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Small cells and the mobile broadband ecosystem

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June 2014

prepared for Euro ITS Conference, Brussels

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Abstract

The growth of mobile broadband and wireless services of all kinds is helping propel the transition toward small cell architectures. This transition has the potential to be as significant for the mobile broadband ecosystem as the transition from mainframes to PCs was for computing. The WiFi and 3G/4G LTE ecosystems highlight two possible directions for small cells. We contrast these ecosystems and explain how the transition to small cells helps drive fixed-mobile convergence, empowers end-users, and facilitates more dynamic spectrum sharing.

1 Introduction

Mobile Broadband traffic is growing exponentially, driven by rapid growth in the penetration of smartphones and tablets and the richer multimedia applications and content thus enabled.[5] Driven by and enabling this growth, wireless broadband architectures are shifting to small cells. The drivers motivating this shift are several, including increased demand for scarce spectrum. The implications for the mobile broadband ecosystem are significant.

Today, there are two principal candidate technologies for use in small cells: WiFi and 3G/4G LTE. Each was developed to address distinct market contexts and each is associated with a distinct business/technology/regulatory ecosystem. Over time, the growth and evolution of wireless technology, broadband markets, and policy have pushed these ecosystems closer together.[6]

In this paper, we examine the implications for the mobile broadband ecosystem of the transition to small cells. In Section 2, we explain why wireless is moving to small cells and contrast the WiFi and 3G/4G LTE technologies. WiFi is the more mature technology, and currently has significant advantages relative to cellular technologies in the race to define the small cell future. However, the future is likely

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[5] See CFP Mobile (2014), available at: http://cfp.mit.edu/publications/CFP_Papers/CFP_Mobile_Broadband_White_Paper_May_2014.pdf

[6] This convergence has been anticipated for some time. See Lehr & McKnight (2003).

to be a hybrid solution that mixes both technologies along with others, some of which have yet to be developed. WiFi may have the advantage in having been commoditized first, but 3G/4G LTE offers benefits in addressing the goal of providing seamless mobility and ubiquitous coverage. While we expect the future to be a blend, on balance, we conclude that the trend to small cells favors WiFi.

In Section 3, we explore three key implications of the transition to small cells. First, it will help drive the convergence of mobile and fixed services. This has the potential to disrupt existing industry value chain economics, depending on how fixed and cellular provider competition evolves. A key factor will be the role that fixed provider infrastructure will play in providing backhaul services to small cells. Regulatory policies and the evolution of consumer demand will also be important, rendering a definitive prognosis uncertain.

Second, the transition has the potential to empower end-users to play a more active role in provisioning and managing end-to-end mobile broadband services. Advanced wireless and networking capabilities coupled to an open architecture for future small cells has the potential to extend end-user choice/autonomy and facilitate a new vector for last-mile facilities-based competition. However, it also poses a challenge for coordinating end-to-end services and ensuring the interoperability and connectivity in the Internet. Small cells are likely to enable multiple wireless networks and control over which network is selected is likely to be an important tussle space among end-users, service providers, and application/content developers.

Third, the transition to small cells is likely to tilt the balance from licensed toward unlicensed spectrum for mobile broadband. More generally, it should favor more dynamic and granular allocation of spectrum resources, or equivalently, favor shared spectrum access.

We conclude in section 4 with a summary of our principal conclusions and thoughts about future directions for research.

2 What is a small cell?

For this paper, we define a *Small Cell* as a low power (20 to 100mW), limited range (no more than 100 m) wireless base station or Access Point ("AP") offering variable data rates (from 10-100Mbps or higher[7]). These may be deployed indoors or outdoors, as a standalone node or as part of a larger network. In their most common deployment, these base stations are owned and deployed by end-users and rely on user-provisioned broadband connections (fixed or wireless) for backhaul to a point of interconnection with wide-area networks and the Internet. There are two distinct families of technologies that are currently the principal candidates for deploying small cells: the 3G/4G LTE family of technologies employed by mobile cellular network operators ("cellular") that are under

[7] Small cells, whether WiFi or femtocells, typically also offer faster data rates than would otherwise be available from wide-area cellular services. Obviously, this may not be true if older and newer generation technologies are compared. The trend has been toward faster data rates.

development in 3GPP[8]; and the IEEE802.11 family of technologies employed for wireless local area networks ("WLANs"), with the best known commonly referred to as Wi-Fi ("WiFi").[9]

Originally, the terminology of "small cells" was used to refer to mobile cellular base stations that were lower power and provided coverage over a smaller geographic area than traditional macrocells. Over time, the cellular industry developed a hierarchy of cell sizes for specific application environments (see Figure 1)

	Macrocell	Microcell	Picocell	Femtocell
Application	Outdoor, Metro-area & Rural	Outdoor, Campus, Metro-area, Rural	Outdoor/Indoor Enterprise/campus	Indoor
Capacity	32-64 channels 1000s users	32-64 channels 100+ users	16-32 channels 20-30 users	4-8 channels 5-10 users
Range	Few to 30km	100m-1km	100m-1km	100m
Power	20-40W	1-2W		20-100mW
Hand-off	Soft, hard	Soft, hard	Soft, hard	Hard

Figure 1: Taxonomy of Cellular Small Cells[10]

The cellular industry has sought to brand the term "small cells" to refer to this hierarchy of cell sizes.[11] Some authors have sought to restrict the definition of "small cells" to refer to low-power wireless access points that operate in licensed spectrum and are fully managed by the operator – a restriction that explicitly excludes WiFi technologies (Bennis et al., 2013). For the purposes of this paper, we retain the earlier terminology of femtocells to refer to small cell technologies based on the 3G/4G LTE 3GPP family of cellular technologies, and use small cells as the more general and technology agnostic term as defined above.

2.1 Motivations for transitioning to Small Cells

The principal motivations for deploying small cells are to expand capacity and coverage. For example, small cells can be used to address coverage gaps both in-doors (dead spots in homes and offices) and in remote locations where ubiquitous coverage is not feasible. In the latter context, small cells have been used to expand

[8] See 3GPP (http://www.3gpp.org/). The first femtocells were for 3G and included both GSM/UMTS and CDMA technology versions. The first LTE (short for Long Term Evolution) standard was release 8 which was finalized in April 2009. This was followed by Release 10 (April 2010) and Release 11 (June 2013), with the Release 12 expected later in 2014. These releases are backward compatible, but add additional functionality. For further discussion, see (Informa Telecoms & Media, 2013). The GSMA (http://www.gsma.com/) is the global industry association representing mobile operators.

[9] See IEEE Project 802 (http://www.ieee802.org/), and more specifically, Working Group 802.11 Wireless LANs (http://www.ieee802.org/11/). The Wi-Fi Alliance (http://www.wi-fi.org/) is an industry association that promotes the technology and works to ensure interoperability across implementations.

[10] Exhibit derived from Zhang, Jie (2012), "Tutorial on Small Cell/HetNet Deployment," slides presented at Globecom2012 Industry Forum, March 12, 2012 (http://www.ieee-globecom.org/2012/downloads/t1/1SmallCellTutorialGlobecom12Jie_v1b.pdf).

[11] The Small Cell Forum (www.smallcellforum.org) definition for "small cell" is *low-power wireless access points that operate in licensed spectrum, are operator-managed and feature edge-based intelligence*. Interestingly, the Femto Forum renamed itself as the SmallCellForum in February 2012 as part of this branding effort.

rural coverage by deploying hot-spot access.[12] Small cells are also attractive for cost-effective incremental capacity expansion in high-traffic areas both inside and outside (e.g., near elevators, in lobbies, in parks, etc.).

While these fundamental motivations are not new and have motivated cellular providers to deploy smaller cells for years, the demand for higher data rate, "always on/everywhere" connected wireless services has accentuated the need to extend coverage and expand capacity. Moreover, the growth of mobile broadband and other wireless services have put increased pressure on scarce radio frequency spectrum resources.[13] Shifting to smaller cells and lower power enables greater spatial reuse of spectrum. The same frequencies may be used without interference by base stations in different locations with non-overlapping coverage areas. By sub-dividing macro-cells (with coverage areas measured in kilometers) into successively smaller sized cells (measured in meters), cellular operators can expand the capacity of their licensed spectrum assets – in effect, enabling the spectrum to be shared more intensively.

Power conservation provides a further compelling motivation for shifting to smaller cells. Meeting the demand for ever-higher mobile data rates and the proliferation of new types of mobile devices (e.g., wireless cameras, wearable gadgets such as fitness bracelets or Google glasses)[14] puts an increasing strain on battery-powered mobile devices, and potentially may raise health concerns if the power is not limited.[15]

Finally, the move to smaller cell architectures has been facilitated by continuing innovation in wireless and networking technologies. Advances in both cellular and WiFi technologies and the process of integration of wired and wireless broadband ecosystems have pushed cellular and WiFi to become closer in terms of the capabilities and performance each can support. This means that for a wider range of contexts, WiFi and femtocells are potential substitutes (see further discussion below).

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[12] This model of deploying mobile broadband via small cells is proving attractive in rural Vermont (US) (http://www.burlingtonfreepress.com/story/home/2014/04/27/vermont-cell-coverage-improve-rural-areas/8230079/) or in Shetlands village (UK) (http://www.theregister.co.uk/2013/06/21/vodafone_reaches_out_to_plug_shetland_gaps/) as well as in Africa (http://www.vanu-africa.com/).

[13] The National Broadband Plan in the US (http://www.broadband.gov/plan/), a Presidential memorandum (http://www.whitehouse.gov/the-press-office/presidential-memorandum-unleashing-wireless-broadband-revolution), and the President's Council of Advisors in Science and Technology (PCAST) (http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast_spectrum_report_final_july_20_2012.pdf) report have all called for significant new allocations of spectrum resources (500 to 1,000 MHz) to meet the needs of mobile broadband services.

[14] These already connected devices start configuring what we currently know as "Internet of Things" performing applications in public sector focused to several areas such as transport, security, environmental monitoring among others (http://www.idc.com/getdoc.jsp?containerId=prUS24087613)

[15] After all, WiFi operates in the same 2.4GHz frequency range as do microwave ovens– only at much lower power. While WiFi maximum power transmitted is below 100mWatts, microwave ovens use a confined power between 750 and 1,100 Watts (four orders of magnitude larger).

As both technologies converge on smaller cell architectures, they share a growing range of complementary assets, and this helps realize learning/scale economies and positive network externalities that are lowering the costs of transitioning to the small cell ecosystem. This ecosystem encompasses end-users (both individuals and businesses), service providers (including value-added providers of applications and content), and hardware and software component providers (from power supplies to antennas to cabling) that build, install, maintain, and sell small cells and related complementary elements. The shift to small cells may be analogous in its value chain effects to the shift from mainframe computers to PCs. Whereas the former were big, expensive "boxes" that were maintained by specialist "IT professionals" in specialized environments (i.e., data centers), the latter were cheap boxes deployed on desk tops everywhere. As with the transition from mainframes to PCs, the move to smaller cells has the potential to transform the entire mobile broadband ecosystem.

2.2 WiFi versus Femtocell trajectories

Finally, while it is clear that both the WiFi and 3G/4G families of technologies offer comparable functionality and have the potential to be substitutes in many situations, their distinct legacies mean that the supporting ecosystems are quite different. Some of their distinguishing features are summarized in Figure 2.

	WiFi	Femtocells
Technology	802.11 WLAN	3G/4G (LTE) 3GPP
-- Spectral efficiency	-- Efficient, MIMO support	-- Efficient, MIMO support
-- MAC	-- Distributed CSMA/CA. Weak support when multiple AP, nomadic mobility	-- Centralized. Strong coordination among base stations, fast mobility support
-- Power mgmt.	-- Constant power	-- Fine-grained highly dynamic
-- Channel flexibility	-- Larger, shared channels and channel bonding	-- Channel aggregation, dynamic bandwidth allocation
-- Network planning	-- Self-configured	-- Critical to manage interference/coordinate APs
Spectrum	Unlicensed	Licensed
Capabilities/capacity	Improving at Gbps (802.11ac)	Improving at Gbps (LTE rel 12)
Hardware	Commodity	Operator custom
Installed base	Huge	Emerging
Deployment model	End-user, single AP	Carrier, integrated

Figure 2: Summary Comparison of WiFi and Femtocell Technologies

First, and as already discussed, WiFi and femtocells represent quite different technical standards. The WiFi wireless LAN standards were originally developed

as an extension of the wired Ethernet LAN technology developed in the 1980s, with an eye toward its principal use in-doors to provide data networking connectivity in a confined (limited range) area. This allowed the original standard to be light-weight which helped ensure that base stations could be low-cost and simple to deploy and manage as (typically) standalone wireless access points.

In contrast, femtocells are lower power, less expensive versions of the same technology used for macrocell cellular networks. They are designed to be integrated into a cellular operators wide-area network. That offers both advantages and challenges. On the benefit side, it allows for more fine-grained management of the cellular network resources (for spectrum, for backhaul, for mobility management, etc.). On the cost side, it requires more careful interference management to ensure that cell sites of different sizes that may have overlapping coverage areas do not interfere with each other, and to coordinate handoffs across base stations.[16] This adds to the complexity and cost of the hardware and software components.

The cellular networks have evolved from 1G/2G mobile voice-telephony-only networks.[17] The service was intended to support high-speed mobility that required coordinating the operation of multiple base stations deployed over a mobile provider's service territory. Over time, these territories have expanded to national scale. With the transition first to 3G (after 2007) and now to 4G LTE, support for higher data services has been added. Relative to the original WLAN standards, more complex and expensive technology was required to support wide-area mobility and high-speed service hand-off, and to meet the more rigorous (delay-intolerant) requirements of telephony service.

Motivated in part by these divergent technical/market legacies, WiFi was developed to operate in unlicensed spectrum, while the cellular technologies have operated in licensed spectrum.[18] A principal justification for these divergent spectrum access models is because WiFi was, by design, intended for low-power,

[16] For a discussion of the interference challenges of integrating femtocells into carrier networks, see (Haenggi & Ganti, 2008) (Chandrasekhar & Andrews, 2008; Kishore, Greenstein, Fellow, Poor, & Schwartz, 2005).

[17] The first generation ("1G") cell phones were based on analog communications. The second generation ("2G") that were introduced after 1992 were the first going digital but were designed for narrow-band communications, supporting voice-only telephony and text messaging, but not Internet access or a fuller range of data services.

[18] Current WiFi networks operate using unlicensed spectrum in the 2.4GHz and 5GHz ISM bands. In general, RF propagation in these bands is subject to large attenuation, making these bands best for short-range and low-power systems. More recent IEEE802.11 standards have extended WiFi to both higher and lower frequency bands. For example, IEEE802.11ad is targeted for high-speed, short-range services at 60GHz, while IEEE802.11af and ah are targeted for long-range operation in the UHF bands.

The 802.11ad standard is targeting a peak data rate of 7Gbps, but operation at 60GHz requires direct-line-of-sight operations. The target application is as a very high-speed data connection between devices that are a meter apart. As such, it will be a replacement for Bluetooth technology, which is limited to 1Mbps.

IEEE802.11af standard competes with IEEE802.22 from a different IEEE802 family of standards. Both are intended to provide long-distance broadband links using the TV white spaces (between 54 and 800MHz), and both are sometimes referred to as "SuperWiFi." The physical layer is adapted to match existing TV channel slots with 6 to 8 MHz bandwidth configurations to achieve 27 to 36Mbps peak data rates. The capability to bond up to four channels, implies a potential aggregate data rate of 430 or 570Mbps.

IEEE802.11ah is designed to create networks for large groups of limited-energy consumption devices such as sensors. Both the 802.11ah and af standards are expected to be issued in 2014.

local operation. In such situations, the challenge of coordinating usage to avoid interference was limited to those individuals operating in the local coverage area of the base station. The principal mode for deployment was for individual business or home owners to purchase WiFi base stations and deploy them for standalone operation as an extension of the wired local network. In such situations, the benefits of acquiring interference protection rights were limited, while the costs of negotiating for such rights might have proved prohibitive, discouraging end-user adoption of the technology. Operating in unlicensed spectrum facilitates decentralized/uncoordinated (viral) deployment of APs since base station owners do not need to acquire licenses or pay for spectrum resources in order to deploy a WiFi hotspot. The downside is that the hotspot users may have to contend with congestion from other APs sharing the spectrum. To date, this does not appear to have been much of an issue in most locations; however, the growth of WiFi usage and widespread deployment of small cells means that it may be more of a concern in the future.[19]

In contrast, the cellular technologies were intended for mobile network operators offering services over large coverage areas. To provide such service, mobile network operators needed to make significant, multi-billion dollar investments in multiple base stations deployed over their service territory. Earlier radio technologies had limited frequency agility. This meant that the wide-area radio network infrastructure and its operating frequencies were co-specialized assets (i.e., most valuable when used together). In this context, a regime of exclusive, long-lived licenses to specific frequency bands in a target coverage area was well suited to the business model of mobile cellular providers. The strong interference protection rights and guarantee of secure spectrum access rights to complement the long-lived, multi-billion dollar investments in co-specialized network infrastructure justified incurring the significant transaction costs associated with acquiring exclusive spectrum licenses. Because femtocells operate in operator spectrum, their deployment and operation is subject to significant control by the operator with the spectrum license. Such tight control is needed if the femtocells are to be integrated into the operators wide-area network (e.g., to enable fast-mobility across base stations and to avoid co-channel interference between overlapping base station coverage areas).

While historically, WiFi and cellular addressed quite distinct market opportunities, over time, each has evolved to add functionality that makes them closer substitutes. For example, a succession of P802.11 standards have added better support for real-time services (VoIP), multi-base station coordination (to support roaming across multiple hotspots), and faster data rates and extended range operations.[20] Analogously, the trajectory of cellular technologies has moved in the direction of expanded support for integrating data services. Indeed, 4G LTE is

[19] The shift to smaller cells means that fewer radios/users are within range of the AP to cause congestion, which shifts interference management to a more local concern (i.e., radios that are likely to interfere with each other are in relatively close proximity). While congestion is a growing concern in dense urban environments (e.g., apartment buildings, airports), there has been little evidence that congestion is a significant problem even in the most heavily used 2.4GHz band (Vries, Simic, Achtzehn, Petrova, & Mähönen, 2013).

[20] For example, IEEE802.11u, also known as "HotSpot 2.0" adds support for roaming (internetworking) of WiFi hot spots, allowing mobile devices to automatically join a WiFi base station that participates in the service.

intended to allow full integration of an Internet Protocol (IP) data layer with a frequency agile radio access network that will support finer-grained and asymmetric spectrum aggregation.[21]

Although the two technologies have added comparable functionality, important technical differences remain. For example, WiFi continues to lack the sort of fine-grained power management control that characterizes cellular technologies. The more sophisticated power management capabilities of 3G/4G allow power to be adjusted dynamically over a much wider range. This allows 3G/4G base stations and handsets to separately adjust transmitted power to optimize the received signal strength on a connection-by-connection basis, which provides for tighter quality-of-service management and interference management control. In contrast, by foregoing such fine-grained power management, WiFi's constant transmit power results in lower-cost hardware, and higher data rate services since fewer resources need to be reserved to support fast mobility. WiFi service adapts to changing RF and network conditions (e.g., distance from the base station or the level of interference) by adjusting the modulation scheme which adjusts the data rate.

There are also important differences in the approach to managing shared media access. The cellular technologies rely on a more centralized resource management approach, which has the advantage generally of supporting higher utilization under increased loads. With femtocells, a controller at the wireless base station provides centralized management of channel access to remote handsets. This allows the base station to dynamically assign bearer channels to address the needs of individual handsets and provide for tighter quality-of-service management. In contrast, WiFi uses a decentralized access control method based on collision avoidance and random access to share network resources.[22]

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[21] Data traffic is much more heterogeneous than digital voice traffic. LTE expands the capabilities of cellular technologies to support asynchronous, asymmetric data traffic and variable data rate flows such as that typically supported on WLANs, enabling cellular to be a more viable substitute for traditional WLAN applications. Historically, cellular services were provided via paired frequencies (one for the uplink and one for the downlink), separated by a frequency gap. The channels could be narrow and symmetric because voice communications are predictable and may be encoded in a small bandwidth. As data becomes a larger share of the traffic, the traffic flows become asymmetric and heterogeneous. For example, web traffic may involve only a few bits upstream, followed by a lot of bits downstream. The LTE architecture supports aggregating channels asymmetrically to allow different upstream and downstream bandwidths from adjacent and separated frequencies.

[22] The IEEE802.11 family included an access protocol with two operation modes: a random access (DCF, which stands for Distributed Coordination Function), or a deterministic polling-based (PCF, or Point Coordination Function). Under the standard, both modes of access can co-exist on the same channel with switching between the random and deterministic access modes being managed by a signal beacon from the base station. Although PCF (deterministic) access can support higher occupancy (utilization) and aggregate throughput, it requires the base station to assume centralized management responsibility for all connected devices. While appearing potentially more chaotic and less efficient, the random access (DCF) approach turns out to offer good robustness and adaptability properties by fully distributing access control. The throughput is also quite comparable under light loads. As a consequence, WiFi device manufacturers have chosen only to implement DCF, and not support the PCF option.

The DCF-random mechanism uses a carrier sense multiple access (CSMA) with collision avoidance (CA) approach. A device that wishes to transmit first senses the channel and if it determines the channel is vacant, it transmits; if it detects that the channel is occupied by another ongoing transmission, it waits until it is free and then adds a random time before re-attempting on the free channel. CSMA/CA is an adaptation for wireless channels of the wired Ethernet protocol, which was standardized by IEEE802.3 and is widely used in wired LANs.

WiFi and Femtocells have similar spectral efficiency[23] and both technologies have been increasing their data rates and channel bandwidth over time.[24] However, WiFi has typically offered higher average data rates and supports wider bandwidth channels.[25] How important these differences are is open to debate and both technologies remain moving targets.

Finally, WiFi is the more mature technology with a much larger global installed base of base stations and with less significant changes to the core technologies than is experienced by cellular technologies when going from 3G to 4G. WiFi equipment has become commoditized hardware, and benefits from being able to share numerous components and network elements with the even more mature wired Ethernet marketplace. In contrast, femtocells based on 3G and 4G are not easily compatible and are more recent technology. Additionally, femtocells are deployed to operate in licensed spectrum and to be integrated into the mobile operator's existing network, which has made it difficult to realize scale economies. Femtocells are customized to be operator-specific and have been inherently more complex than WiFi base stations.[26] Thus far, this has precluded commoditization of femtocells. However, there is no fundamental reason why femtocells could not be commoditized, and with some modifications, match the unit costs of WiFi equipment. For example, femtocells could have functionality (complexity) stripped out to allow them to operate at lower cost as standalone base stations or to operate in unlicensed spectrum, and with the growth in the installed base, scale and learning economies will accumulate (and average unit costs will decline).

The transition to small cell architectures presents an opportunity to potentially disrupt traditional technical and market trajectories. Such disruptions may include still newer wireless technologies that may complement or disrupt either or both WiFi and femtocell ecosystems. Indeed, as we explain further below, the choice of small cell technology is likely to be a hybrid mix of multiple generations of WiFi and femtocells, as well as other wireless technologies.

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[23] Spectral efficiency is measured in bits/s/Hz and the latest commercial WiFi and LTE standards offer roughly comparable efficiencies. Future generations are expected to offer additional improvements by exploiting more sophisticated MIMO techniques (by which multiple antennas are used to disentangle the multipath information to enhance the signal-to-noise performance).

[24] For a discussion of data rates in recent 802.11 updates, see Note 18 supra. LTE (first introduced in Release 8) provides peak downlink/uplink rates of 100Mbps/50Mbps respectively, and allows channels to be allocated dynamically from 1.4 to 20MHz. LTE Advanced (first in Release 10), which was completed in June 2011, raises the peak data rate to 1Gbps. In actual deployments, realized peak rates will depend on the distance from the base station and the amount of shared use, and are likely to be significantly lower (http://www.3gpp.org/specifications/67-releases).

[25] The legacy of higher WiFi than cellular data rates is due significantly to the fact that WiFi were smaller cells and hence available wireless resources could be shared among fewer users and because smaller cells allow higher data rate services to be transmitted with less power. Lightly loaded LTE macrocellular networks or small cell LTE APs can match or exceed the performance of more congested or earlier generation WiFi APs.

[26] For example, LTE femtocells require much more expensive filters to separate adjacent channel signals and manage the interference properly than macro or microcells to get the targeted performance. Empirical measurements of performance under situations that more closely approximate practical real world conditions are significantly different than simulation results based on ideal conditions. Achieving target design performance goals is likely to be expensive. See, e.g., http://www.rttonline.com/ttfluid/TT2014_005.html.

2.3 Small Cell Deployment Scenarios

In addition to the choice of technology, the small cell future will vary based on the deployment scenario. These deployment scenarios may be differentiated based on whether the base stations are indoors or outdoors,[27] whether access is open or closed,[28] and whether the goal is to provide wide-area (involving many APs) or local (involving a single or small number of APs). Figure 3 illustrates four relevant cases, but only three of these will be discussed here (Scenario A, B1 and B2).[29]

	User Access	Coverage	Deployment Management
(A) Homes/Business	Open/closed	Indoors	End-user or with network operator
(B0) Hotspots/Local	Closed	Outdoors	Private campus/enterprise
(B1) Hotspots/Local	Open	Outdoors	Business, Aggregators, Operator
(B2) Wide area/many APs	Open	Outdoors	Cellular or New (e.g., fixed broadband provider)

Figure 3: Small Cell Deployment Scenarios

In each of these deployment scenarios (discussed further below), several key questions arise. These include:

- *(1) AP owner/management?*

In most cases of local deployments of isolated base stations, the site owner (home owner, small business) owns, deploys and manages/controls the AP; whereas in most wide-area deployments, a service provider or network operator is more likely to own and deploy the APs. It is also possible to separate the owner and management of the APs. For example, with WiFi, the end-user usually manages the AP; whereas with femtocells, the operator is responsible for remotely managing the AP.

- *(2) Backhaul?*

Generally, the backhaul from the AP to the Internet is provided by a fixed broadband network provider. An interesting question is how that backhaul is managed and paid for. In most cases today, the backhaul is provided by the end-user who deploys the AP and connects that AP to the Internet via the end-user's fixed broadband service. Usually, the backhaul is provided over an Internet

[27] By "outdoors," we mean to include deployments that are outside or, if inside buildings (e.g., coffee shops, public libraries), provide broadband access outside-of-the-home.

[28] A closed access system restricts usage to a closed user community. However, closed networks may be opened to allow more general public access.

[29] We do not discuss B0 (local hotspots deployed for outdoor coverage to support a closed network) in the interest of space. This is the scenario applicable to a private campus or enterprise, potentially including a shopping mall. We expect such deployments to be important and analogous to the earlier deployment by businesses before home and small business adoption took off. The presence of such networks has the potential to provide a large installed base of equipment and network infrastructure that could become part of the public infrastructure later, if it is open for shared access. We skip this case in order to focus on the more distinctive other cases that will highlight the key issues.

Protocol (IP) network, but that might be over the broadband "Internet" (the typical case today), or over a separate, managed IP network.[30]

- *(3) Spectrum?*

As noted earlier, WiFi operates in unlicensed spectrum and femtocells operate in licensed spectrum. However, that need not be the case. There are also newer and hybrid models of spectrum access that may be used in the future, many of which depend on more dynamic and flexible radio technologies that are becoming available.[31] The choice of spectrum has implications for deployment and operating costs.

In the following sub-sections, we consider each of these deployment scenarios more closely.

2.3.1 Scenario A: In-home open/closed small cells

This is the classic model for WLAN access and WiFi has emerged as the dominant technology choice thus far. In this scenario, end-users deploy small cell APs to extend the wired broadband services in their premises.[32] The initial architecture is quite simple and consists of a single base station linked to a fiber, cable or DSL connection to extend and share broadband service among several devices. It facilitates cable-free networking (which can ease installation and configuration) and provides in-home mobility.

After initially opposing such WLAN/small cell deployments, wired broadband providers have become strong supporters.[33] The in-home sharing, mobility support, and ease of service configuration complements and helps drive demand for fixed broadband services. Today, most fixed broadband provider modems come with WiFi APs, and increasingly, these are the default mechanism for connecting subscriber devices to the fixed broadband service in the home. The in-home deployment model has been quite successful and more than 73% of broadband households worldwide have in-home WLANs.[34]

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[30] For example, Comcast offers subscribers basic telephone services that are provided as VoIP. However, unlike Skype or Vonage that provide their VoIP services via the broadband Internet, Comcast uses a separate managed IP network for its telephone service. Similarly, there are multiple technical options for back-hauling traffic from small cell APs to a point of interconnection with the general Internet.

[31] Generally, these models are described as Dynamic Spectrum Access (DSA) systems that allow frequency-agile radios to change their RF operating behavior dynamically to better match spectrum resource requirements to available spectrum. PCAST (2012) discusses these developments. Examples of new sharing models are under consideration for spectrum in TV white spaces, 3.5GHz and 5Ghz bands (see, for example, CFP Spectrum WG, 2014).

[32] We use Base Station and Access Point (AP) interchangeably here.

[33] Many fixed broadband providers had service agreements that precluded connecting WLAN access points to the broadband service. This was motivated by concerns that providing customer support for WLANs would add to costs (e.g., to help configure WLANs or increase quality assurance problems that might threaten the providers brand image) and by the potential threat that WLANs might enable households to share connections, thereby cannibalizing fixed line penetration. However, few broadband providers actively opposed subscribers deploying WLANs.

[34] According to Strategy Analytics, "by the end of 2012, 678 million households worldwide will be connected to the internet via broadband -- a 8.5% increase from 2011. Of these 678 million broadband households, 492 million households (73% of broadband households) will use a wireless router to create to WLAN, or Wi-Fi home network" see https://www.strategyanalytics.com/default.aspx?mod=reportabstractviewer&a0=7215.

Such home networks may be deployed either as open or closed networks. If open, the APs may be shared with the general public that is within range of the AP (i.e., typically within 100 meters). Carriers have started leveraging the huge base of in-home small cells by configuring an additional radio interface.[35] This has the potential of enabling small cell infrastructure that is installed in homes to be managed for sharing as part of a larger small cell deployment.[36] Shared usage can be configured so as to prioritize the traffic of the home user.

2.3.2 Scenario B1: Outdoors, open local access

Another common deployment scenario is one in which local businesses, governments, or other entities install local hotspots with one or a few APs. Coffee shops and other small businesses, public libraries and other anchor institutions, and local governments may deploy such hot spot access to attract customers or as a public service benefit for the community. These local hotspots are typically not integrated in order to support wide-area coverage. The mobility they support is nomadic (i.e., users have to wander to within range of the small cell for access). While there are hot spot aggregators like Boingo[37] and FON[38] that provide a retail model for managing these distributed hot spots, and new standards that support WiFi roaming (e.g., Hot Spot 2.0) that make aggregation easier, this is still the exception rather than the rule.

Nevertheless, the growing installed base of hotspots outside of homes provide valuable wireless infrastructure that can be used to complement or substitute for the wide-area coverage of mobile cellular networks. An important and growing use of such hot spots is to support mobile cellular traffic "off-loading" (i.e., shifting traffic that would otherwise need to be carried on the mobile network to a hot-spot).[39]

By far, the most common technology choice for such local public access deployments is WiFi. In most cases, the backhaul is provided via a wired broadband service. Because of the significant heterogeneity in management practices (whether such networks are fully open or complementary but password protected,[40] whether they support full or limited access,[41] and how well-

[35] Wireless nodes can be configured with several network identities over the same radio interface to allow multiple users or groups of users to share an AP. It is also possible to include multiple radios in an AP. Comcast has started deploying APs with this capability, which has the potential of allowing Comcast to turn-up a network of public WiFi hotspots that piggy-back on the broadband connections and small cell deployments of Comcast's household subscribers (see Brodkin, J., "Comcast turns your Xfinity Modem into public Wi-Fi hotspot," ArsTechnica, June 10, 2013, available at: http://arstechnica.com/information-technology/2013/06/comcast-turns-your-xfinity-modem-into-public-wi-fi-hotspot/).

[36] The ability to share in-home small cell APs with users outside the home is limited by the range of the APs. It is likely to work better in dense deployment scenarios (e.g., apartment buildings) than in sparse settings (e.g., neighborhoods with standalone dwellings).

[37] See http://www.boingo.com/retail/.

[38] See https://maps.fon.com/.

[39] There is no general agreement on how to classify or forecast off-loaded traffic, so we put it in quotes here. See below for further discussion.

[40] Even when service is complementary, many local WiFi access networks have some access security which may be associated with the AP or implemented using a Web portal. The mechanisms for employing such security vary and

provisioned the backhaul is[42]), the performance on such public networks can be quite variable.

2.3.3 Scenario B2: Outdoors, open wide-area access

A final deployment scenario that is emerging, in part because of the advances noted in the above two scenarios, is to deploy small cells using WiFi or femtocell technologies as part of a wide-area deployment. Such deployments have the potential to realize the vision of seamless mobility for ubiquitously available broadband access. In its fullest realization, this means filling in the coverage gaps that currently exist so that users can obtain at least a minimal level of mobile broadband access service everywhere.[43]

Because femtocells are smaller versions of cellular base stations, which by design are intended to support wide-area coverage and continuous service support, these might seem a more natural candidate technology because they have the multi-AP coordination technology already built-in. While true, it is worth pointing out that there are a number of technical details that still need to be worked out. As already noted, integrating different sized cells into a common shared band presents a challenging interference/network management problem. The expectation is that mobile devices will connect to the closest AP available, which may be a femtocell, or in a cellular network, a microcell or even macrocell. Current femtocell equipment has important limitations with respect to providing a fully-integrated cellular solution. For example, AP hand-offs from femtocells to macrocells are feasible, but handoffs in the other direction are not. The hand-off mechanisms have been difficult to resolve for two important reasons. First, security concerns make operators reticent to accept traffic from users who were first authenticated via femtocells (which may not be fully under the control of the operators)[44]; and second, there is a difficult near/far interference management challenge associated with the fact that the power-levels needed to connect to the femtocell (near, low power) and macrocell (far, high power) are so different.[45]

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can be confusing for neophytes. In some cases, patrons need to subscribe to a service (e.g., pay a daily or hourly rate for access), accept advertising, or reveal private information in order to obtain access.

[41] Usage controls are also variable. Some networks limit the services that users may access, including throttling the data rates or limiting the volume of data that may be downloaded. There are a wide-range of techniques and practices that may be employed to manage individual subscribers level of access which can significantly impact the quality of the user experience.

[42] Public access may be congested and variable quality backhaul may be the cause. A provider of complementary broadband access may seek to manage costs by severely limiting the quality of backhaul from the AP (e.g., by purchasing lower-tier, lower data rate broadband service to the AP).

[43] Presumably, service quality will remain variable and not all services will be available or well-suited for all forms of mobility. For example, nomadic mobility is likely to have greater need for and realize the benefits of higher data rate services than will fast mobility. Thus, we might expect video conferencing to be less common in airplanes and cars than in stationary locations.

[44] Although operators may remotely manage the femtocells, they are unlikely to be able to physically observe where the femtocells are placed, and potentially, what else is connected to them. Additionally, because the femtocells may be purchased/owned by end-users and are located on user premises, end-users may expect to have a greater degree of flexibility and control over how the femtocell is configured and used.

[45] Although there is a significant body of femtocell research, seamless integration into cellular networks remains an open challenge (see, (Andrews, Claussen, Dohler, Rangan, & Reed, 2015; Chandrasekhar & Andrews, 2008; Ghosh et al., 2012)).

Although cellular technology has advantages in managing large multi-AP area networks, there are some large WiFi deployments with 1000s of APs covering relatively large areas.[46] A number of these large deployments are associated with community broadband initiatives. Advances in network management and new standards like Hot Spot 2.0 make it easier to manage roaming and larger networks of WiFi APs.

Hybrid solutions are also possible. Fixed broadband providers, both wired and wireless (WISPs), as well as mobile cellular providers are deploying networks of WiFi hotspots. For cellular providers, the addition of WiFi hotspots provides a low cost way to manage broadband traffic costs (off-loading, discussed further below). For fixed broadband providers or other entrants, WiFi might offer a low cost way to get into the mobile broadband business.

2.4 Current status and future prospects

Currently, WiFi is the dominant technology for small cells. The first WiFi networks began to be deployed in the 1990s.[47] Global deployments are estimated to have exceeded 439 million by 2012 and are expected to rise to 646 million by 2015.[48] The vast majority of these are deployed in homes (Scenario A), representing a penetration rate of almost 25%.[49] A much smaller number of WiFi APs have been deployed as public hotspots (Scenario B1, B2), although forecasts are for those numbers to increase significantly. Global deployments of public WiFi hotspots were estimated to be 1.3 million in 2011, and are projected to grow to 5.8 million by 2015.[50] Finally, since 2000, it is estimated that cumulative shipments of WiFi-

[46] Communities following several deployment models have done some of the largest WiFi deployments. Guifi.net in Catalonia groups over 20,000 WiFi active hotspots or the Personal Telco project in Oregon (personaltelco.net) or Freifunk (berlin.freifunk.net/) in Berlin are some examples of grass-roots communities building remarkable small cell networks.

[47] The original 802.11 standard was first released in 1997 and the Wi-Fi Alliance was formed in 1999 (an industry association to promote standardized, interoperable 802.11 WiFi equipment).

[48] By the end of 2011 Strategic Analytics estimated that there were 439 million WiFi APs and predicted that number to rise to 800 millon by 2016 (see http://www.businesswire.com/news/home/20120404006331/en/Strategy-Analytics-Quarter-Households-Worldwide-Wireless-Home#.U5Ej-JSwacA); Informa reported that there were 233 million private and 0.5 million public WiFi APs as of 2009, and projected that those numbers would rise to 646 and 5.8 million, respectively, by 2015 (see "Global developments in public Wi-Fi," report prepared for World Broadband Alliance (WBA) by Informa Telecoms & Media, 2011, available at: http://www.wballiance.com/wba/wp-content/uploads/downloads/2012/07/16_WBA-Industry-Report-2011-_Global-Developments-in-Public-Wi-Fi-1.00.pdf).

[49] The home penetration of WiFi varies significantly across countries and is highest in countries where Internet penetration is highest. For example, the home WiFi penetration rates were South Korea (80%), Germany (73%), France (72%), US (61%) and Spain (57%) in 2011 (see, "Strategy Analytics: A quarter of households worldwide now have wireless home networks," 4 April 2012, available at http://www.businesswire.com/news/home/20120404006331/en/Strategy-Analytics-Quarter-Households-Worldwide-Wireless-Home - .U5IORpRdXl1).

[50] See "Global developments in public Wi-Fi," report prepared for World Broadband Alliance (WBA) by Informa Telecoms & Media, 2011, available at: http://www.wballiance.com/wba/wp-content/uploads/downloads/2012/07/16_WBA-Industry-Report-2011-_Global-Developments-in-Public-Wi-Fi-1.00.pdf. More than half of the operators surveyed by the WBA are considering deploying WiFi hotspots as part of their mobile broadband services (see http://www.informa.com/Media-centre/Press-releases--news/Latest-News/Wifi-hotspots-set-to-more-than-triple-by-2015/).

enabled devices exceeds 5 billion and that annual shipments reached 1.5 billion in 2012.[51]

In contrast, 4G LTE services are of much more recent vintage and are significantly less advanced. The first 4G LTE networks began offering commercial services only in 2009. By 2013, LTE network coverage reached about 20% of the global population, but adoption rates remain quite low. The largest LTE market currently is the U.S. with almost 100 million (20%) of mobile subscribers on LTE networks that provide coverage to 90% of the population.[52]

Informa Telecoms & Media estimated that there were over 6 million femtocell nodes in use by the end of 2012, surpassing finally the number of macrocells (5.9 million). Most of these were deployed in homes. As of 2013, analysts forecasted that shipments would rise to 8 million units per year by 2017 (and 50% of those are expected to include WiFi).[53]

Most US cellular operators have announced ambitious femtocell deployment plans, with projected total deployments of between 1 and 2 million femtocells in 2012.[54] The current status of femtocells in Europe is similar to the US. In UK, multi operator femtocells were introduced as an incentive to promote in-house and small businesses small cells and improve in-building coverage. The base of femtocells installed in 2014 is expected to reach 300K.[55] Indicative of the challenges associated with cellular operators femtocell roll-outs, Telecom Italia

[51] See "Wi-Fi enabled device shipments will exceed 1.5 billion in 2012, almost double that seen in 2010," ABI Research News, 11 October 2012, available at https://www.abiresearch.com/press/wi-fi-enabled-device-shipments-will-exceed-15-bill.

[52] Analysts estimate that there were 176 million global LTE subscribers by the end of 2013, with about 99.4 million LTE subscribers in the US. The highest penetration was in South Korea with 62% of mobile subscribers on LTE networks, compared to 19% in the US. (Sources: Informa Telecoms & Media, 2014; "Mapping the world's LTE coverage – it's in fewer places than you think," Gigaom, 20 September 2013, available at https://gigaom.com/2013/09/20/mapping-out-the-worlds-lte-coverage-its-in-fewer-places-than-you-think/; "LTE heating up the global mobile market," 20 September 2013, available at http://forums.juniper.net/t5/The-New-Mobile-Network/LTE-Heating-Up-the-Global-Mobile-Market/ba-p/208669; and "GSMA Intelligence study predicts one billion LTE connections by 2017," 26 November 2013, available at: http://www.gsma.com/newsroom/gsma-intelligence-one-billion-lte-2017/)

[53] See "Small cell market highlights," prepared for Small Cell Forum by Mobile Experts, February 2014, available at: http://www.scf.io/en/get_email.php?doc=050. Annual shipments are expected to rise to 8 million units by 2017, with 50% expected to include WiFi ("Small Cell Market Status, Informa Telecoms & Media, February 2013, available at http://www.smallcellforum.org/smallcellforum_resources/pdfsend01.php?file=050-SCF_2013Q1-market-status report.pdf). It is unclear from the information provided whether these are femtocells or also include microcells and picocells, which are included in the Small Cell Forum's definition of "small cells."

[54] Sprint announced plans to deploy 1 million femtocells in March 2012, prompting AT&T and Verizon to announce their own plans to deploy several hundred thousand additional femtocells. (Sources: "Sprint's femtocell tally tops 1M," FierceWireless, March 2012, available at http://www.fiercewireless.com/story/sprints-femtocell-tally-tops-1m/2012-10-24; "Verizon to deploy LTE femtocells, small cells," FierceWireless, March 2012, available at http://www.fiercewireless.com/story/verizon-deploy-lte-femtocells-small-cells/2012-03-05; "AT&T to test small cells, counts 'several hundred thousand' femtocells," FierceWirelessTech, February 2012, available at http://www.fiercewireless.com/tech/story/att-test-small-cells-counts-several-hundred-thousand-femtocells/2012-02-28 - ixzz2xZxzSp1b).

[55] Ofcom encourages the use of femtocells in UK as a means to improve capacity and coverage in the mobile sector. http://stakeholders.ofcom.org.uk/market-data-research/other/telecoms-research/improving-building-coverage/

Mobile (TIM) cited a mix of technical and business issues as reasons for abandoning its femtocell deployment plans at the end of 2013.[56]

Summarizing, it is clear that the installed base of WiFi APs is significantly larger than the number of femtocells (see Figure 4), and that the vast majority of the small cells have been deployed in homes and offices (Scenario A). In the move to expand public hotspots, however, the two technologies have been much more closely matched thus far. Forecasts for deployments of both technologies, however, call for significant growth.

	WiFi	Femtocells
Scenario A (in-house)	439	4.8
Scenario B (hotspots)	1.3	1.2
Overall base installed	440.3	6

Figure 4: Global Deployments of Small Cells as of 2012 (millions)[57]

For the foreseeable future, it is hard to see how femtocells might catch up to WiFi deployments for in-home/indoor use, while outdoor use is more of a mixed bag. We would expect femtocells to be strong competitors, especially for services/networks for which support for fast mobility remains a premium. Additionally, it looks like future small cells will blur the boundary between WiFi and femtocells, and potentially, between in-home and outdoor deployments. With respect to the first, the trend is toward including multiple radios in wireless devices (both APs and end-user devices). WiFi is an obvious candidate for inclusion in APs whether the device is principally intended as a femtocell (for outdoor or indoor use) or pure WiFi hotspot. Moreover, the trend in radio systems is to include increased functionality in software (e.g., cognitive and software defined radios, and other smart radio system components) which makes it easier to include multiple radios.

Finally, as both public femtocell and WiFi hotspots proliferate in outdoor deployments, there will be increased incentives to tie these together with in-door small cells. Operators like Comcast, FON, and Free have been leveraging in-home hotspots to support public access for others that are within range.[58] We expect this trend to continue, which will blur the boundary between deployment scenarios. The hybrid solutions will present a more complex management challenge to support seamless mobility across multiple small cell APs and networks. As we discuss further in the next section, managing such "roaming" will engage all participants in the mobile broadband ecosystem.

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[56] Telecom Italia (TIM) has decided to give up on its femtocell strategy (http://cel-fi.com/the-blog/Telecom-Italia-jumping-off-the-Femtocell-bandwagon)

[57] Sources: notes 48, 52, and 53 supra.

[58] For operator plans to leverage home hotspots for public WiFi access, see (for Comcast in US) "Comcast unveils plans for millions of WiFi hotspots," 10 June 2013, available at: http://corporate.comcast.com/news-information/news-feed/comcast-unveils-plans-for-millions-of-xfinity-wifi-hotspots-through-its-home-based-neighborhood-hotspot-initiative-2; see (for Free, in France) "France's Wi-Fi gates swing open: Free Mobile activates 4M hotspots," 19 April 2012, available at http://gigaom.com/2012/04/19/frances-wi-fi-gates-swing-open-free-mobile-activates-4m-hotspots/; see (for FON, globally) "Crowdsourced Wi-Fi Network FON passes 5 million hotspots worldwide," 22 February 2012, available at http://techcrunch.com/2012/02/22/crowdsourced-wifi-network-fon-passes-5-million-hotspots-worldwide/.

3 Challenges and implications for small cell deployments

In this section, we consider three important implications that the transition to small cells is likely to have for the mobile broadband ecosystem. These include:

- *Fixed-mobile convergence*: small cells help drive fixed-mobile convergence;
- *End-user empowerment*: small cells enable end-user control and provide a new vector for last-mile competition; and,
- *Spectrum management*: small cells propel the movement to unlicensed and dynamic spectrum access.

While we believe the above are likely, and indeed desirable, outcomes, none are foreordained. Significant challenges will need to be overcome and alternative scenarios are certainly possible. In the following sub-sections, we examine each more closely.

3.1 Fixed-Mobile Convergence

As the wireless ecosystem shifts toward increased reliance on small cells, mobile and fixed broadband will converge. This has the potential to expand the capabilities and markets for mobile broadband services. Historically, fixed broadband services (mostly wired, but also including fixed terrestrial and satellite wireless) were accessed at stationary locations. The later addition of more limited data capabilities to mobile has expanded opportunities for using Internet services (e.g., enabling Internet commerce to become mobile commerce), but limitations in the quality of mobile broadband has limited the growth of such services. Just as the transition from dial-up to first generation broadband helped drive innovation and demand for broadband-enabled applications and content, so the transition to more capable mobile broadband services is fueling another round of Internet-related economic growth. A key aspect of this is the enabling of greater personalization and customization of service offerings. Whereas fixed broadband access was traditionally shared among multiple users in a household who also shared the end-user devices, the transition to mobile devices has expanded options for "personal broadband," which allows individuals to access their broadband services potentially wherever they are.[59] With this transition, consumers' perceptions of what constitutes broadband service and the distinction between fixed and mobile broadband services is blurred. From a demand perspective, mobile broadband can be simultaneously a complement or substitute for fixed broadband – depending on the end-user and market context.[60]

[59] See CFP (2006) for a vision of personal broadband service. For example, cable television content that was previously only accessible from home, can now be accessed via mobile applications like Netflix, HBOGO, and others via mobile broadband access away from the home. The choice of where access is permitted/supported is increasingly a business decision.

[60] For example, for some broadband users, with limited needs or financial resources, mobile broadband may be a viable substitute for fixed broadband, especially if the fixed broadband services are of lower quality. For most subscribers, the quality of mobile services are sufficiently lower quality to fixed broadband services that the services are complementary. Fixed broadband service in the home provides higher-speed access and supports an alternative mobile broadband service option in the household. See (Chapin & Lehr, 2011).

Moreover, because fixed broadband is the most common backhaul option for connecting small cells to the Internet, the transition to small cells increases the reliance of mobile service providers on access to fixed network infrastructure. Demand for small cell backhaul provides an additional source of demand for dense neighborhood fiber deployments (i.e., FTTx where "x" may be all the way to the home or close to the home),[61] thereby lowering the average costs of deploying fiber. Thus, faster mobile broadband helps accelerate demand for fiber.

The economics of deploying small cells also shares many features of the challenges of deploying fixed broadband. For example, as with fixed broadband, the end-user premises need to be negotiated to deploy small cells (at least in Scenario A, B1, and ultimately in B2 to realize ubiquitous coverage). That means obtaining access to local sites for antennas and conduit for power and backhaul to serve the small cells. This also means provisioning for local maintenance. Unlike in macrocell cellular services where resources are managed on a per-connection/per-subscriber basis, with small cells, the resources are more likely to be shared collectively with all users/devices in the household – analogous to the traditional model for fixed broadband access. Increasingly, the end-users are being engaged as partners in investment and configuring of small cells. The home/building/campus owner/resident and the local municipal government need to be involved in the placement of each small cell, which puts a premium on ensuring the transaction/management costs are low.[62] The potential shared cost elements between fixed and mobile networking increase in this context.

Finally, and potentially as an industry disruptor, the transition to small cells opens the door for new models for mobile broadband service entry and infrastructure deployment. Today, the principal model for providing mobile broadband services outside the home is via cellular operators and their 3G/4G LTE networks. Cellular providers have been actively interested in taking advantage of WiFi APs as lower-cost alternatives to handling mobile traffic. Such "off-loading" of cellular data traffic is wide-spread and growing, but its implications are complex. In the next sub-section we consider how this empowers end-users.

It also has the potential to tilt the balance of competition between fixed and mobile broadband facilities based providers.[63] In addition to increasing the needs of cellular providers to rely on wired infrastructure providers for backhaul services, the growth in (mostly) WiFi-fueled mobile broadband ecosystem has created a new option for delivering mobile broadband services. In many contexts, a more natural and prevalent model of mobile broadband use is nomadic, where usage is quasi-stationary. Instead of having support for fast-mobility be the norm for mobile broadband networks, it may increasingly be viewed as a special case. In this scenario, WiFi-style access with more limited support for coordinating hand-

[61] See (Domingo & Lehr, 2013).

[62] With less expensive, user-installed small cells, the per-unit installation/configuration costs need to be quite low. In many cases, small cells will be self-installed as customer premises equipment.

[63] Overall, the growth of mobile broadband is likely to enhance overall broadband competition (Lehr, 2009). Our focus here is more narrowly on competition in mobile broadband.

offs across APs might prove adequate for a sufficient share of mobile broadband applications inside and outside the home to make this the preferred model. In the future, we may talk of off-loading from WiFi-style networks to the cellular network for the exceptional traffic that requires fast-mobility support.

Backhaul is a significant cost for mobile services, and fixed infrastructure providers could leverage their existing investments to lower their costs for competing in mobile broadband. Fixed broadband providers such as Comcast, without a cellular offering[64] may view the deployment of wide-area WiFi coverage as a viable option to expand its portfolio of bundled services from a triple play (cable television, telephony, and broadband Internet) to a quadruple play (with the addition of mobile broadband).[65] Earlier we mentioned efforts by WiFi aggregators such as Boingo and FON to create models for (nomadic) wide-area coverage. Today, a growing number of operators are exploring models for wide-area WiFi deployment that blur the boundary between fixed and mobile providers. Comcast's Xfinity wifi service in the US[66] or Telefonica's O2 service in the UK[67] (from Telefonica/UK) are examples of carrier orchestrated deployments to provide outdoor public WiFi services. BT is following a similar strategy leveraging the 5.5 million of in-house small cells already deployed in the UK market.[68]

Providers like Verizon and AT&T, with significant fixed and cellular networks and offerings are also looking to expand WiFi small cell coverage.[69] These hotspots provide a lower-cost way to off-load traffic from their mobile networks, and to

[64] In 2012, Comcast transferred its interest in AWS spectrum licenses it had acquired at auction to Verizon, while at the same time, negotiated a joint-marketing agreement to allow Comcast to market Verizon Wireless cellular services to its subscribers (see, "What $3.9 billion Verizon/cable spectrum deal means for you," C-Net News, August 25, 2012, available at: http://www.cnet.com/news/what-3-9-billion-verizoncable-spectrum-deal-means-to-you-faq/.

[65] For example, "Unleashing the power of triple-play – and quad-play," Global Telecoms Business, September/October 2008, available at: https://www.communigate.com/Papers/CommuniGate_GBT_SepOct08.pdf.

[66] Comcast has been leveraging a mix of customer-provided (in-home) and operated-provided WiFi hotspots to expand access to its Xfinity broadband services outside the home. Comcast has announced plans to expand its reach of WiFi to 8 million hotspots by the end of 2014, providing coverage in the large urban areas of US. Already, Comcast claims that 54% of its neighborhood traffic is going over Xfinity WiFi service and Comcast expects to be serving 200 million subscriptions by the end of the year (see http://corporate.comcast.com/news-information/news-feed/comcast-to-reach-8-million-xfinity-wifi-hotspots-in-2014).

[67] O2, Telefonica's UK mobile subsidiary, is deploying an outdoor free WiFi metro network in London to provide expanded coverage and to off-load traffic from its cellular network. See http://www.o2.co.uk/connectivity/free-wifi and "O2 blankets London's Canary Wharf in free Wi-Fi," Gigaom, July 13, 2013, available at: https://gigaom.com/2013/07/31/o2-blankets-londons-canary-wharf-in-free-wi-fi/.

[68] BT currently provides Wi-Fi coverage for around 43 per cent of the population through the 5.5 million hotspots it supports. These hotspots are mostly based on its broadband customers' routers. For coverage, BT has an MVNO deal with Everything Everywhere and 50 MHz of 2.6 GHz spectrum it acquired recently which its press office tells us will be integrated into the company's mobile offering through the use of Wi-Fi/4G cores. BT's case is somewhat unique in so far as UK regulators have thus far limited BT's options for becoming a cellular provider. Since 2007, BT has had an alliance with FON in deploying access to a mix of (mostly) in-home (customer-owned) WiFi hotspots and some outside the home. BT has now decided to unify and rebrand its WiFi offerings as BTWiFi, and with roaming agreements negotiated with cellular providers, is well-positioned to provider national mobile broadband services. BT is now the largest unlicensed provider in UK.

[69] See "Verizon hunts for Wi-Fi Small cell smarts," LightReading, August 9, 2013, available at: http://www.lightreading.com/mobile/carrier-wifi/verizon-hunts-for-wi-fi-small-cell-smarts/d/d-id/703693; and, "Wireless Week honors AT&T for Wi-Fi leadership and growth as Customer connections triple year-over-year," AT&T Press Release, May 9, 2012, available at: http://www.att.com/gen/press-room?pid=22830&cdvn=news&newsarticleid=34424&mapcode=.

expand their offerings to support users with multiple devices (e.g., tablets without cellular radios or service). Generally, hybrid solutions for managing backhaul costs appear to offer a number of important benefits. Backhaul expenses can be significantly reduced by adding intelligence to APs. Enabling more capable APs adds only moderately to capital costs, but can have a large impact on operating costs.[70]

The potential that fixed and cellular providers might compete more aggressively in a small cell world has the potential to significantly disrupt the industry because of the very different legacies of the competitors. Figure 5 highlights some of the key differences between traditional fixed broadband and mobile cellular providers.

Implications	**Fixed Broadband**	**Mobile Cellular**
Regulatory burden[71]	Regulated last-mile, Net neutrality, legacy natural monopoly	Less regulated, more competitive from start.
Retail/customer contact	Per household. Aggregates traffic of multiple customers.	Per user. Follow-anywhere, customized
Access? (local backhaul)[72]	In-house wiring. Last-mile.	In-house wiring. Wireless last-mile limited.
Backhaul availability[73]	Wide-area network	May have wide-area network or not.
Spectrum[74]	On-the wire or fiber. Unlicensed	Licensed Unlicensed (potentially)

Figure 5: Legacy Fixed v. Mobile Broadband

The stylized comparison of fixed and mobile broadband providers suggests that as mobile broadband moves toward smaller cells, the fixed broadband providers may be in a stronger position because of their generally superior position with respect to access to backhaul facilities. However, the future of regulatory policy which has historically been asymmetric, renders this prognosis hypothetical at this point.

[70] (Intel, 2011) estimated that having more intelligently managed small cells in London reduced backhaul expenses from $301 Million to $191 Million.

[71] Wired networking has historically been regarded as a natural monopoly or public utility, subject to significant regulation. Wireless networking, which emerged after wired telephone networks were already widely deployed, confronted competition from the start, and hence, a reduced regulatory burden. For example, two cellular providers were licensed in each market initially, and the number of licensed operators expanded with the expansion of spectrum resources to enable additional facilities-based competition to emerge.

[72] Access requires connecting to the small cell inside the building where it is deployed, via inside wiring, and then to the first point of traffic aggregation in the local access network. While wireless backhaul options are available (e.g., mesh networking technologies like Canopy and point-to-point wireless backhaul), most of the backhaul is via wired infrastructure.

[73] Most wired broadband providers have extensive backhaul networks. Cellular providers differ in the extent to which they own/operate backhaul networks. For example, AT&T and Verizon have extensive backhaul capabilities, whereas Sprint's capabilities are substantially less.

[74] Both wired and wireless data transport relies on RF spectrum. With fixed broadband services, most of the RF is on the "wire" (where RF is relatively abundant) and when wireless is provided, it is typically via WiFi in unlicensed spectrum. Cellular providers principally rely on licensed spectrum, but efforts are underway to enable LTE in unlicensed.

Moreover, technical and market trends have been blurring the boundary between fixed and mobile networking for some time and this trend is likely to continue.

At this point, the long-term implications of fixed-mobile convergence for facilities-based competition remain ambiguous. On the one hand, this convergence has the potential for expanded service provider facilities-based competition in mobile broadband. In light of the increased concentration in 3G/4G cellular services (mostly due to mergers) and fixed broadband services (where more than duopoly competition has remained infrequent), additional facilities-based competition is especially welcome. However, the more complicated vertical relationships (e.g., when fixed broadband provides essential backhaul services to small cells and when fixed and mobile providers engage in joint marketing agreements) and the potential closer technical linkage between mobile and fixed broadband services (i.e., when broadband becomes personalized and access is increasingly seamless) raise concerns that the additional small cell infrastructures will, in fact, offer effective facilities-based competition.[75]

3.2 End-user Empowerment

Perhaps the best prospect for facilities-based competition in mobile broadband arises because of the potential for small cells to empower end-users to play a more active role in provisioning, and potentially controlling, broadband services. The move to small cells blurs the boundary between the network and the end-user.

As already noted, the switch to small cells creates a larger role for end-users in the deployment and management of the wireless infrastructure. In most cases, small cells are placed in end-user homes/businesses where the operator has limited access. While other business models are possible, in most cases, end-users purchase and own the small cells, provide power and the "real estate" to site the cell, and may also provide the backhaul services. Taken together, these represent significant capital and operating costs that are undertaken by the end-user, that might otherwise have been the responsibility of the mobile broadband service provider. The end-user is becoming a more active participant in provisioning the end-to-end infrastructure for mobile broadband.

As noted already, a significant volume of traffic that might otherwise be carried via cellular networks and their wide-area macrocell networks is being off-loaded to customer and other WiFi hotspot networks. Estimates of the extent to which traffic is being off-loaded and forecasts for future growth vary widely, but are generally significant ranging from 1/3rd to 2/3rd of the traffic in 2012, and rising to over 50% by 2016.[76] Forecasting is difficult because not everyone agrees on how to identify off-loading traffic. For example, should all traffic from dual network-capable

[75] For a discussion of the challenges of sustaining facilities-based competition in small cell architectures, see (Chapin & Lehr, 2011).

[76] See (Marcus & Burns, 2013) for a detailed discussion of challenges of estimating WiFi off-loading traffic. They highlight how Cisco's VNI estimates increased significantly from the report they issued in 2011 and the report they issued in 2013. Earlier they had forecasted WiFi offload as accounting for 11% of mobile traffic in 2011, rising to 22% by 2016; while by 2013, Cisco estimated 33% of traffic was off-loaded in 2012 and that would rise to 46% by 2016. Marcus & Burns reported that Informa and Mobidia estimated that 2/3rds of Android traffic was off-loaded in homes.

devices (e.g., smartphones, PCs and tablets with both WiFi and active cellular subscriptions) that is not carried by cellular networks be counted as "off-load" traffic, or only such traffic that occurs outside the home via hot spots? How to account for the usage where end-users have not activated cellular subscriptions or where end-users may mix devices or use tethering solutions?[77]

Answering the question of how much of mobile traffic is "off-load" is important for more than just academic interest. It is central to debates over the relative role that different wireless networks and spectrum management models currently play and should play in markets for mobile broadband. For example, in the on-going debate over the value of unlicensed versus licensed spectrum, proponents of unlicensed have pointed to the value of off-loading to demonstrate the economic contribution of unlicensed to the economy. (Katz, 2014) has estimated that unlicensed spectrum use contributes $140 billion to the U.S. economy, of which 45% is attributable to the use of WiFi in off-loading mobile traffic. WiFi-offloading enables cellular providers to better manage their capital expenditures for capacity and coverage expansion, and thus arguably, complements their efforts to expand mobile broadband services.

Who makes the decision of which network to use in which contexts is also important. For example, some users might wish for seamless mobility services in which the network decides automatically which network to use to best meet the consumer's needs. Those needs may vary by location, time, and what the user is doing. For example, the generally higher-quality fast-roaming support for voice calls may induce a consumer to prefer to use the cellular network for mobile voice telephony everywhere.[78] At the same time, many consumers and a number of applications and content services prefer WiFi over cellular data services, and may either limit entirely or restrict access to data when WiFi is not available. The reduced coverage/availability of WiFi-speed-comparable 3G/4G services and the potential higher toll on battery life (when 3G/4G is provided via a distant macrocell) often mean that WiFi hotspot offers a superior data experience.

Price is also an important factor. In the home and in many cases outside the home, WiFi is either free or substantially less expensive (for high volume usage). Many consumers deactivate their 3G/4G LTE data roaming services when traveling internationally to avoid incurring high data-roaming charges. With respect to voice calling, the fact that most cellular service is sold in buckets offering a large (and increasingly unlimited) number of calls means that the incremental cost of a cellular call is free for subscribers who have not exceeded their monthly call allowance. Arguably the same may be true for mobile data services for users with unlimited or high volume data plans, but consumer's uncertainty over data usage

[77] Mobile broadband access may also be obtained via cellular networks by making use of a 3G/4G handset in "tethered" mode. In that mode, the handset serves as a mobile hotspot for other user devices (e.g., a personal computer or tablet) that may be attached either directly (via USB cable) or wirelessless (via Bluetooth or even WiFi) in order to obtain a broadband connection. Cellular providers have varied in their willingness to permit tethered access. In 2012, the FCC ordered Verizon to permit Android applications that supported tethered access and fined Verizon (see, http://www.fcc.gov/document/verizon-wireless-pay-125-million-settle-investigation).

[78] A growing number of telephony subscribers are mobile-only. As of 2013, 38% of adults in the U.S. lived in households with only wireless service (see, http://www.cdc.gov/nchs/data/nhis/earlyrelease/wireless201312.pdf).

may still induce them to assign a high marginal cost for cellular data relative to WiFi data.

In principal, consumers might trust their service provider to make these decisions on their behalf, optimizing for each consumer's price and quality preferences, based on the networks potentially better knowledge of available options. For example, cellular providers already make use of information about a mobile devices location to customize basic service provisioning, and many operators, use data on WiFi hotspot locations as part of their positioning technology.[79] However, not all users may be comfortable with the service provider making these decisions and may not want to reveal (or even know) the information that an operator would need to adequately customize services. Also, other value chain participants may wish to help manage the wireless network selection decisions. Application and content providers, device manufacturers, and others might be expected to want to participate in the management of the small cells.

Indeed, today, much of the data needed to optimize the mobile broadband experience is only available on mobile devices (e.g., data on the history of usage which might be useful in learning about user preferences and habits; data from accelerometers, GPS, temperature and other on-board sensors).[80] This data is valuable market research for designing better products and services. A number of platforms are currently collecting such information.[81] While this has the potential to result in better services for all, it also poses a threat to personal privacy. The challenge of protecting privacy in a world of always on/everywhere connected broadband is a topic of active debate around the globe.

As long as the small cells are based on a single technology and tied to a single frequency, the range of choices will be limited. Increasingly, customer devices (PCs, tablets, smartphones) are coming equipped with multiple radios capable of operating at multiple frequencies and a wider range of modes. Additionally, software and hardware innovations in customer equipment and networks is making it increasingly feasible to support multiple management models. For example, a novel Future Internet Architecture, Mobility First, is developing the

[79] For example, Skyhook Wireless launched a service to provide WiFi-based positioning information to cellular operators in 2005 (see http://news.cnet.com/Wi-Fi-used-for-location-services/2100-7351_3-5754288.html). Since then the proliferation of WiFi hotspots and the accumulation of data on where these are located has allowed more wide spread and granular use of such techniques, to complement other approaches such as GPS-based approaches.

[80] In contrast to iOS/Apple devices, Android smartphones allow third party applications access to any data available on the phone with no restrictions.

[81] Mobidia regularly collects user's data through Modibia My Data Manager application installed in millions of active users ("Mobidia My Data," 2012). Cisco is also following a similar strategy to collect information from volunteers running a mobile application and displaying the collected information in real-time (http://www.ciscovni.com/data-meter/). Samknows is a third company following a similar methodology to collect directly data from mobile volunteers running an app (http://www.samknows.com/). SamKnows has developed a specific version for the FCC to measure the speed and performance of mobile broadband in the US.

The range of information collected is vast: user's device preferences and set up, volume of traffic delivered uplink and downlink, network performance (speed rate, packets lost, delay), traffic per application and per interface (cellular or WiFi), traffic per carrier, cellular coverage for each mobile generation, or specific location where data was generated, among others. Growing repositories of data are accumulating for these various platforms.

networking infrastructure to greatly expand the current Internet's ability to support mobility much more flexibly and dynamically.[82]

This includes building in better support for multihoming, in-network cloud storage and computing, end-user control over routing, disruption tolerant networking (DTN),[83] and dynamic networking resource configuration. Multihoming allows users and applications to dynamically and flexibly spread their communications across multiple interfaces, potentially allowing portions of a flow to travel over different wireless networks (e.g,. allowing delay-tolerant data to follow one path while delay-intolerant traffic to follow another path). The support for in-network cloud storage and computing helps facilitate support for thinner clients and new models for managing application and content services (part of the vision for cloud computing). All of these features, including DTN support, are informed by the needs of operating in wireless which is inherently more heterogeneous than wired Internet communications.[84]

Such developments make it technically feasible for end-users to directly or indirectly play a much larger role in the provisioning of end-to-end mobile broadband services. A key to this is the ability for end-users to deploy alternative last-mile access infrastructure. When limited to a wired world, it is difficult to imagine individual users or small groups of users self-provisioning alternatives if there is inadequate facilities-based competition. Community-based networking (e.g, fiber deployments) offer one option, but those confront numerous challenges. In contrast, wireless holds the potential of creating a new vector for facilities-based competition for last-mile access networks. Wireless entry has the potential of being more viral (distributed, decentralized) and scalable than wired entry. A single macrocell can be deployed to provide an access alternative for a large number of subscribers. Small cells indirectly impact this since they help lower the costs of wired deployment (e.g, community-based networking) since they may offer a last couple of hundred feet or less connectivity to less extensive (and less expensive) wired infrastructure.

Expanding end-users choices over wireless access by enabling them to choose their own or choose among multiple service providers directly addresses the last-mile bottleneck problem. In addition to delivering competitive benefits, empowering end-customer choice is consistent with personal autonomy and freedom, and so is generally desirable in its own right. A richer and more open small cell ecosystem, with a larger role for end-users, also expands communication and networking options. Much of the traffic may be inherently local and have little need for wide-area connectivity. For example, consider sensor-enabled video

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

[83] Disruption Tolerant Networking (DTN), or what is sometimes more narrowly referred to as Delay Tolerant Networking, recognizes that the presumption of an end-to-end path existing for the duration of time it takes for data to flow from the source to its destination is often not valid. This is often true in wireless networking where variable conditions can disrupt the transmission path with some regularity. DTN adds network-layer support to deal with such disruptions (e.g., by providing in-network storage to buffer traffic during disruptions and by other methods).

[84] For example, the standard congestion control mechanism in the Internet, TCP, relies on inferring that dropped packets are a sign of congestion. With wireless, this is often a bad assumption. It is often the case that dropped packets are a sign of poor physical layer connectivity. Thus, optimal networking in wireless is more likely to require consideration of cross-layer issues. See (Lehr & Chapin, 2010).

cameras used for security monitoring or control. Much of this might only need to be transferred remotely in the event that something happens. For example, an alarm signals that a window is open in my vacation home, inducing me to review video from the day before to determine the cause.

The decoupling of wide area networking from local network management (a key potential of small cells) can help facilitate uncoordinated, edge-based innovation. Different local contexts (places, times, usage contexts)[85] may benefit from being able to better adapt small cell infrastructure to local needs based on local information and decision-making.

Enabling this future, however, will not come without challenges. First, enabling source-based routing or multihoming, by which end-users play a more direct role in selecting how traffic is routed end-to-end is likely to complicate end-to-end service management. If there are quality/reliability problems, how to figure out where the problem is and apportion responsibility? Second, providing more discretion to end-users might make it harder for network operators to provision and negotiate cost-saving deals. For example, an ISP's low-cost offer might be conditional on the user's traffic flowing across a particular route. A user who can bypass an ISPs routing choices might unbundle such offers and make them infeasible. A similar tactic might be employed by a malicious edge user seeking to inject malware or other harmful traffic into the network. An uncoordinated proliferation of heterogeneous edge-based decision-making could threaten the connectivity of the Internet if it lead to islands of local connectivity which lacked wide-area interoperability/interconnection options. These coordination problems are not new, and are a natural byproduct of decentralizing decision making and enabling more complex systems with additional degrees of freedom. Likewise, the Internet makes it easier for communication in both good and harmful cases (e.g., terrorists) to communicate.

Policymakers will be challenged by how to best take advantage of the potential small cells have for promoting competition and expanded end-user choice. The appropriate design of open and standardized interfaces, interoperability mechanisms, and modularized designs are likely to be important for this purpose.

3.3 Spectrum Management

The final implication and challenge we address here concerns what small cells imply for spectrum management. Briefly, we believe that the move to small cells tilts the balance from licensed toward unlicensed spectrum sharing models; and more generally, toward more dynamic spectrum access models.

Historically, cellular technologies have operated in licensed spectrum, while WiFi has operated in unlicensed spectrum. However, there is no fundamental reason why the technologies need to be limited to a particular regulatory framework, although there are costs associated with transitioning a technology to a new

[85] Mobility enables more granular resource assignment, which may be in terms of space (smaller cells), time (dynamically resources can be directed to different uses over time), and context (any other dimension such as security or trust regime).

regulatory regime (e.g., modifications/additions to standards, new business models, and potentially, new regulatory frameworks). (Hazlett, 2001) noted that the choice of technology does not map uniquely to particular regulatory regimes.

Today, work is underway to explore LTE's operation in Unlicensed spectrum (LTE-U).[86] Similarly, new regulatory frameworks for unlicensed use (at 3.5GHz and 5GHz in the U.S.)[87] are shifting the model for unlicensed to enable greater coordination of base-station usage by unlicensed devices; and prospects for expanded services for WiFi-based broadband services by (traditionally) wired broadband providers raise the potential for wide-area mobile BB coverage that addresses most (potentially all) of the functional needs currently met by cellular providers (see discussion above).

Moreover, as noted above, the two technologies are more nearly substitutes when viewed within the context of small cell architectures. A key original (and still important) justification for exclusive licensing of cellular spectrum was to support investment and management of wide-area mobile network infrastructure. For cellular providers to be willing to undertake the significant investment commitments associated with deploying (near) ubiquitous coverage mobile networks capable of supporting high-speed mobility, those network operators needed to be assured of spectrum availability over their wide-area coverage. And because those assets would be in place for many years, they needed long term protection. And, finally, because the technologies used to deploy mobile networks were tightly coupled to specific frequencies, the cellular operators needed to feel secure not only in the protected quantity (MHz) of spectrum resources they had available over their coverage areas, but also that those resources were in specific and pre-determined frequencies.

With the movement to small cells, the growth in traffic (and cost-driver for capacity) shifting to asynchronous/asymmetric data flows (and away from real-time communication services like voice or SMS), and the transition to LTE (with greater support for IP data plane services and spectrum agility/flexibility in the radio access network), this original justification is reduced.

When it comes to small cell deployment, other factors begin to loom larger. For example, site acquisition, preparation, and management for antenna/base station sites represents a large and significant fixed cost for macro-cellular deployments. Each of the far fewer macrocell sites is quite expensive (on order of $100k or more) and, once sited, re-locating/deploying new cell sites takes significant time and additional expense. Deploying small cells represents a fundamentally different

[86] For example, see Qualcomm's discussion of the benefits of enabling LTE to operate in unlicensed spectrum (http://www.qualcomm.com/solutions/wireless-networks/technologies/lte-unlicensed), or "Evolution of LTE-Advanced Carrier Aggregation," Unwired Insight, March 2014, available at: http://www.unwiredinsight.com/2014/lte-carrier-aggregation-evolution.

[87] See 5GHz proceeding (http://www.fcc.gov/document/fcc-increases-5ghz-spectrum-wi-fi-other-unlicensed-uses) and 3.5GHz proceeding (http://transition.fcc.gov/Daily_Releases/Daily_Business/2014/db0425/FCC-14-49A1.pdf). For further discussion of these, see CFP Spectrum (2014), available at: http://cfp.mit.edu/publications/CFP_Papers/CFP Spectrum Sharing Paper 2014.pdf.

and significantly lower cost per cell site, although aggregate total infrastructure investment is likely higher with small cell deployments.[88]

With small cells, and especially with small cells operating in unlicensed spectrum,[89] the share of total costs represented by such considerations as local siting, backhaul, and base station management are likely to be higher and control of small cells is likely to be more dependent on "local" information in precisely the ways in which unlicensed spectrum access was argued to be more suitable for local, limited range (power) uses. Traditionally, and still today, unlicensed usage is restricted to short range (low power) usage to facilitate interference management. In a local area, only a relatively small number of users are likely to be impacted by shared wireless usage and interference management is more easily coordinated informally if the group doing the coordination is small. That is, when locating a small cell in my home, I am the best person to decide where to put my microwave (if WiFi) or where I want my small cell to be located for optimal coverage (dead spots where it matters for my usage). When locating small cells in a building (e.g., in the lobby, near elevators or in office suites), the service provider or tenant may need to negotiate with the building owner about where the cells may be sited, how they may be powered, and how connected for backhaul to in-building wiring. The rights and restrictions on access may differ by local jurisdiction (type of building/location, town/state, or user), engaging many more layers of potential decision-making authority and regulations than just spectrum management regulators. Thus, while the technology, *per se*, may not be biased in favor of either licensed or unlicensed spectrum, the shift to smaller cell architectures would seem to favor unlicensed spectrum.

On the other side, and still largely unknown, the costs of managing a much larger number of small cells across heterogeneous deployment scenarios (mixed technologies, ownership, and business models for interconnection) may create a growing need for wide-area coordination. Ceteris paribus, this would tend to favor the cellular service provider business model and potentially their bias for licensed spectrum resources. Moreover, for the foreseeable future, supporting high-speed mobility will require high-speed base station hand-offs of the sort that cellular providers have excelled at, and have relied on licensed (protected) spectrum access to provide. Finally, tighter coordination of the base stations to manage spectrum interference while supporting higher rates of utilization (narrower guard bands) [90] may also increase the relative value of more centralized management of spectrum resources (and hence, favor the "licensed" model).

[88] Emphasis on "total" investment, because to extent a cellular provider is able to shift investment to the end-user (who purchases/leases the small cell base station) and local backhaul provider (fixed broadband), the investment by the cellular provider might be lower. (Also, investment requirements may be lower because of technical advances that deliver "Moore's Law" like cost savings in deploying both macro and smaller cell wireless networks.)

[89] Key here is that "unlicensed" spectrum is less valuable than "licensed " spectrum to the user since it lacks interference protection rights granted to the latter. (Note, although the individual user might regard unlicensed as a less valuable/less expensive resource, this does not mean that it is less valuable in aggregate.)

[90] In the absence of base station coordination, additional spectrum resources (in frequency, time, geo-space, or direction) need to be reserved to manage interference. (Andrews et al., 2015)

Figure 6 provides a summary of some of the key differences between the legacy licensed and unlicensed spectrum models.

	Licensed	Unlicensed
Examples	Cellular, broadcast TV	WiFi, cordless phones
Coverage (power)	Wide-area (high)	Local (low)
Interference protection	Legal right (strong)	No legal right (weak)
Spectral utilization	High (cooperative)	Low (uncooperative)
Management	Centralized (Licensee)	Decenralized/Distributed
Barrier entry/use	High	Low
Cost	High (to acquire) Asymmetric opportunity costs for users	Free (not really – congestion and uncertainty are costs)

Figure 6: Comparison of Licensed and Unlicensed Legacy Models

From this it is clear that much of the traditional justification for exclusive licensed spectrum for mobile broadband has been weakened. With the transition to frequency agile radios and new wireless architectures like LTE, the services, radios, and frequencies are becoming unbundled. Increasingly, the radio infrastructure and the frequencies are no longer co-specailized assets and the possibility that these might be allocated separately (in time, location) is becoming feasible. Indeed, the FCC's proposed approach in the Incentive Auctions[91] and for allocating licenses in the 3.5GHz band is to allocate a bandwidth for each license location, but not assign specific frequencies. This is like buying movie ticket that guarantees you a seat in the theater, but without a specific seat assignment.

The shift to small cells and more dynamic radios helps enable more decentralized and distributed spectrum management. The technologies of cognitive radios, smart infrastructure, and small cells make it feasible to manage and direct resources locally with finer granularity. New ownership models (relying on end-user ownership and deployment) and other complementary adaptations (such as multi-homing and wired/wireless convergence) reinforce this trend.

In the future, the value of interference protection will be both more and less. On the one hand, the move to smaller cells ought to facilitate the reduction in artificial spectrum scarcity by unlocking the potential to share existing resources more intensively. Of course, this might result in sufficient growth in wireless services of all types, that spectrum will become really (as opposed to just artificially) scarce. However, the move to smaller cells does offer a scalable way to address that challenge – just increase the extent of spatial reuse. Additionally, with an open and flexible small cell infrastructure, the potential to share small cells to implement network MIMO or other capacity-expanding technologies will expand. On the other hand, the need to coordinate usage among a larger number of small cells may render the coordination challenge worse. This may increase the aggregate benefits of managing interference, while at the same time rendering the value protection of

[91] For incentive auctions plans, see https://prodnet.www.neca.org/publicationsdocs/wwpdf/fcc1450.pdf; for 3.5GHz proceeding see Note 87 *supra*.

rights to any particular frequency in any location less valuable as usage shifts more dynamically over time, space, and context.

This would seem to argue in favor of moving toward a Spectrum Access System (SAS) such as was discussed in PCAST (2012) and is under development in the context of the FCC's 3.5GHz proceeding. The SAS is anticipated to be comprised of multiple components, with databases of spectrum usage rights at the core. When combined with sensing and possibly other mechanisms (e.g., control pilot channels), an ambitious vision of the SAS anticipates it providing a way to manage multiple spectrum bands dynamically for multiple tiers of usage rights.[92] With a sufficiently complex architecture, the SAS may evolve into the spectrum control plane, providing a mechanism for aggregating data on all aspects of the spectral environment (terrain details, regulatory rules, and past/current usage) on a local level. Arguably, today's current regime already does this but in a highly inflexible and static way. The goal is to make this much more dynamic and flexible so that spectrum resources can be better matched, on a more granular basis, to meet the needs of all kinds of wireless services. This is likely to include a mix of users with varying degrees of interference protection rights, ranging from strong (and presumably, therefore, more costly) interference protection rights to unlicensed users. The small cell infrastructure that emerges will help shape the kind of SAS that is needed and likely to emerge.

4 Conclusions and future directions

In this paper, we explained why the growth of mobile broadband and wireless services of all kinds is pushing towards wider adoption of small cell architectures for wireless. This trend has important implications for the mobile broadband, and indeed, the entire wireless ecosystem. The change may be as profound as the move from computing environments dominated by mainframes to the world of PCs, and now post-PC mobile devices such as smart-phones, tablets, and the Internet of Things.[93] Whether this will happen and what it may mean for the Internet industry value chain is uncertain and depends on how wireless technologies, markets, and policies co-evolve.

To understand this better, we considered the two principal ecosystems that are the prime candidates for the small cell future: the WiFi-family of technologies and the 3G/4G LTE cellular family of technologies. These were developed to address quite different market contexts, but over time, the ecosystems have converged such that the potential for them to be both substitutes and complements is much greater.

[92] For example, the 3.5GHz SAS is expected to identify by location and by frequency, which spectrum is available for use by incumbents, priority access licensees, and general authorized access (i.e., unlicensed) users. Precisely what data is to be included, who has access to the data, and what role the SAS will play in actively enforcing the dynamic sharing regime is still under discussion.

[93] The Internet of Things (IoT) refers to the vision of a world where computing/networking intelligence (principally, sensors) is embedded in all kinds of things so that potentially anything and everything could be connected. For several visions of IoT, see Mckinsey & Co., http://www.mckinsey.com/insights/high_tech_telecoms_internet/the_internet_of_things; Microsoft, http://www.microsoft.com/windowsembedded/en-us/internet-of-things.aspx; or, IBM http://www.ibm.com/smarterplanet/us/en/overview/article/iot_video.html.

In the race to build small cells, WiFi has a significant lead and many compelling advantages over the femtocell (cellular) approach. Were we forced to choose a likely winner, we would choose WiFi. However, we expect that the future will actually be more likely to involve hybrid solutions, and evidence of this is clear in emerging business models by both incumbent mobile network operators and by new entrants (which include fixed broadband providers that are expanding their wireless offerings). Both technologies continue to evolve in ways that further blur the competitive advantages of the two technologies: WiFi-like small cell networks have the potential to support wide-area coverage; while LTE-like small cells could match the commoditized economics of WiFi-deployments. In any case, neither WiFi (802.11ac and beyond) nor LTE (Release 12+) comprise the universe of possible future technical architectures for small cells.

Moreover, as we increasingly move toward software radios, we can expect that future small cells will include multiple radios (potentially, loadable and modifiable on the fly). This suggests that some important areas to consider for future research are how to design modular small cell components (power supplies, I/O port configurations, antenna elements) that could be integrated with software radio designs to allow more flexible, and ideally, user-controllable small cells.

In addition to discussing the technical architectures for small cells, we also considered three implications for the mobile broadband ecosystem:

- Small cells drive mobile-fixed convergence.

This will expand opportunities for wireless-enabled Internet growth (mobile broadband, IoT, smart everything, etc.), and will also alter the competitive dynamic between fixed and mobile broadband access providers. How this evolves will depend significantly on the industry structure (e.g., mergers and acquisition, strategic alliances) and regulatory policies (e.g., interconnection and open access regulatory frameworks). A key determinant of what happens is likely to hinge on the question of how backhaul is provided. Further research on small cell backhaul options is needed.

- Small cells have the potential to empower end-users, and in so doing, may provide a new vector for competition in access networks.

The shift to small cells that are most-typically located on customer premises engage small users more directly in the end-to-end path, blurring the boundary between operator and customer networks. This opens up new options for shifting responsibility for investment, operating costs, and control. Granting greater control to end-users and enabling small cells with richer options for wireless connectivity expands options for end-user/community-based networking. Additional research on how community backhaul solutions might be integrated with user-deployed small cells to provision last-mile alternatives would be helpful in exploring the challenges of empowering end-user controlled networking.

- Small cells facilitate more dynamic spectrum sharing models

Small cells tilt the balance in favor of unlicensed (or lightly-licensed) spectrum management of the sort that is anticipated by the FCC in its 3.5GHz proceeding. A central component of this model is the development of a Spectrum Access System (SAS). The SAS has the potential to evolve into the policy control plane for spectrum management. Virtually all aspects of the SAS design are under discussion. We need to consider how to design the SAS so as to best facilitate the emergence of a small cell ecosystem that is flexible and open to innovation and competition. This implies a SAS that supports sharing among multiple usage tiers, including unlicensed.

Small cells will play a critical role in realizing the future for seamless broadband mobility. We are still in the early stages of this transition, but the future potential is large. The technology makes it possible to choose many paths. This paper provides our initial efforts in mapping and trying to understand possible paths to the future, but we have many more questions than answers.

5 References

Andrews, J. G., Claussen, H., Dohler, M., Rangan, S., & Reed, M. C. (2015). Femtocells : Past , Present , and Future, *30*(3), 497–508.

Bennis, M., Simsenk, M., Czylwik, A., Saad, W., Valentin, S., & Debbah, M. (2013). When Cellular Meets WiFi in Wireless Small Cell Networks. *IEEE Communications Magazine*, (June), 44–50.

Brodkin, J. (2013). 23Mbps down, 44 up: A tech insider's view from the Super Bowl. *Ars Technica*. Retrieved from http://arstechnica.com/information-technology/2013/02/23mbps-down-44-up-a-tech-insiders-view-from-the-super-bowl/

Chandrasekhar, V., & Andrews, J. G. (2008). Femtocell Networks : A Survey, (September), 59–67.

CFP Broadband (2006), "A Vision of Personal Broadband," a white paper by the MIT Communications Futures Program Broadband Working Group, available at: http://cfp.mit.edu/docs/vision-pbb-jan2006.pdf.

CFP Mobile (2014), "Mobile Broadband: toward a sustainable ecosystem," a white paper by the MIT Communications Futures Program Mobile Broadband Working Group, available at: http://cfp.mit.edu/publications/CFP_Papers/CFP%20Mobile%20Broadband%20White%20Paper%20May%202014.pdf.

CFP Spectrum (2014), "Toward More Efficient Spectrum Management: New Models for Protected Shared Access," a white paper by the MIT Communications Futures Program Spectrum Working Group (CFP Spectrum), available at: http://cfp.mit.edu/publications/CFP_Papers/CFP Spectrum Sharing Paper 2014.pdf.

Chapin, J. M., & Lehr, W. H. (2011). Mobile Broadband Growth , Spectrum Scarcity , and Sustainable Competition. In *TPRC* (pp. 1–36).

Domingo, A., & Lehr, W. (2013). Will broadband pricing support 1Gbps services? In *24th European Regional Conference of the International Telecommunication Society*.

Ghosh, A., Mangalvedhe, N., Ratasuk, R., Mondal, B., Cudak, M., Visotsky, E., … Novlan, T. D. (2012). Heterogeneous Cellular Networks : From Theory to Practice. *IEEE Communications Magazine*, (June), 54–64.

Haenggi, M., & Ganti, R. K. (2008). Interference in Large Wireless Networks. *Foundations and Trends in Networking*, *3*(2), 127–248. doi:10.1561/1300000015

Hazlett, T. W. (2001). *The Wireless Craze, The Unlimited Bandwidth Myth, The Spectrum Auction Faux Pas, and the Punchline to Ronald Coase's "Big Joke": An Essay on Airwave Allocation Policy* (Vol. 14). Retrieved from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=286932

Informa Telecoms & Media. (2013). *Small Cell Market Status* (p. 24).

Intel. (2011). *Rethinking the Small Cell Business Model*. *Case Study*.

Katz, R. (2014). *ASSESSMENT OF THE ECONOMIC VALUE OF UNLICENSED SPECTRUM IN THE UNITED STATES*. Retrieved from http://www.wififorward.org/wp-content/uploads/2014/01/Value-of-Unlicensed-Spectrum-to-the-US-Economy-Full-Report.pdf

Kishore, S., Greenstein, L. J., Fellow, L., Poor, H. V., & Schwartz, S. C. (2005). Soft Handoff and Uplink Capacity in a Two-Tier CDMA System. *IEEE Transactions on Wireless Communications*, *4*(4), 1297–1301.

Lehr, W. and L. W. McKnight (2003) "Wireless Internet Access: 3G vs. WiFi?" Telecommunications Policy, 27(5-6), 351-70.

Lehr, W. (2009), "Mobile Broadband and Implications for Broadband Competition and Adoption," a white paper prepared on behalf of Broadband for America, November 2009, available at: http://people.csail.mit.edu/wlehr/Lehr-Papers_files/LehrMobileandBroadbandCompetition RELEASED Nov 22 2010.pdf.

Lehr, William H. and John M. Chapin (2010) "On the convergence of wired and wireless access network architectures," Information Economics and Policy, 22.1 (2010): 33-41.

Marcus, J. S., & Burns, J. (2013). *Study on Impact of traffic off-loading and related technological trends on the demand for wireless broadband spectrum* (p. 152). doi:10.2759/19531

Mobidia My Data. (2012). *Mobidia*.

Vries, J. P. De, Simic, L., Achtzehn, A., Petrova, M., & Mähönen, P. (2013). The Emperor has no Problem : Is Wi-Fi spectrum really congested ? (pp. 1–34).