be willing to share spectrum resources.[18] Meeting the technical requirements of sharing physical radio infrastructure will have the parallel effect of reducing the technical costs of sharing spectrum. Moreover, sharing of one type of asset will break down business resistance to sharing other assets, especially when those assets are closely coupled.

Aggressive cell size reduction, in turn, provides the key technical leverage for escaping the collision between demand growth and limited spectrum resources. Cell size reduction increases total broadband capacity within a fixed spectrum allocation in several ways.

a) There is better spatial reuse of each radio channel.
b) The reduced distance between transmitter and receiver enables higher data rates within the same transmit power and noise level.
c) If the capacity metric of interest is battery life or transmit power, for example in sensors for the Internet of Things or in small and light-weight personal devices, a particular target data rate can be achieved with less power.[19]
d) Below a threshold cell size, network MIMO techniques become feasible.[20]

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[18] While advances in wireless technology such as software defined radio are reducing the extent to which physical radio infrastructure and the radio frequencies used by that infrastructure are co-specialized assets, there remains a close coupling. This close coupling has been a key justification for the "silo" networks we see today. In today's architectures, sharing occurs at the application or service level (e.g. when customers roam across operator networks for telephone network coverage). While such sharing helps reduce aggregate capital costs, we are calling for even more extensive sharing here.

[19] Enabling data rates to increase while limiting transmit power is also desirable to mitigate health risks. Whether one believes these concerns are real or not, the debate over this issue seems likely to intensify in coming years.

[20] Most users are familiar with the new class of WiFi routers that use 802.11n MIMO (Multiple Input-Multiple Output) technology. This is implemented on each wireless router by using three antennas to take advantage of multipath to disentangle the desired signal from noise, and thus improve system performance. Similar strategies can be employed by integrating the signals from multiple networked base stations to enable network MIMO, if cell size is small enough that mobiles are in range of multiple base stations at the same time. In addition to expanding capacity, network MIMO provides benefits in reliability (because of path diversity and redundancy), coverage (dead-spot elimination), and data rate. See, for example, Gesbert and Akhtar (2002) or Zhou et al. (2003).

Spectrum sharing is an essential part of sustainable competition under spectrum scarcity. Two types of spectrum sharing are necessary: sharing between CMRS providers to increase efficiency, and sharing with non-CMRS licensees to enable mobile broadband use of spectrum that cannot be fully cleared of other users. Cell size reduction is a critical enabler for spectrum sharing.

a) Tunable transmit and receive technologies are much further advanced for low-power systems (handset-class and femtocell-class) than for high power systems (macrocell base stations).[21] Higher levels of tunability permit access to a wider range of bands for shared or secondary use.

b) Lower transmit power enables secondary access to a channel closer to a protected primary with less risk of harmful interference.

c) If a shared channel only permits short-range transmission, a small cell size implies that a higher fraction of users will be within range of the base station. Thus a higher fraction of traffic can be offloaded from dedicated CMRS spectrum to the shared channel.

Sharing of infrastructure and of spectrum, if not done carefully, creates a risk of cartelization that would keep prices artificially high and/or prevent new entrants. There are several primary options that can be used individually or in combination to mitigate the risk.

a) Public disclosure rules providing transparency in sharing arrangements and management of shared resources, enabling existing antitrust mechanisms to be applied if necessary.

b) Municipal, county or state ownership as appropriate of key infrastructure components ensuring promotion of long-term community development interests.

c) Open access regulations, including line-of-business restrictions on private entities that limit their ability to vertically integrate upstream or downstream from control of the shared resource into affiliated mobile broadband markets.

The following sections explain the many details glossed over in this high level description of the strategy.

4   Infrastructure sharing

This section analyzes how best to share infrastructure to overcome barriers to cell size reduction. Infrastructure sharing is not new. The first-generation macrocell buildout leveraged the shared PSTN by leasing T1 lines for backhaul rather than laying new cables

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[21] An example of the advanced state of technology for low-power systems is (Cafaro 2007) which describes a single-chip highly-tunable transceiver. In contrast, for high-power systems basic research continues on individual components such as tunable capacitors. Some recent efforts are summarized in the July 2010 issue of High Frequency Electronics, available online as http://www.Highfrequency electronics.com/Archives/Jul10/HFE0710_TechReport.pdf.

from towers to the switching centers.[22] As the mobile cellular industry evolved we saw the emergence of shared towers (owned by third party entities such as Crown Castle and American Tower) that amortize the real estate, construction and maintenance cost of a macro tower among two or three service providers.[23]

We need to continue this trend and share substantially more of the mobile broadband infrastructure, in a way that promotes competition among all the service providers sharing the infrastructure and opportunity for new entrants to enter at roughly parity cost. Going beyond tower sharing, system components that might be shared include backhaul, antennas, radio electronics, and so on. The different tradeoffs of sharing various components are discussed below. With more of the infrastructure shared, the available economic resources for investment will enable getting to smaller cell sizes, reducing the impact of spectrum shortage.

In promoting shared infrastructure, we believe it is important to select an approach that preserves the option for competing providers to adopt different RF technologies. The opportunity to pursue alternative technical solutions is a key ingredient of the dynamics of competition and is important for innovation.[24] Some might argue that the network effects associated with widespread adoption of a single technology (e.g. LTE) reduces costs and enhances interoperability, and these benefits are so critical that even non-CMRS usage classes such as Public Safety should hop on the same bandwagon. While the cost benefits are obvious and important, a market in which no provider can strike out in a new direction without loss of shared resources essential for a competitive cost structure is a market in which innovation will be slower and less responsive to evolving user needs.

Two primary types of infrastructure sharing are network sharing and component sharing. In network sharing, the shared infrastructure is a complete network, containing radios, backhaul capacity, and some portion of the network core. Such a network is deployed and managed by an entity that shares its capacity (megabits/second of communication over the air) among the mobile broadband providers. In component

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[22] The ubiquitous coverage, mostly copper-based infrastructure for these T1 lines was put in place, principally, to support fixed line telephony and data communication services. Public utility regulation of the incumbent telephone carriers who owned and operated the PSTN infrastructure ensured that it was made available under appropriate terms for use by new emerging services, such as mobile telephony. Thus, the earlier regime enabled shared access to bottleneck facilities.

[23] Tower sharing – which has only been lightly encouraged by regulations – demonstrates how asset sharing may arise in competitive markets in the normal course of business.

[24] It appears to us that the development of the WiMax standard in the US led to substantial improvements in the technical quality of the European-based 3G standards (culminating with LTE), whose proponents were forced by competitive pressures from WiMax deployments to incorporate significant modifications that rapidly evolved their system from a voice-optimized to a data-optimized design. We would likely be suffering with a much less aggressive and optimized LTE design if all major operators had had to remain within the 3G standards family. See Lehr and Chapin (2009) for further discussion of the benefits of technical diversity in the wireless ecosystem.

sharing, the shared infrastructure is one or more components of a network (backhaul, amplifiers, chassis space, etc.) but not a complete network. Each of the competing providers deploys and manages its own network, exploiting shared components to reduce cost where desirable and appropriate.

Both forms of sharing are already well established in the mobile broadband ecosystem. Network sharing occurs in the form of roaming agreements to extend coverage, while component sharing occurs in the form of tower sharing to reduce site buildout costs and zoning challenges. Either model could be extended to the infrastructure sharing needed to reduce cell size in spectrum congested areas. We recommend both forms of sharing be used. In some areas one or the other will be preferred; in other areas both can be used.

4.1   Network sharing

Network sharing is an important part of the infrastructure sharing needed to reduce cell size. However, it is critical to select the appropriate form of network sharing. Three forms of network sharing are roaming, offloading, and a Virtual RAN. This section compares them and concludes that offloading is the best option to pursue in the near term.

In roaming, a mobile device is temporarily affiliated with a network owned and operated by an entity different from its home network. The device initiates and receives all calls and data transfers via the radio and core network resources of the roaming provider. Using the roaming model for shared infrastructure would require a fundamental change in current business practices. Providers would have to rely on a roaming partner for the small-cell infrastructure. This might be a wholesale provider, municipal utility, or competitor. Spectrum congested markets are likely to correspond to high revenue markets, and many providers would be reluctant to cede control over the network experience of users in those markets.

Leaving the business practices issue aside, the roaming model has other disadvantages. It ties all providers to the air interface standard selected for the shared network, reducing the rate of technical innovation. Moreover, if the deployment of the roaming partner's small-cell infrastructure is implemented as an overlay network (i.e., to supplement the capacity of operators' existing macrocell sites), it is likely to offer only limited increases in total broadband capacity. In an overlay situation, the capacity benefits of cell size reduction are limited by the fraction of total spectrum assigned to the smaller cells.[25] Allocating sufficient CMRS spectrum to the small-cell infrastructure operator may prove problematic.

There are two other forms of network sharing that appear promising. One is an offload model, where the shared network uses a different air interface technology optimized for different purposes than the primary mobile broadband network. In offloading, mobile devices remain registered on their home network, but when appropriate, transfer data for specific applications via the offload network. Normally mobile devices have a separate radio chip enabling them to communicate via the primary network and the offload network at the

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[25] An application of Amdahl's Law. http://en.wikipedia.org/wiki/Amdahl's_law.

same time, which is a key difference from the roaming model. For example, smartphones are able to receive a phone call via a 3G network while transferring data over a WiFi hotspot.

There is a strong synergy between infrastructure sharing via an offload network and spectrum sharing. The offloaded traffic may be selected to be the traffic that has lower quality of service requirements, so the offload network can rely on shared spectrum rather than exclusively licensed spectrum. Thus there is much more spectrum available for the offload network than would be available for a CMRS class network capable of supporting roaming. AT&T's use of WiFi in its hotzones for data transfers but not voice calls is an example of this. We discuss the implications for spectrum sharing further in Section 5.

The other form of network sharing that may be useful is a nascent technology called a Virtualized Radio Access Network (RAN).[26] This design exploits software radio to allow each of the providers sharing a network to select its own technology standard. The different air interface standards are implemented as different software applications running on a single hardware base station provided by the network. Each provider manages its user's experience independently through control of its software applications running on the shared RAN. In this approach, the provider configures its fraction of the Virtualized RAN's capacity (number of carriers the shared hardware is able to transmit and receive) to operate in spectrum licensed to that provider. That is, the spectrum used by the shared infrastructure is from the pool allocated to the mobile service provider, not the entity that deployed the Virtualized RAN. Thus the two major objections to the roaming model are overcome.

The Virtualized RAN approach appears promising to enable competition in coverage-limited rural areas. However, the underlying software radio technology used to support it has not yet reached the capacity and efficiency levels required for high-density urban and suburban deployments of 4G class services. While worth further investigation, it cannot currently be relied on as the solution for cell size reduction to overcome spectrum limitations in mobile broadband.

The form of network sharing that we consider further in this paper is the offload network.

4.2   Component sharing

Component sharing can be implemented with much less change to current business arrangements than network sharing. In this section we discuss the technical questions of what to share. The structural issues of component sharing are covered in subsequent sections.

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[26] See Muir (2009).

The extreme of cell size reduction for maximum data capacity from limited spectrum resources is "a base station on every light pole." We call these *utility-pole base stations*.[27] It is important to consider component sharing strategies that enable getting all the way to this extreme density, even though most regions would likely use larger cells. We raise this point because the small physical size of utility-pole base stations forces sharing of components that otherwise would be simpler to leave unshared.

We take it as a given that antenna sites will be shared, since this is already widespread in the industry. Backhaul fiber runs also require little discussion; they are a major cost driver and are easy to share once sites are shared. Even when sites are not shared, it is much cheaper to connect a standalone site with a short run to an existing fiber network than to connect it all the way to the provider's core. Thus it will be natural to share most or all of the fiber backhaul. Additionally, demand to backhaul mobile broadband traffic may help tip the balance toward expanded deployments of dense-neighborhood fiber, expanding the range of communities where fiber networks may become economically viable.[28]

One potentially surprising observation, however, is the importance of shared antennas at the shared sites, at least in capacity-limited urban and suburban areas. Without shared antennas, each provider must emplace its own antennas at the site. At the smaller cell sizes required for mobile broadband capacity growth, most sites will be building-mounted or on utility poles rather than on traditional towers. In these types of sites there is normally no room to replicate antennas. Each additional provider has to negotiate its own space arrangements with the landlord in the former case, and find its own unique set of poles in the latter. Normally one expects the second and third provider to acquire lower quality locations creating a significant competitive disadvantage. Given that a major goal of infrastructure sharing is to support new entry with fair opportunities to compete, antenna sharing for the small size cells will be highly desirable.

There are multiple technical options for sharing a base station antenna, each of which has its tradeoffs but may be optimal in different contexts. At one extreme is using an analog splitter/combiner to join multiple independent base stations, so nothing is shared but the antenna and the splitter. At the other extreme is a distributed antenna system (DAS) where all transmit/receive electronics at the site are shared. In a DAS the signal processing is performed by equipment located at a central facility, connected to the antenna site via optical fiber; the electronics at the site can be air interface standard-neutral. DAS is the most likely choice for utility-pole base stations since it has the smallest size and least power draw at the base station site.

There are other interesting and potentially useful antenna sharing architectures between these two extremes. Policy can and should be neutral about the architecture to be

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[27] For excellent pictures of base stations of this type, see Gerber (2011).

[28] Of course, there remains the risk that fiber backhaul may become the limiting bottleneck facility in many communities, so ensuring shared access to the dense-neighborhood fiber will remain a policy challenge. However, that is not a new challenge, as we noted earlier.

used, as long as the design is capable of adding a new competitor post-initial-deployment who is not at a significant competitive disadvantage to the previous providers sharing the antenna.[29]

All antenna sharing technologies that the authors are aware of have frequency range limits, due in part to hardware in the sharing subsystem and in part to the limited operating range of the shared antenna itself. Thus, by requiring antenna sharing, we are making it more difficult to use the shared infrastructure to provide coverage in newly allocated or newly accessible frequency bands. We believe this limitation is worth accepting given the benefits of antenna sharing discussed earlier. In coverage-limited rural areas, there is normally plenty of spectrum available in the core CMRS bands supported by off-the-shelf antenna sharing subsystems, so the limitation does not harm competition. In capacity-limited urban and suburban areas, providers sharing the infrastructure also have their own macrocell sites overlaying the same area. Any frequencies licensed to the provider but not supported by the shared infrastructure can be allocated to the macrocell sites (for example, to communicate with users driving at high speed, who are difficult/expensive to support from small-size cells due to high handover rates). Thus, we only require that the shared infrastructure support some frequencies used by each provider, and that it has additional operating range available to support the frequencies used by late arriving competitors. It is not required to support all frequencies used by all providers.

4.3   Distributed Antenna Systems

We now focus on shared infrastructure components consisting of very-low-power utility-pole base stations, most likely implemented as Distributed Antenna Systems (DAS). This is the most interesting case for radically increasing total mobile broadband capacity in dense urban areas within limited total CMRS spectrum.

As previously noted in Section 3, the frequency range supported by current technologies grows as the transmit power decreases. We expect utility-pole base stations could provide quite wide frequency coverage if there is a market driver for them to do so. Given the wide frequency coverage, it should be possible for the utility-pole base stations to do double-duty for both component sharing and network sharing. That is, the utility-pole base stations would be directly used by the mobile broadband providers as CMRS sites, integrated into each provider's network, but would also be used by an offload network operating in shared

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[29] Any antenna sharing method will have hardware capacity limits. For example, a splitter/combiner has ports for a certain number of base stations; a DAS unit has a certain maximum transmit power shared among all operating carriers. It would be counterproductive to place excess cost onto the entities sharing the initial deployment to provide unused capacity in case a new competitor arrives in the future. The best option to overcome this is to use a modular architecture in which the critical capacity limits can be upgraded at incremental cost post-deployment. If that is not possible, a business option is to finance the marginal cost of excess capacity in the initial deployment, planning for that cost plus interest to be paid by a late arriving competitor as its buy-in to the system.

spectrum. The offload network might also deploy its own macrocell base stations to exploit frequencies or areas not covered by the shared utility-pole base stations.

There is an interesting technical choice associated with the backhaul fiber supporting a DAS. The information transferred between the central signal processing facility and the antenna site can be sent as digital information, in which case it is just a stream of data packets that can share a metropolitan area fiber network with many other uses. Alternatively, the signal information can be sent as an analog signal. The RF waveform is modulated directly onto an optical carrier just like a voice waveform is modulated directly onto an RF carrier in analog AM or FM radio transmission. Use of analog backhaul provides greater air interface neutrality since the radio head at the antenna site no longer performs digitization or timing functions. However, it becomes harder to share the radio head among multiple independent providers, especially if each has its signal processing equipment at its own site. Also the quality of the signal can be degraded due to imperfections or switching in the optical run. Therefore digital backhaul appears preferable, although policy can be neutral about this choice. One caveat if digital backhaul is used is that the timing subsystems at the antenna sites should be designed to provide a sufficient level of cross-site accuracy to support network MIMO (see footnote 20 above).

4.4   Business structure for sharing

The proceeding discussion suggests a vision of infrastructure sharing that incorporates:

- an offload network provider
- operating largely in shared spectrum
- which leases use of some of its infrastructure components to the mobile broadband providers
- who use those components to support their CMRS operations in exclusively leased spectrum
- with both the offload service and the mobile broadband services running on the same low-power highly-tunable DAS units (potentially utility-pole mounted) in areas where the highest capacity and smallest cell size are required.

For this vision to be realized, a number of business structure challenges need to be addressed. The offload provider should have three core competences that are not currently found in any one organization. It needs to be skilled at leasing infrastructure components to mobile broadband providers; today that expertise is found in tower companies like Crown Castle and American Tower. It needs to have skills and the capital structure to fund and operate a hugely expensive fiber plant for the long term; today that capability is found in wireline service providers (legacy telcos, cable television providers, rural co-ops). Finally it needs to be skilled at running a wireless network in shared spectrum; today that expertise is found in WISPs and at least one of the major broadband providers.

We can imagine several evolutionary paths that might work, depending in part on the core competencies available in the local market. One potential path to develop an offload

provider is as a partnership between a tower company and a local wireline service provider. The necessary WISP expertise can be hired or acquired much more easily than either of the other two core competencies. This evolutionary path would naturally lead to an organization whose primary revenue stream comes from leasing use of shared components, with a smaller revenue expectation from selling offload network services. This matches the revenue balance we expect to see, at least in the near term where mobile broadband providers can quantify an immediate cost savings from reducing infrastructure expenditures by leasing access to shared components, but cannot as easily quantify the benefits of improving service to their users via offloading some data traffic.

An alternative path would be for a local government or county to take on the role as offload provider. Local governments have made investments in public safety infrastructure, and in some cases are already acting as the last-mile wired or wireless Internet access providers. While this approach may make sense in some locales, we hesitate to recommend it more broadly because of the competing imperatives driving local governments and their focus on other core competencies.

Instead, there is an attractive opportunity for a public-private partnership between the local government and an offload provider. The local government can leverage its control of local assets to significantly reduce the costs of fiber network build-out and antenna siting.[30] In exchange for that consideration and potentially funding or tax relief, the local government may be able to emerge from the partnership with ownership over some of the dark fiber or other communications assets. This provides long-term leverage to promote community development interests as the mobile broadband service evolves, for example by enabling the local government to invite in a new competitor if its needs are not being met.

5 Spectrum Sharing

This section discusses spectrum sharing from the viewpoint of improving CMRS competition under spectrum shortage conditions. The goal of spectrum sharing in this context is: Increase the number of providers that can compete at parity level (similar high class of service) in given total amount of CMRS spectrum and at a given cell density, by moving an increased fraction of traffic out of dedicated spectrum and into shared spectrum.

The perennial issue with shared spectrum is that access is not as predictable and congestion levels are not as controllable as in dedicated spectrum, so there may be delays in data transfer. In response, we observe that there is a natural division into (at least) 3 types of application traffic over mobile broadband networks:

- Delay-intolerant: VOIP, gaming, video-conferencing
- Delay-sensitive: text messages, operations when user is waiting (some fraction of file transfer, web page browsing, email), streaming video

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[30] An example is Chicago's efforts that facilitated the AT&T DAS buildout previously cited (Gerber 2011).

- Delay-tolerant: unattended file transfer (backups, syncing media, preloading news, software updates), telemetry

If these traffic types are differentiated from each other at the network layer, then when desirable due to high utilization of dedicated spectrum, some of the traffic can be moved into shared spectrum without impacting the user experience. Depending on conditions, in some cases even delay-intolerant traffic can travel over shared spectrum.[31] In other contexts, dedicated CMRS spectrum is required for delay-intolerant traffic. The decision about whether delay-sensitive traffic requires dedicated spectrum will depend on the congestion level of available shared spectrum, the QoS promised to the user based on their contract level, and other factors.

5.1 Comparison to "hotzones"

Shared spectrum and traffic splitting are already employed by leading operators to relieve congestion in the highest use areas. AT&T has deployed WiFi "hotzones" exploiting the unlicensed 2.4 GHz ISM band in Times Square, Austin, Charlotte, and San Francisco. Verizon announced its plans to exploit WiFi offload in May 2011.[32] The AT&T hotzones handle data traffic but voice calls still flow only over CMRS spectrum; this is a simple form of traffic splitting.

The key differences between our vision of spectrum sharing and the current hotzones deployment are the following.

In our vision, shared spectrum is used in a way that does not significantly increase infrastructure cost in areas covered both by dedicated and shared spectrum. Today each provider builds out a separate network for shared spectrum operation, with its own antenna sites and backhaul. A separate network is needed because hotzone access point density is very different from CMRS spectrum base station density. Since infrastructure cost is one of the main impediments to future competition, we believe that it is critical to achieve spectrum sharing without duplicated infrastructure per provider. This can be accomplished in two ways.

a) Exploit shared spectrum in a way that the necessary infrastructure is integrated into the existing cell sites of a CMRS network. For most current shared spectrum bands, range restrictions (due to propagation, congestion or both) imply that only portions of the geographic area covered by the CMRS network will be reachable via shared spectrum.[33] This is acceptable provided there is smooth handover between shared

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[31] For example, the authors regularly make Skype audio and video calls over their home WiFi networks.

[32] http://connectedplanetonline.com/3g4g/news/tia-2011-verizon-wireless-to-offload-3g-4g-data-through-free-wi-fi-hotspots-0519/.

[33] There are three potential objections to this statement, which can be answered as follows. (1) The unlicensed 902–928 MHz ISM band permits effective coverage at the site density used in urban CMRS deployments. While this technical observation is correct, the band is already heavily congested

spectrum and dedicated spectrum as users move. The capacity benefits of sharing will depend on what fraction of users are able to exploit shared spectrum, which in turn depends on the ratio between the range of communications in the shared spectrum bands and the existing inter-tower spacing.

b) Share (at least part of) the infrastructure along with sharing the spectrum, as discussed in Section 4.

In our vision, shared spectrum operation may involve novel air interface standards that exploit the fact that only authorized CMRS systems are in the channel, in order to increase efficiency, range, and quality of service compared to air interface standards such as WiFi optimized for free-for-all unlicensed spectrum.

In our vision, spectrum may be used that is secondary to a protected primary licensee, rather than dedicated for unlicensed use or for CMRS use. We expect it will be much easier to acquire access to secondary use spectrum (e.g. on the secondary market) than to get access to entirely clear or entirely unlicensed spectrum (e.g. through regulators moving existing users out of bands). Thus as CMRS usage continues to grow over time, it will be important to be able to exploit secondary use spectrum as opposed to just unlicensed spectrum. One result of this is radical time variation in capacity (sometimes the spectrum is available and sometimes it is not) and thus the need to separate delay-sensitive from delay-tolerant traffic. Another potential result is the need for coordination among multiple CMRS providers. For example if operation in the secondary spectrum requires sensing then the provider networks must coordinate quiet times, which impacts the appropriate sharing mechanism and may argue for shared infrastructure to simplify the coordination, (depending on how challenging the coordination problem turns out to be, which is a function of the specific rules required to protect the primary user).

5.2   The high availability requirement

When considering spectrum sharing that doesn't follow the current WiFi hotzone model, one guideline for architecture and policy evaluation that arises repeatedly is high availability. This term has two subtly different meanings.

• A spectrum band must be available across a wide geographic area. This is necessary due to mobile device scale requirements. The technology driver for this constraint is that any one circuit/chipset can only handle a single band. Mobile devices have to be specifically

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and cannot be considered a significant option for CMRS offload. (2) The TV Whitespace rules permit unlicensed access to a significant amount of currently lightly utilized spectrum with excellent propagation characteristics. However, the amount of TVWS available in congested urban areas is already small (a few channels), and this may shrink even further if proposals in the 2010 National Broadband Plan to reclaim and auction an additional 120 MHz of television spectrum are realized, so it is also not likely to provide significant CMRS offload. (3) The authors of the present paper have proposed a mechanism that enables congested unlicensed bands to be used for longer-range communications, as long as the data transfers are delay-tolerant. See Chapin and Lehr (2010). This proposal requires regulatory action which is not currently being considered.

designed for the bands they support and thus getting support for a new band requires sufficient geographic area to achieve a high volume of mobile device sales. There is relatively mature technology for more tunable circuits/chipsets (as discussed in Section 3). This suggests this constraint may be relaxed somewhat in the future, but these components have not yet been deployed in mass-market handsets.

- Within the tuning range of each deployed hardware infrastructure unit (for example, the hardware components at one site required to transmit and receive one LTE carrier), there must be the expectation that some channel will be available most of the time. This requirement comes from return on investment concerns for the provider deploying that hardware – idle hardware does not earn revenue. This constraint limits the number of CMRS providers who can share a band if each deploys their own infrastructure, and it limits the ability to exploit secondary access to non-CMRS-dedicated bands with active primary users. The requirement for high spectrum availability per deployed unit of infrastructure creates a significant constraint on spectrum sharing, because current infrastructure equipment has low tunability and thus there are only a relatively few channels whose availability to that provider can be combined to achieve the required high availability level. The technology driver for this is the fact that highly tunable filters and power amplifiers do not achieve power efficiency and selectivity competitive with fixed-frequency components. We are not aware of research that promises to support much higher tunability for high power (macrocell) infrastructure any time soon.

It is important to note that, for both of the above constraints, a channel being "available" does not mean it has to be exclusively available. Air interfaces such as WiFi allow multiple systems to be active on a channel at the same time. For delay tolerant traffic and in some situations for delay sensitive traffic, a WiFi-like channel even with a relatively high level of traffic from other systems can be considered to be available.

The fraction of time/place that spectrum is required to be available, and the fraction of time that infrastructure is required to be active, goes down as the level of equipment/infrastructure cost sharing goes up. In this context we are talking about sharing between the equipment for operation in the shared band and the equipment for operating in dedicated CMRS bands, not about sharing infrastructure between providers. When we talk about equipment sharing, we are talking about both infrastructure and handsets. As an example of this dynamic, the proposed standard that is supported by the most organizations for operation in the shared TV whitespace (TVWS) bands is 802.11af, which simply reuses the WiFi MAC and most of its PHY design in a 6 MHz TV channel. While proponents of other standards argue that standards custom-designed for the TVWS offer higher performance and other desirable features, the handset cost savings of being able to reuse the baseband WiFi chip are determinative for exploiting a band that has varying availability and hence unclear payoff for vendors/providers.

5.3 Sharing of spectrum dedicated to CMRS

We first discuss mechanisms for sharing the capacity of newly allocated spectrum dedicated to cellular, thus improving competition compared to the alternative of dedicating it exclusively to one bidder. In this form of sharing the spectrum is not unlicensed in the current sense of being open to all users. The spectrum is allocated and managed as a private commons where behavior of users is controlled by industry standards/norms. Proponents argue this will enable more predictable QoS, high efficiency and longer range transmission than current, fully unlicensed shared bands.[34]

The requirement for high availability of channels to justify infrastructure deployment has significant impact on this policy approach. One way to implement this strategy that might initially appear promising would be to simply allocate one LTE channel worth of spectrum in the existing CMRS bands for sharing among CMRS licensees. This has the advantage of requiring only minimal changes to current LTE architectures and equipment, thereby hopefully minimizing network and handset cost impacts.

Access to the shared band might be traded among the CMRS providers on a time-basis, with the shared LTE carrier assigned for exclusive use to a single CMRS provider in each time period. A number of mechanisms might be considered to support such time-based shared access. For example, one might consider periodic auctions that would assign control of the shared band to the winning CMRS bidder. At the start of each period, the winning bidder would light up the additional LTE carrier for expanded capacity, and then would turn the carrier off if another operator won in a successive round.

For this type of time-based sharing to be effective, the demands of the CMRS operators would need to be decorrelated in time/place. Since the demand peaks for different providers are likely to be highly correlated on coarse time scales, the time-based reassignment of right to use the shared LTE band would need to occur on a fine time scale (seconds or tens of seconds).[35] At such short time scales, there are significant technical and cost challenges. Current hardware systems (e.g., power amplifier linearization) and mobile

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[34] For example, Nokia and Qualcomm have proposed a model for Authorized Shared Access (ASA) to allow sharing with predictable quality-of-service by limiting it to authorized operators (see, http://policytracker.blogspot.com/2011/03/qualcomm-and-nokia-propose-authorised.html). Steve Shellhammer (Qualcomm) elaborated on this idea in a presentation to the White Space Communications Summit 2011 in June (see http://groups.winnforum.org/d/do/4476).

[35] Demands are correlated on coarse time scales because aggregate demand is driven by aggregate user behavior in the environment which is the same across carriers. Examples include: most users at home, most users at work, most users on the road for rush hour, activity bursts due to external news or entertainment events, and sensor network activity triggered by temperature or precipitation events. If user behavior is sufficiently different across providers to decorrelate the peaks at coarse time scales, it is because the service providers are segmenting the market and going after different demographics (corporate vs. young adult, similar to current postpaid vs. prepaid split) which is a more limited form of competition than we are focusing on here.

standards (e.g., for 1xEVDO, 3G, LTE) are not designed to light up and tear down carriers at high rates. Moreover, migrating users on and off LTE carriers at high frequency would incur significant overhead costs.

An alternative to time-based assignment of exclusive use is for the CMRS operators to keep the shared LTE channel lit continuously, and to use some sort of capacity-sharing mechanism to share the channel. Were the shared LTE channel assigned to a third-party roaming operator, it would confront the same spectrum capacity and customer-control challenges we noted earlier in our discussion of infrastructure sharing. Moreover, there would be additional challenges associated with how user handsets would select between the dedicated and shared LTE channels (e.g., current mobile systems don't support registration on two systems at the same time and dynamic selection of which one to use for specific data transfers).

Consequently, we believe that use of LTE or other current-style CMRS standards in shared CMRS spectrum is unlikely to prove desirable, even though to do so might appear to offer the path of least resistance and to minimize handset and network cost.

The alternative that remains is to employ a different technical standard from the one used in exclusively licensed spectrum. The standard used should not have a "lit carrier" that assumes and asserts continuous use of the channel by one base station or a collection of base stations that are part of one system. Instead, the standard needs to be designed for multiple independent base stations to share a channel in a single geographic area, perhaps through time-division based on Carrier Sense Multiple Access as is used in WiFi, or perhaps through some other technical mechanism. With a standard like this, there is a gradual reduction in capacity available to each of the sharing providers as congestion increases, but for the reasons described above this is preferable to an all-or-nothing design. This approach has the significant corollary benefit that new entrant providers can join the competition on an equal access footing with the incumbents.

It is important to emphasize that WiFi is not the only or even necessarily the best air interface to use for shared CMRS spectrum. The usage model for spectrum dedicated to CMRS is quite different from the usage model for which WiFi was designed and optimized. Propagation distances are longer, the infrastructure is planned and can be coordinated across all users (since only a limited number of CMRS providers have access to the spectrum), real-time coordination is possible through the backhaul links and RAN that support each access point, and there is a strong desire for predictable QoS and high spectral efficiency that WiFi does not provide. It seems likely that the CMRS industry would establish a new air interface standard optimized for this usage model if encouraged by regulatory policy to share a newly allocated CMRS-dedicated channel or band. Quite likely the standard designed would share as much as possible of the hardware and software components of LTE or whatever other CMRS standard is the widely used baseline, minimizing design cost and radio unit cost impacts.

Even if a new standard were to be developed with the best possible features, the fundamental shared nature of the spectrum results in offering a quality of service that is

noticeably different from that provided by exclusively licensed spectrum. Equally as important, handsets will have to have a separate chipset for operation in the shared band (or at least some separate components). Thus this option turns out to be similar in key ways to the sharing of spectrum with non-CMRS users discussed in the next sections. An important difference from a pure unlicensed band is that providers can predict the level of congestion and the level of access, which may prove important to some in making the business case for investing in infrastructure to support the shared band.

5.4 Fully unlicensed spectrum

Access to unlicensed spectrum is unrestricted and does not offer explicit interference protection.[36] This makes it difficult for CMRS operators to predict or control the quality of unlicensed spectrum, which renders it unsuitable for many CMRS business models.

Furthermore, current unlicensed bands are subject to strict power limits that limit their range. Moreover, unlicensed allocations at high frequencies have shorter propagation ranges with existing equipment.[37] The power/range limitations of unlicensed are often cited as necessary to manage congestion and limit the potential for interference with other bands and users.[38] However, these range limitations make it difficult to integrate unlicensed into macrocell CMRS networks.

The move toward small-cell infrastructure that we discussed earlier helps mitigate the range challenge associated with integrating unlicensed spectrum. Thus, the move to smaller cell sizes that is driven, in part, by spectrum scarcity, makes infrastructure sharing between dedicated and unlicensed (range-restricted) spectrum easier. It is important to note that cell density does not need to increase to the point that unlicensed bands can be used to reach any mobile device. Unlicensed spectrum can be used for mobile devices that are close to the infrastructure antenna, with dedicated CMRS spectrum used to reach mobile devices that are further from the antenna. The cell density merely needs to reach the point that a substantial fraction of mobile users are within range of the unlicensed band from an infrastructure antenna, in order to provide significant offload.

One key use of unlicensed spectrum is to support in-home femtocells. Today most operators reserve a CMRS channel for the femtocells since they are not planned/managed like the outdoor network is. We expect carriers will increasingly turn to using unlicensed spectrum in support of their femtocell deployments to free up CMRS spectrum that could be used for wider-area coverage and to take advantage of the growing share of customer handsets that are smartphones with WiFi or other local area network capability.

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[36] Access is limited to compliant devices; this restriction offers implicit interference protection.

[37] A significant share of the current allocation for unlicensed is at 5GHz.

[38] For example, limited power/range limits the number of potential users that can hear each other, and hence, congestion in any geographic area. It also makes it potentially easier for users to resolve interference problems directly (e.g., if my WiFi is interfering with cordless phone use, it is probably my cordless phone that is being interfered with rather than someone else's).

With the growth of high-speed wireless services within the home (e.g., high-quality multimedia home entertainment systems) and increased use by CMRS operators to offload traffic from CMRS spectrum, we expect unlicensed spectrum usage to increase, increasing the need for additional allocations. Moreover, as we have argued elsewhere, dedicated unlicensed supports different wireless entry models – including end-user deployed infrastructure models.[39] Enabling such entry options is important for competition and innovation, and therefore, provides an additional motivation for allocating a portion of any new allocations to mobile broadband as dedicated unlicensed spectrum. Because our focus here is on the challenges faced by CMRS operators, we do not discuss the relevance of such alternative wireless entry models further in this paper.

5.5 Secondary spectrum access

Secondary spectrum access provides exclusive access to a channel whenever the primary is not using it. This may be either non-cooperative secondary use (e.g., unlicensed use of TV white spaces) or cooperative secondary use (i.e., when the primary user has contracted with the secondary user).[40] Cooperative secondary use access might be negotiated as a privately negotiated lease contract with a primary user, or might be obtained in a secondary market. Such secondary markets might trade both primary and secondary usage rights.

When used non-cooperatively, via a so-called "easement," the spectrum adds to the pool of spectrum for unlicensed usage. Whether unlicensed secondary access or dedicated unlicensed is more attractive to a potential unlicensed spectrum user will depend on a number of factors, including the burden associated with avoiding interference with the primary user.[41] For CMRS users, we have already discussed some of the challenges associated with integrating unlicensed spectrum into their business models.

Cooperative secondary use, however, offers potential advantages because it is subject to contractual control. The times, amount and locations of primary usage can be contractually limited in the secondary market transaction, giving a higher degree of predictability for

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[39] See, for example, Chapin and Lehr (2007) or Lehr (2004).

[40] See Chapin and Lehr (2007) for a discussion of secondary use models.

[41] Generally speaking, because most of the prime real estate spectrum has already been allocated for primary users, the spectrum pool allocated for dedicated unlicensed use will be much smaller than the potential pool that may be allocated for secondary unlicensed use. The relative abundance of secondary use spectrum (at least potentially) and the fact that in many circumstances the primary users may not be operating so as to interfere with a secondary users (e.g., operating at isolated locations or in non-interfering modes) means that it may often prove to be the preferred option, even when there are dedicated unlicensed bands available. However, if the primary user has sufficient flexibility to change its usage or if the requirements imposed to ensure non-interference are sufficiently burdensome (whether warranted by a real technical need or not), then secondary access may be unattractive for many unlicensed uses and users.

secondary users than is possible with fully unlicensed spectrum.[42] This type of shared spectrum could potentially support use of "lit carrier" CMRS air interfaces like LTE at propagation ranges comparable to current CMRS macrocell buildouts.

One minor challenge is achieving high enough availability of the spectrum to justify the deployment of infrastructure hardware needed to operate in the secondary-access channel. Presumably as congestion of CMRS spectrum increases, the rising opportunity cost associated with using scarce spectrum inefficiently will provide incentives to deploy new infrastructure and handsets.

A much bigger challenge for this type of spectrum sharing is the tunability of chipsets in mobile devices. Mobile manufacturers are unlikely to specialize affordable models to operate in a band that is only used by a tiny fraction of the market. There is a discontinuity in the market that will occur when the flexible tuning technology described in Section 3 is deployed in mass-market devices. Before that technology is widespread, successful secondary access may require very long-term arrangements (years of exclusive access to the purchasing CMRS provider) covering a very large geographic region (likely the entire lower 48 states of the US) – generating enough sales volume to justify custom devices – or a fortuitous situation where the spectrum being leased is immediately adjacent to an existing CMRS band so handsets can be given tunability into that spectrum as a minor tweak to existing hardware.

After tunable mobile device technology is widespread, secondary spectrum access can succeed in channels with lower availability levels and more restricted geographic area, with shorter term arrangements, as long as there are enough secondary-friendly channels close to each other (where "close" means within the tuning range of infrastructure equipment) that the infrastructure experiences a high aggregate availability level (at least one channel available most of the time). Increasing cell density lowers the bar to secondary sharing by lowering base station power and thus permitting increased tuning range.

5.6   Candidates for Secondary Use Spectrum

As we noted above, there is a lot more spectrum available for secondary use than is available for new primary use allocations. It is an open question (beyond the scope of this paper) whether additional secondary use allocations will be imposed by regulators as non-cooperative "easements" – most typically, as unlicensed[43] – or, will be negotiated with primary users as contractual secondary use sharing agreements. Nevertheless, we can identify two attractive candidates for such secondary use allocations: first, there is the

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[42] The predictability is increased for both primary and secondary users, which means that the spectrum may be used more intensively (higher utilization).

[43] Non-cooperative secondary use could be enabled by policymakers on a licensed or unlicensed basis. Most of the discussion to date has focused on unlicensed secondary use (e.g., unlicensed access to TV white spaces or lower power unlicensed access by ultrawideband devices).

potential for CMRS users to share with government spectrum users; and second, the potential for CMRS users to share with other licensed commercial users.

In light of the fact that current spectrum allocations assign a majority of the spectrum below 3GHz to primary use by government (for national defense, air control, weather monitoring, public safety, etc.), it seems likely that this will figure prominently in policymakers' plans to make an additional 500MHz of spectrum available for commercial broadband services. While some of this spectrum may be cleared and reallocated for primary use by commercial service providers, there is much more spectrum that may be available on a secondary use basis. Radar bands are of special interest because these comprise a significant share of the government spectrum and because certain types of radar may be more (or less) easy to share with CMRS-type services. The issues here are complex but were the focus of the recent ISART2011 conference, sponsored by the NTIA, which is tasked with developing the Administration's plan for managing Federal spectrum.[44] Some of the key technical problems that need to be addressed include figuring out how CMRS devices that might share radar bands would detect and avoid interfering with radars, especially when many of the radar operators may be unwilling to share sensitive technical information (e.g., because they are military radars). Potentially even more daunting are the business and economic concerns of how to build trust between Federal and commercial spectrum users, when each operates under such different "business" models (i.e., non-profit/public-mission driven v. for-profit). Or, how to ensure that adequate agency budget allocations are granted to fund the costs incurred by Federal users who must relocate to new bands or invest in new equipment to accommodate sharing.

In the spectrum already allocated for commercial uses, there are also opportunities for significantly expanding secondary use. For example, one obvious candidate is for terrestrial over-the-air and satellite TV broadcasters to provide downlink offload services for CMRS, especially for media-rich content. Broadband traffic is highly asymmetric with much more traffic flowing downstream to the customer than in the reverse direction. With the rise of streaming media content, this asymmetry does not appear likely to change in the near future. Since much of this media is cacheable and in demand by many users, using a broadcast medium for distribution offers many advantages. Furthermore, in this case there is already a high-volume market for the chipsets capable of receiving transmissions in the band, thus the barrier to low-cost handsets is minimal.

5.7   Synergy between cell size reduction and spectrum sharing

We now tie together the two key components of the strategy we recommend for sustaining mobile broadband competition under spectrum shortage: cell size reduction (enabled by infrastructure sharing) and spectrum sharing.

We observed in Section 3 that technologies are being developed to significantly improve the tunability of low power systems like handsets, but we do not see technologies being

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[44] See http://www.its.bldrdoc.gov/isart/.

commercialized that significantly increase the tunability of high power systems like macrocell base stations. Because macrocell base stations have limited tunability, and because of the need for acceptable return on investment for infrastructure hardware deployments, the ability to exploit spectrum bands with moderate to low availability for CMRS offload is limited.

Going to much lower power infrastructure as used in dense cell deployments provides a way past this barrier.

- Use of more tunable transmit and receive technology permits exploiting spectrum bands with lower availability, by collecting a larger number of potential operating channels together into a collection whose aggregate availability is what matters for justifying the investment in infrastructure hardware to exploit it.
- The lower transmit power of dense cell deployments enables secondary reuse of spectrum closer to protected primaries (in both space and frequency) with less risk of interference.
- The shorter spacing between infrastructure sites in dense cell deployments enables use of shorter-propagation-range bands as a supplement to dedicated CMRS bands. The additional bands opened up include free-for-all unlicensed spectrum and higher frequency bands (above 3 GHz) where there appear to be many opportunities for sharing. This can be accomplished without the excessive infrastructure investment associated with current "hotzone" buildouts of entirely independent overlay networks dedicated to the unlicensed spectrum.

In other words, *the denser the cells, the more spectrum sharing is possible*. There may be the possibility of establishing a virtuous cycle where providers are incentivized to invest in increasing cell density in order to gain opportunities to exploit additional spectrum, and the additional communications traffic carried at lower per-unit spectrum cost generates the marginal revenue needed to further increase cell density.

Finally, as we noted earlier, denser cell infrastructure implies a need for greater infrastructure sharing (of towers, fiber backhaul, antennas, etc.) which reduces the technical and business barriers to increased spectrum sharing.

6 Mitigating the risk of cartelization

While the potential benefits of infrastructure sharing and spectrum sharing are substantial, realizing those benefits in a way that is compatible with maximizing prospects for wireless competition are also substantial. When critical spectrum and infrastructure inputs are shared, they will constitute "bottleneck" facilities.[45]

The existence of a bottleneck facility poses a risk to competition in upstream and downstream markets if access or control of the bottleneck facility is cartelized, or in the

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[45] These are bottleneck facilities because they are essential inputs for the production of goods and services, and there is limited availability of alternatives.

extreme case, monopolized. Because the bottleneck facility is an essential resource, control or access to the resource might be abused to leverage market power, potentially resulting in significantly higher prices, reduced choice, and deterring innovation and investment both upstream and downstream of the bottleneck resource. This is not a new problem for policymakers with respect to network resources, where the prospect that last-mile infrastructures may constitute a natural monopoly has motivated a variety of regulatory solutions. For example, we have generally opted for public ownership of roads and bridges, and public utility regulation of a monopoly provider for water, gas, and electric power last-mile distribution grids. With wired telecommunications, we are transitioning from a world of public utility regulation of a monopoly provider to market-mediated competition between multiple platform service providers in most markets (i.e., telephone versus cable-based broadband platforms). The transition to facilities-based competition, where feasible, eliminates the bottleneck facility and thereby directly addresses the competitive risk.[46] In this paper, we have explained why the status quo that relies on a model of facilities-based competition in wireless (each mobile provider owns/operates their own spectrum and mobile network infrastructure) needs to change so as to encompass more sharing -- or in effect -- needs to introduce "bottleneck facilities." From a policy perspective, this suggests confronting the same regulatory options as have been addressed in other bottleneck resource environments.

It is important to be clear about what the goals of a good policy framework should be. It should encourage open and efficient access that does not (unduly) favor one user of the resource over another and avoids either over-charging or under-charging for access to the resource.[47] It should allow maximal flexibility with respect to technology choices and other business operating decisions (e.g., service/product design and market selection) that are consistent with shared use of the bottleneck resource. It should strive to provide efficient incentives to invest in the bottleneck resource, and in upstream and downstream markets. And, whatever regulatory interventions are needed to ensure efficient provision and access to the bottleneck, should be minimally distorting to upstream and downstream markets. Line of business restrictions on the provider of the bottleneck facility and entry restrictions limiting direct competition with the bottleneck facility provider are motivated, in part, by this last concern.

We can now consider some of the key regulatory approaches for ensuring open access to bottleneck facilities in the context of 4G mobile services.

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[46] The need for regulation remains to the extent that the facilities-based competition is not perceived to be adequately robust (e.g., because broadband platform providers may retain terminating monopoly control over subscribers or because duopoly competition is not vigorous enough) or because of other potential market imperfections (e.g., interoperability issues).

[47] Over-pricing access dampens demand and deters incentives to invest in upstream (e.g., handsets, base stations) and downstream (e.g., mobile content and applications) markets. Under-pricing access may result in a "Tragedy of the Commons" with excessive congestion of the bottleneck resource.

First, we recognize that facilities-based competition offers important benefits in terms of competition and innovation with respect to technology and business models, and as such, is preferred wherever feasible. Moreover, we recognize that moving from the entrenched status quo model of silo-based architectures will be easier if the movement is incremental. Consequently, the policy initiatives to promote sharing should focus initially on sharing only those resources that are most necessary and easiest to share. With respect to spectrum, we do not expect operators to wholly renounce their dependency and preference for exclusive-use, dedicated spectrum and for operator-owned/controlled infrastructure. This implies that we expect operators to manage hybrid networks, and that operators will adopt service/network architectures that allow them to segment traffic into categories appropriate for the dedicated and shared resource components. Hence, we advocate that a portion of any additional spectrum that is made available to support commercial broadband services, be made available under a shared spectrum regime, preferably as dedicated unlicensed.

In the following two sub-sections, we consider the implications for public policy of our vision on spectrum management and infrastructure sharing. With respect to spectrum, policymaking is national (and international) in scope, whereas with respect to infrastructure sharing, there is also an important role for local and regional governments.

6.1   Unlicensed and Closed Commons Spectrum

The reason we prefer allocating the spectrum as dedicated unlicensed is this provides a well-understood model for ensuring open and non-discriminatory access to the resource – not just for incumbents but potential future entrants. Preserving the option for future entry helps ensure that the bottleneck resource (spectrum) is not cartelized so as to limit competition (and thereby, also hampering prospects for innovation). A potential downside to allocating the spectrum under a traditional unlicensed model is that this may result in a "Tragedy of the Commons," because free access may encourage excessive use. Because congestion imposes real usage costs, it is not true that unlicensed is a free resource. If the uses of the resource are amenable to congestion-based resource management than this may work fine – as it has worked well, thus far, for WiFi, cordless phones, and other applications.

In the context of mobile broadband, we accept that mobile operators whose service models are premised on supporting reliable wide-area coverage and invest in expensive wide-area infrastructure networks may be loath to risk their service to spectrum with variable quality of service (congestion) properties. Thus, we expect that they will continue to require and rely on exclusive-use, dedicated spectrum allocations for the services that are most sensitive to quality-of-service degradation like increased jitter or latency. This may include VoIP and real time video (video conferencing) services. On the other hand, a lot of the mobile broadband traffic will be latency and disruption tolerant (e.g., streaming video that may be buffered in network or user caches). Operators who segregate their traffic may be better positioned to take advantage of dedicated unlicensed spectrum to supplement their overall capacity needs. The growth in the practice of offloading data traffic from

mobile networks to WiFi to ease the capacity bottlenecks on mobile networks proves that mobile operators are capable of adapting and utilizing less reliable spectrum resources when the need arises.

A potentially more worrisome problem is what happens if today's allocations of dedicated unlicensed become excessively congested in the future, and that if much of that congestion comes from low-value, junk applications and devices. While WiFi networking continues to operate even in dense urban markets, the current regulatory regime for unlicensed that relies on extreme power limitations (restricting range) and open entry (without fees or other access limitations) may be potentially too limiting to address all future needs for shared spectrum by mobile broadband operators. Hence, it may be worthwhile considering an additional allocation of shared spectrum for CMRS operators as a "closed commons."

Earlier we noted that there are a number of economic and technical reasons why we might restrict access to a limited number of CMRS operators. This would allow them to have a much higher degree of confidence and control of their spectrum and networking environment, and to employ technically more sophisticated resource sharing strategies resulting in higher effective spectrum utilization, than would be the case if the spectrum is potentially shared with random collections of unlicensed devices and users. The problem is that the closed commons would need to be managed so that it was not used to cartelize markets for mobile broadband services. There are several regulatory strategies that might be employed to address that risk.

First, public disclosure and transparency in how the closed commons spectrum is shared and managed would provide a first-line of defense against any attempt to cartelize spectrum access through manipulation of the management of the shared spectrum. If there is adequate public disclosure and insight into how spectrum access to the shared commons is being administered, then we can rely on general antitrust enforcement to help protect against anticompetitive abuses. In this special context, the spectrum database and the publication of spectrum measurement data (for the shared and other bands) will help audit overall use of spectrum resources and will contribute to making management of any shared spectrum easier. Moreover, ensuring that the access rules, technical standards, and management protocols that are developed to manage the shared spectrum are developed by established standards development organizations (e.g., like ANSI approved SDOs) would provide additional protection against abuse of a closed commons because those SDOs are designed, in part, with the express goal of protecting against anticompetitive abuses via industry standardization.

Second, the shared spectrum could be held in trust and managed by a spectrum broker. This might make the most sense if the entity also owned and managed the small-cell infrastructure, including the neighborhood fiber used for backhaul. We believe that such a model might prove most attractive in less dense suburban or rural environments, where the prospects of deploying even one, let alone two, small-cell mobile networks is economically challenged. This entity might be a publicly owned utility such as a municipal provider, or an

investor-owned entity. If the former, the challenges of operating a municipal utility are likely to strictly limit its applicability to specific circumstances (e.g., communities that already have a municipal electric, cable, or telecommunications provider). More generally, we might expect that the entity might be an investor-owned provider. If that is the case, it may be desirable to ensure there are line-of-business restrictions that limit the provider's ability to vertically integrate upstream or downstream into affiliated mobile broadband markets. For example, were a leading national mobile service provider to offer such a management service on behalf of other mobile broadband service providers, policymakers would need to ensure that their involvement in this wholesale market was not abused to consolidate any market power they may have in retail mobile broadband services.

Because spectrum is regarded as a national resource, its management is entrusted to the FCC, for spectrum allocated to commercial uses, and to the NTIA, for spectrum allocated for government uses, in the United States.[48] National governments seek to harmonize their spectrum management policies to limit cross-border interference and to help maximize the potential for realizing scale and scope economies in radio equipment and technology. Moreover, because exclusive spectrum licenses may be auctioned for significant sums that may be directed to general government revenue coffers, many policymakers with only a limited understanding of the issues may find themselves engaged in spectrum management debates. While the goal of harmonizing spectrum internationally remains important, wireless technologies like software and cognitive radios, are making this less necessary, which is fortunate, since achieving international harmonization is very time consuming and difficult. Nevertheless and whether at the national or international level, spectrum management reform is complex and uncertain.

Without a clear articulation of what may be expected as an outcome from the U.S. spectrum reform efforts, it would be premature to discuss our thoughts on specific bands and how they should be managed. The proposal to proceed with incentive auctions, while promising, leaves the future for TV white space use uncertain; and the NTIA is in the midst of formulating its longer-term strategy for Federal spectrum and identifying which bands might be cleared or shared with commercial users. Suffice it to say, we support the view that spectrum management reform is desirable, and that in proceeding, it is important to preserve options for diverse models of spectrum management, including both dedicated and secondary unlicensed access, as well as increased flexibility for exclusively-licensed spectrum to allow the licensee to negotiate contracts for cooperative sharing. Achieving the correct balance will present a difficult challenge, but one with little scope for local government involvement. That is not the case with the issue we turn to next.

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[48] In a number of countries, spectrum management is unified under a single agency. The bifurcation of responsibility in the U.S. poses a challenge for regulatory reform which has as an important goal, increasing sharing between commercial and government spectrum users.

6.2   Shared infrastructure and Facilities

In this section, we consider public policies for encouraging the transition to shared small-cell infrastructures.

In Section 4.2, we examined three possible models for structuring an offload network provider to provide the shared small-cell infrastructures that will be needed: a private partnership between a tower company and local wireline provider; a municipal network; or a public-private partnership. As we explained, these are not the only paths to realizing our vision of a future with increased infrastructure sharing, but they are sufficient to illustrate the different ways local government may participate in shaping our wireless future. In all cases, local government helps shape the environment for local infrastructure investment and network operations. Local government has numerous levers to pull, including as a consequence of its role as an anchor tenant and, often, the largest consumer of information technology services in the community; as the manager of access to critical components like rights-of-way and structures for siting antennas; as a maker of rules for local zoning and construction; as a potential source of funding through municipal or town bonds; and as a provider of critical services such as schools, libraries, and public safety. As a consequence of these many roles, all three of the paths discussed in Section 4.2 may be viewed as forms of public-private partnerships, with different levels of direct local government participation in owning, financing, and managing the shared small-cell infrastructure.

The focal entity in local government is usually taken to refer to the municipal or town government, but more generally, it includes regional authorities (county, state, and even inter-state governing bodies).[49] In the U.S., there is a lot of heterogeneity in the structure and operation of local government, which is due, in part, to differences in the legal/institutional foundations, and in part, to local environmental factors (human and capital resources, patterns of settlement, terrain). As is the case with designing radio networks, local context is very important in determining what the right role should be for local government.

As we explained in Section 4.2, one option for providing the shared small-cell infrastructure is via a municipal utility. However, as we also explained, there are significant difficulties with owning and operating a municipal utility. First, in most markets, there are already multiple mobile broadband providers who might justifiably look askance at confronting competition from a public entity. Also, most municipalities lack the human and other resources and the scale required to operate a municipal network efficiently. This is not true of all communities, and so the option of community-owned and operated last mile dense-cell mobile broadband infrastructure remains a viable and interesting option in those circumstances where it is applicable. There are a number of municipalities that have been

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[49] County, state and interstate regional management are especially important in shaping policies that impact the deployment of backhaul facilities, and are also important sources of public funding for development projects that cross town/municipal boundaries.

operating municipal networks for many years and there are multiple reasons for expecting municipal governments to play a greater role in broadband in the future.[50]

More generally, however, we expect that the municipality's role may be more limited. Policymakers can help foster the development of dense-cell infrastructures by lowering the costs for accessing certain shared elements for deploying such infrastructures. This may include access to rights of way for fiber backhaul and antenna siting. One might even anticipate making the municipality the residual rights holder for the shared spectrum. While this might initially seem an attractive option, we do not advocate it based on the legacy of cable franchising. While that model served its purpose in an earlier age, we believe that the risk of heterogeneous franchising frameworks or hold-up by communities that are strapped for general revenues seeking to extract revenues from mobile service providers are too great. On the whole, we believe efforts to standardize access rules for outside structures and conduit, and for deploying shared infrastructures will offer the best way to reduce the costs of deploying shared infrastructures. In a number of communities, there is critical infrastructure (like public schools and light posts) that might be used to support dense-cell deployments.

Municipal governments may encourage the deployment of additional dense fiber in support of both community fixed broadband availability and for backhaul for dense antenna infrastructures by providing funding support and by helping to promote demand aggregation efforts. In many communities, the local government is the largest single user of electronic information services and host to important anchor institutions (for its police, libraries, schools, and local government operations). Additionally, a significant portion of the requisite investments in components for the dense-cell infrastructure future such as dense fiber deployments and structures are very long-lived investments (more like real estate than like high-tech) that are sunk. As such, it may make sense for communities to invest in these assets directly since their value is so tied to the interests of the community. Long-term community bonds might provide a suitable source of low-cost funding to help lower the costs of entry into dense-cell infrastructures.

Of course, if communities provide funding, they also should look to preserve their long-term interests, and protect themselves from potential hold-up by service providers. For this reason, we advocate the communities retaining an ownership interest in any infrastructures, and reserve as part of that interest, the opportunity to enable additional entry in the future. While many communities that decide to invest in local infrastructure may choose to license that for use initially to a sole provider (e.g., after a competitive bid RFP process), the community ought to preserve the option to allow further competition in the future. For example, if the community funds the deployment of dark fiber, the community ought to consider retaining control of some dark fiber. This may be especially useful in the future to support backhaul from dense-antenna systems, which significantly reduces the costs of the equipment required at each dense-antenna cell site. The signals for multiple wireless systems could be backhauled to a local aggregation point (e.g., the

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[50] See, Lehr, Sirbu and Gillett (2004, 2006).

basement of a government building or school) with adequate supplies of power and access to rack space for multiple providers to connect their gear.

7 Conclusions and Future Directions

In this paper, we have explained why the growth in mobile broadband and the increased pressure this implies for scarce spectrum resources poses a challenge for continued quality improvements and competition in mobile services. To address this challenge, the U.S. government is proposing to make available an additional 500 MHz of spectrum for commercial broadband services. Under the hypothesis that this goal will be extremely difficult to achieve, we believe that the future for high quality mobile broadband competition will require significantly more sharing among Commercial Mobile Radio Service (CMRS) network operators of both infrastructure and spectrum.

A key driver of the need for increased sharing among CMRS operators is the need to shrink cell sizes. Smaller cell sizes enable efficient spatial reuse of spectrum and support lower power operation, as well as a number of other technical options such as network MIMO. Lower power operation has many benefits, including ameliorating concerns about any potential health risks. Moreover, lower power operation facilitates the sharing of spectrum. There are multiple reasons for this, including the fact that it provides better range matching between licensed and unlicensed spectrum and the technology for frequency agility is more advanced and affordable.

Shrinking cell sizes to increase spectrum capacity and enhance performance comes at a cost. The increased costs per subscriber associated with deploying small-cell infrastructure poses its own threat to competition. As cells get smaller, the requisite infrastructure to support multiple local deployments becomes more expensive and difficult to acquire (e.g., multiple antenna/tower sites and multiple dense-neighborhood fiber deployments for backhaul for multiple providers). In less densely populated suburban and rural markets, service providers are likely to find themselves coverage rather than capacity limited. In such markets, constructing even a single small-cell infrastructure may be economically challenged. A solution to this quandary is to also share the small-cell infrastructure. Fortuitously, infrastructure and spectrum sharing are complementary with the deployment of small-cell infrastructure. Because the infrastructure and spectrum are co-specialized assets (although less so in light of the advances in technologies like software radio), the sharing of one makes the sharing of the other also easier.

Realizing a future in which mobile broadband services are provided over small-cell infrastructures, supported by new architectures and business models for CMRS network operators that share both spectrum and network infrastructures more intensively, will represent a significant change from today's world. It will move us from a world in which competition relies on largely independent facilities and spectrum to a world where critical infrastructure and spectrum resources will be shared more intensively. The potential for these shared resources to become bottleneck resources that might be cartelized to the detriment of competition requires us to consider policy options for addressing those

challenges. Fortunately, there are a number of regulatory options, ranging from relatively light-handed disclosure requirements to more interventionist open access regulation that may be considered if access to the bottleneck facilities requires regulatory intervention. To preserve light-handed options and in the interests of efficiency, we believe it will be desirable to preserve incrementally. This has the obvious implication that we see a hybrid future for mobile broadband, in which CMRS operators continue to operate private infrastructures and utilize exclusively-licensed spectrum, as well as relying on shared infrastructure and spectrum for portions of their traffic.

To get started on implementing this vision of shared infrastructure and spectrum, we propose exploring the case of commercial and public safety sharing.[51] There are a number of reasons why this provides an attractive opportunity for initial focus. First, there is a recognized national need to enhance the quality and capabilities of the mobile broadband services available for public safety, and that the users of such systems need to be more interoperable, across multiple agencies (including across local and regional authorities as well as Homeland Security), including the ability to interoperate and share resources with commercial users.[52] Second, in meeting the goal of finding 500 MHz of additional spectrum for commercial use, it is clear that increased sharing between Federal and commercial users will be a major focus.[53] Third, putting in place the next generation public safety network will require significant new investment, much of it in deploying small-cell/dense antenna infrastructure. Addressed properly, this provides an opportunity to create a new sharing regime and a forum where public involvement (and the resulting regulation that it portends) is to be expected. In moving to a world with a bottleneck facility, this may be the right application opportunity at the right time.

Finally, it is worth noting that we believe that a significant side benefit of the push toward smaller cells advocated in this paper will be the facilitation of better integration of wired and wireless services (which includes 4G LTE, but also many other types of wireless networks[54]). In today's world, interconnection between the mobile Internet and the rest of the (mostly wired) Internet is via IP gateways maintained by mobile network operators. At least one vision of a future architecture, Mobility First,[55] posits a future where support for mobility is embedded in and much more firmly supported by the basic Internet. In the full realization of this vision, mobile LTE base stations will become full-fledged Internet routers and the connection between the mobile and fixed node worlds will be much more seamless

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[51] See Lehr and Jesuale (2008).

[52] For example, in disaster scenarios, private individuals with commercial mobile broadband services, may be the first on the scene with available capacity that may be shared to alleviate capacity constraints or to crowd-source information.

[53] For just this reason, the NTIA-sponsored ISART2011 conference focused on commercial sharing with Federal radar users (see http://www.its.bldrdoc.gov/isart/).

[54] See Lehr and Chapin (2009, 2010).

[55] See http://mobilityfirst.winlab.rutgers.edu/.

than it is today. Distributing wireless and wired integration closer to the edges also makes it more feasible to opportunistically take advantage of investments that may be in place for reasons other than to support 4G mobile services (at least with respect to their original motivations). Femtocells and WiFi-offload to take advantage of excess capacity on wired broadband networks are examples of this. Dense antenna architectures will help facilitate integration of the mobile (wireless) and general (mostly wired) Internet worlds and will help open prospects for greater exploration of user-deployed infrastructure models for supporting Internet services.[56]

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[56] The focus of this paper is on 4G mobile services and the networks that support them, but elsewhere we have discussed the importance of end-user deployed infrastructure and expanded spectrum sharing options for promoting a healthy and competitive wireless ecosystem. For example, see Chapin and Lehr (2007).

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