Rethinking Wireless Broadband Platforms

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

Abstract

A platform network is an integrated high-capacity general-purpose network. The platform model dominates the market for wired broadband services, reducing the amount of infrastructure required and enabling rapid deployment of new services. We argue that wireless broadband is fundamentally different from wired broadband in ways that limit the benefits of platform networks. Instead, for both technical and economic reasons, wireless broadband services have developed as converged aggregations of heterogeneous specialized wireless networks. This design is optimal given that the primary constraint on broadband services is capacity due to limited spectrum allocations and other effects. In the following, we explain why it is a mistake to view wireless broadband services as embodying or growing toward the platform network model. We advocate for an alternative hybrid wireless broadband model to better understand and regulate wireless broadband systems.

1. Introduction

The evolution of electronic communication networks has been driven, in part, by technical innovations that have enabled network operators to expand the range of services they offer. Single-purpose "silo" networks have evolved over time toward "broadband platform" networks capable of supporting mixed/multimedia bundles of services. This is the process of network convergence that is reflected in the architectures of next generation networks being deployed by service providers around the globe.[3]

While the details of the new broadband networks vary from carrier to carrier, they share many common features. These networks are characterized by physical layer infrastructure that is fiber-optic intensive and thus supports high capacity across all network cross-sections. The improvement from prior networks is especially large in last-mile access links. Moreover, increasingly these networks are based on IP packet-switched transport/network layers enabling support for services with diverse traffic requirements over a shared network infrastructure. The infrastructure is normally, at least in the backbone, largely agnostic to traffic type (i.e., "a bit is a bit"). This evolution enables operators to offer a cost-effective bundle of services covering most user needs from a single network.

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[1] wlehr@mit.edu

[2] jchapin@csail.mit.edu

[3] See for example, OECD (2007) and Ofcom (2008).

1.1. Services provided by current broadband platforms

The core services provided by current broadband platforms are telephony, television, and data. Data consists of email, web browsing, and chat. Table 1 compares the requirements of handling these core services on a packet-switched data network. A network that seeks to serve all three traffic types must meet the most stringent requirements of each. It must offer high data rate, low latency, low jitter, low Bit Error Rate (BER), any-to-any connectivity, and symmetric (upstream/downstream) data rates.[4]

Interactive and mixed-media offerings are also becoming increasingly important. These include social networking (FaceBook), hosted services (WebEX, software-as-a-service), remote monitoring (healthcare), and gaming. Each of these new services have different traffic requirements (latency/jitter/BER tolerance, burstiness/bandwidth) that impose additional constraints on the quality of the underlying infrastructure and shape the aggregate traffic that the network must handle.

Table 1. Traffic Characteristics of Current Core Services for Broadband Platforms

	Audio (Telephony)	Video (Television)	Data (Internet)
Data rate (bandwidth)	**< 100Kbps** Traditional voice was encoded in 64Kbps channels, but can be compressed to under 10Kbps Higher quality audio may use higher bit rates.	**1 Mbps** Traditional TV (PAL/NTSC) can be encoded in a 1Mbps stream HDTV requires roughly 10Mbps. Higher quality or multiple streams (multiple TVs in the house) require higher rates.	**Variable** Dial-up access may be supported at <64Kbps. This allows email and limited Web access. Higher data rates support faster downloads of larger files (whether email, music/video, or presentations) and greater interactivity (lower latency/jitter) Data traffic is inherently variable data rate. Various applications have widely divergent tolerances for reliability, BERs, and other traffic characteristics.
Connectivity mode	**One-to-one** Traditional telephony supports realtime calling between single origination and termination end-points. Voice mail, conferencing	**One-to-many** Traditional TV is broadcast. PayTV, narrowcasting, and multiprovider content delivery change the model.	**Any-to-any** Data transport may have any type of connectivity mode.

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[4] As long as the interactive services (legacy voice/data) are narrower band than the broadcast services (e.g., TV), asymmetric data rates are acceptable (downstream larger than upstream). With growth of videoconferencing or user-originated content, the need shifts toward symmetric data rates.

	services, 800- services, etc. expand range of connectivity requirements		
Symmetric traffic	**Symmetric** Telephony is inherently symmetric with equivalent data rates in both upstream and downstream directions.	**Broadcast** Traditional TV is one-way, downstream Introducing interactivity raises need for upstream connectivity, but still leaves traffic highly asymmetric Other forms of video such as video conferencing, user-originated content increase symmetric traffic.	**Mixed, Asymmetric** Traditional Internet was asymmetric with more traffic flowing downstream The rise of p2p, user-originated content, and interactive services have moved traffic toward a more symmetric profile.
Latency/jitter sensitivity (Latency=delay, Jitter=variation in delay)	**Intolerant**	**Mixed** With exception of realtime TV, broadcast video is relatively tolerant to delay and jitter.	**Tolerant** Traditional Internet traffic (email, web browsing) was "best effort" and both network and users were accustomed to delay and jitter.

1.2. Reasons for dominance of broadband platform networks

Platform networks have grown to dominate telecommunications because they virtualize the underlying physical infrastructure. There is no longer a one-to-one mapping between network and end-user service as existed in the legacy silo-based, single-purpose networks. Virtualization provides significant economic benefits in multiple ways.

Sharing: The cost to provide any given service is reduced because the infrastructure is shared with multiple services. For example, adding new voice circuits as Voice-over-Internet-Protocol (VoIP) on top of a high-speed data network is substantially cheaper than providing an incremental dedicated copper twisted-pair line per circuit. This occurs in wired networks because the marginal cost of deploying and operating a given amount of wired capacity declines with increasing total capacity over a very wide range. At the upper extreme, it is only slightly more expensive to deploy multiple optical fibers in a conduit than to deploy a single fiber, providing massive capacity headroom at minimal incremental cost.

Virtualization also reduces the cost of provisioning for peak load. If service loads vary independently, or if some traffic is latency-tolerant and can be delayed when the network is temporarily loaded, sharing of common infrastructure by multiple services increases average utilization without hurting performance. Indeed, the increased amount of peak capacity available to each individual service when infrastructure is shared means that end users get better quality of service than they would from a collection of non-virtualized silo-based networks.

Scale: The cost of the underlying network resources is reduced by volume effects. With virtualization, different services make use of commoditized or standardized components and benefit from increased scale and learning economies. This translates into lower capital costs for equipment and lower operating costs (e.g., because of deeper markets for skilled personnel).

Virtualization of network resources to support multiple services allows network architects to "have their cake and eat it too." Namely, virtualization provides the benefits of scale and scope economies associated with standardization and commoditization of lower level components, while avoiding the loss of flexibility that is usually the price of standardization.

Flexibility: Virtualization gives the service provider the ability to flexibly adapt services and network capacity. The provider need not decide the resource allocation among individual services before network deployment. Fine-grained resource reallocation in response to rapidly changing loads is more easily supported over a shared platform network than among independent specialized networks.

Once the network has been deployed, new services can be added quickly and cheaply, meeting user demands more efficiently, because the underlying infrastructure need not be changed to deploy new services. For example, deployment of YouTube—a two-way video sharing service that differs significantly from the preexisting broadcast-only video service—did not require investment by access network operators like Verizon or Comcast.

The economic advantages of the broadband platform model have proven so significant for wired networks that it has come to dominate all other approaches. Even in cases where the end user purchases a specific service, for example cable TV or a telephone line, providers today support that service using an underlying broadband platform.

1.3. Wireless networks and broadband platforms

The compelling advantages and dominance of broadband platforms in the wired space has led to a widely accepted, unexamined assumption that wireless networks will also evolve toward broadband platforms.[5] After all, wireless networks appear at a superficial level to be following the same trajectory that wired networks did, only with a lag. Were this analogy to hold across the various important technical and economic factors at play, one might conclude that regulatory policy should aspire toward technical and service neutrality that does not distinguish between wired and wireless broadband platforms.

In this paper, we explain why closer inspection reveals the trajectories for wired and wireless evolution to be fundamentally different. We explore the fundamental technical, economic, and policy differences that make the optimal endpoint for wireless broadband networks different from the broadband platform model that has been so successful for wired networks.

Our perspective strives to be international. We seek to emphasize the fundamental aspects of wired and wireless networks rather than issues specific to particular markets and regulatory

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[5] Although what is meant by a broadband platform more generally, or a wireless broadband platform more specifically is often not explicitly defined, the general presumption that wireless will evolve toward a platform model (whether as a standalone wireless network or integrated into a single mixed wireline/wireless network) is apparent in much of the policy and technical literature. See for example, WCAI (2007), NTIA (2008), Chen (1996), Hemmady, Maymir and Meyers (1994), or Ohmori, Yamao, and Nakajima (2000). Webb (2001) discusses the many options for technical evolution of broadband wireless access (BWA), and is noteworthy in highlighting how many different options based on very different technologies exist.

contexts. However, our examples reflect a US-centric bias due to the greater familiarity of the authors with U.S. markets and regulation.

As a brief introduction to our arguments, the root technical differences between wired and wireless are summarized in Table 2. This table is repeated and discussed in detail later in the paper (section 4).

Table 2: Persistent Key Differences in Wired v. Wireless Networking

	Wired	**Wireless**
Capacity	Abundant	Scarce
Topology	Point-to-point	Broadcast
Reliability	Reliable	Unreliable
Mobility	Fixed	Mobile
Layering	Effective	Inefficient

These differences affect the fundamental network design tradeoffs that make broadband platform networks desirable in the wired context. In particular, stringent capacity constraints facing wireless broadband networks drive designers away from general-purpose layered designs in which "a bit is a bit."

In addition to the technical differences, wireless networks were introduced for voice and evolved to support data access many years later than the corresponding evolution of wired networks. The time lag coupled with inherently different economics led to different regulatory models for the two network types. This regulatory history has shaped the current competitive playing field with significant implications for future growth trajectories.

We analyze all these factors to explain why the broadband platform model is not the right model for current or future wireless broadband services. Having drawn this distinction, we describe an alternate model that is a better description of current wireless broadband services and a better guide for future planning and regulation. The alternate model is called *hybrid wireless broadband.* A full explanation of our views on the hybrid model and suggestions for its public policy implications are reserved for a separate, companion paper.

1.4. Organization

We begin in Section 2 by defining the term "broadband platform" more precisely. In Section 3 we review the history and current debates surrounding regulation of broadband services, insofar as this affects the broadband platform model. In Section 4, we examine the core differences between wired and wireless networking that were summarized in Table 2. In Section 5, we use this understanding of fundamental differences to make the case against wireless broadband platforms. Section 6 examines the communications policy implications of divergent evolutionary paths for wired and wireless networks. Finally, Section 7 summarizes our conclusions and introduces the more likely evolutionary path toward hybrid wireless broadband networks.

2. Broadband platforms

In other contexts or used colloquially, "broadband platform" may have multiple meanings. For example, the term "broadband" is used to refer to Internet access services, or more generically, to high data rate services.[6] In the spectrum management community, "broadband" refers to a large contiguous spectrum allocation. "Platform" may be used to describe any networking technology that delivers one or more services (as in, "telephone service may be supported over IP, circuit-switched, or wireless *platforms*"). Or, "platform" may be intended to emphasize the ability of a network to deliver multiple services (as in "3G and Wi-Fi offer alternative *broadband platforms* for accessing mobile voice and data services"). "Platform competition" may be used to refer to competition between facilities-based network operators (as in "3G, cable television networks, and telephone networks are providing Internet access *platform competition*"). Finally, in economics, the notion of a platform (as in "the Internet is a *platform*") may be used to explore multi-sided markets.[7]

In this paper, our use of the term "broadband platform" is quite specific. We use the term as short-hand for a description of the generalized architecture and service model that we see wired networks evolving toward. We define a "broadband platform" as an *integrated high-capacity general-purpose network*. The following sections define each of the terms in this definition more precisely.

2.1. Network

A broadband platform is an integrated high-capacity general-purpose *network*.

Our focus is on the resources providing data communications. In technical terms, we use "network" to refer to a single system under common control providing at least Layers 1 through 3 of the OSI stack (physical, data link, and network layers). In economic and policy terms, we focus on facilities-based providers. The arguments in this paper do not apply to the various entities such as VPNs, value-added service providers, and resellers that operate over the top once underlying data communications is available from a facilities-based provider.

Moreover, our focus is on access networks offering communications services to mass-market consumers; and exclude from consideration backbone networks and niche access networks (those supporting the specialized requirements of small numbers of customers). The issues surrounding these latter network types are quite different from mass-market access networks.

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[6] See Lehr, Smith-Grieco, and Woo (2008) for discussion of varying definitions of broadband Internet access. Often what is meant by "high data rate" is not specified or varies by context.

[7] For example, the Internet may be modeled as a two-sided network connecting content providers and consumers. See, for example, Rochet & Tirole (2004) or Economides (2007).

Our analysis is meant to include networks such as those operated by AT&T, BT, Clearwire, Comcast, Sprint-Nextel, T-Mobile, and Telefonica.[8] It excludes networks such as those operated by Akamai, Vonage, Boingo Wireless, Level 3 Communications and Virgin Mobile.[9]

2.2. Integrated

A broadband platform is an *integrated* high-capacity general-purpose network.

A network is integrated when different services (traffic types) share common communications resources at Layer 3 and below. From another perspective, a broadband platform virtualizes an underlying set of common resources to support multiple services.

Our focus on integrated networks excludes service bundling at the retail level. Retail-level bundling creates consumer perception of a converged service, for example by offering a single bill, single sign up, single point of contact for maintenance issues, and so on. However the underlying networks are not integrated: there may be coax for broadcast television, copper twisted-pair for fixed telephony, and GSM or CDMA for mobile telephony. Such a retail-level converged bundle is not a broadband platform.[10]

The key resource that identifies an integrated network is a frequency range or noncontiguous set of frequency ranges. These frequencies correspond to an integrated network if they meet two tests: (1) they are managed by a single entity; and (2) their collective data communications capacity can be dynamically reallocated across multiple services without changing the underlying layer 1 through 3 communications standards. This definition applies whether the frequencies propagate over the air in wireless networks or in a cable or fiber in wired networks.

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[8] Clearwire is seeking to provide wireless broadband services via WiMAX. Their business plan includes both mobile services and fixed services. While recognizing the potential for fixed services, we regard this as a niche application of "wireless" and focus our discussion on the mobile service. Fixed wireless broadband is most attractive in rural markets (where wired infrastructure is cost prohibitive) or as an over-build technology in wired markets (where it may enable economic viability for new entrants at lower market share penetration rates). When used as a fixed service, however, WiMAX cannot match the per-user capacity of a fiber based wired network and cannot easily match the areal capacity of even a copper twisted pair wired network. When used in mobile mode, WiMAX is just one of the many possible 4G technologies we consider in our general discussion of the differences between wired and wireless networking.

[9] Akamai and Vonage both operate networks that exist "on top of" the Internet. Although each owns and manages server facilities that they call a network, they deliver services on top of the data communications platform provided by the access network operators. Boingo Wireless aggregates access to 802.11 networks from multiple providers but does not own or operate layers 3 and below of an access network. Level 3 does not provide mass market access services and Virgin Mobile is not a facilities-based provider.

[10] The opportunity to offer wireless services a la carte or as a retail bundle that competes with wired services in the marketplace is likely to be an important source of intermodal competition (e.g., consumers potentially switching to 3G offerings instead of buying fixed line telephone and Internet broadband access services). As we explain further below, such competition reenforces our arguments for why wireless is architecturally less likely to evolve toward a platform architecture.

We focus on the frequency range or ranges rather than on equipment or cables as our definition of an integrated network. Equipment or cables can be shared by multiple independent networks through various unbundling arrangements. Moreover, in wireless networks, multiple transmitters and antennas at the base station sites may be required if the frequency ranges assigned to the network are discontiguous (e.g. 800 MHz and 1900 MHz bands). Even though separate equipment is used, these frequency ranges may be operationally part of an integrated network if their combined communications capacity is managed by a single entity and any part of that capacity may be allocated to any of the supported services.

There is not one set of frequencies that identifies an integrated network across its entire geographic footprint. Because of multiplexing in wired distribution networks and geographically varying spectrum licenses for wireless networks, the set of frequency ranges corresponding to the network varies from location to location.

2.3. High capacity

A broadband platform is an integrated *high-capacity* general-purpose network.

A network is high capacity if it provides data rates sufficient for mixed media services (telephony, data, video, gaming and other services). This means that the network is capable of supporting the most stringent minimum requirements of any individual service. The service with highest capacity demand in common use today is Internet video. Today, video on the Internet is normally streamed at a resolution and frame rate requiring 600–700 kilobits per second (examples include CNN and YouTube). As a result broadband is considered to require roughly 1 megabit per second of downlink capacity per active user. Uplink rates that are 20-25% of downlink rates are judged acceptable in current practice.

As consumer expectations grow, for example to demand HD quality video and to support multiple users within the home simultaneously, the lowest data rate considered to be broadband will rise. On the other hand, if a substantial fraction of consumers switch to mobile data devices from fixed PCs or nomadic laptops, the drop in capability may cause application/content providers for mass-market-oriented services to limit their data rate expectations. Such convergence of the retail markets for wired and wireless broadband services may constrain the growth in the lowest data rate considered to be broadband.[11]

It may seem generous to call a 1 megabit per second connection a high-capacity network, when any consumer with fiber to the home has access to 10 or 20 megabits per second at a reasonable price. We selected this relaxed criterion because that is the provisioning of current wireless 3.5G networks. Theoretically, we are unaware of any fundamental reason why wireless access rates could not be substantially increased.[12] However, as a practical matter and given reasonable

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[11] Whether broadband services will continue to evolve toward ever faster data rates has important implications for retail service convergence and the evolution of competition between wired and wireless network operators. However, as we explain further in a companion paper ("Hybrid Wireless Broadband," forthcoming) this does not change the conclusion reached here that wireless networks are unlikely to evolve toward broadband platforms.

[12] Mechanisms for increasing wireless capacity include greater spatial reuse of spectrum (smaller cells, smart antennas) and advanced modulation techniques that increase the achieved bits/second/MHz.

forecasts of technical progress and likely costs, it seems reasonable to expect that data rates provided by wide-area mobile services will continue to substantially lag wired data rates as has historically been the case. Therefore any definition of a broadband platform that does not a priori exclude mobile wireless networks will have a capacity threshold that is low relative to contemporary wired network capacity.

2.4. General-purpose

A broadband platform is an integrated high-capacity *general-purpose* network.

A general-purpose network is one that supports a broad and extensible set of services or traffic types. From a technical perspective, this currently implies bidirectional support for Internet Protocol (IP) packet transport with sufficiently low latency and jitter for web surfing, compressed video, voice, and gaming.

Although a general-purpose network supports a broad set of services, it may have components or design features that optimize its performance for specific classes of traffic. These include asymmetric upstream and downstream data rates, traffic management/shaping, differentiated service offerings/tiering, or other ways of segmenting traffic and giving special handling to certain services. Admittedly there is a grey area here. At some level of optimization for specific services, the network should be considered a special-purpose network rather than a general-purpose network. However in actual practice, it is normally quite clear whether a network is designed to support a broad and extensible set of services or not, and therefore whether it is a candidate to be considered a broadband platform.

3. Regulation of broadband services

We now survey the history and trajectory of regulation of broadband services. Given space constraints, the discussion is limited to a brief review of this large and complex topic. We focus on issues that affect the applicability of the broadband platform model to wired and wireless networks.

3.1. Regulatory legacy of silo networks

Traditionally, wired networks were built specifically to support telephone and cable television services. The technical architectures of these networks were optimized to meet the very different requirements of the two services (see Table 3). With infrastructure specialized to serve narrow markets (from a network traffic perspective), it made sense for the entities that provided such infrastructure to be vertically integrated. Additionally, each of the silo networks could be managed with silo-based regulatory policies.

The focus of regulation of telephone providers was on ensuring universal and non-discriminatory access to basic telephone services. The focus of regulation of cable television providers was on ensuring non-discriminatory access to diverse television programming. Both regulatory models encompassed analogous but ultimately very different notions of service neutrality. The telephone providers were regulated as common carriers and the focus was on ensuring the technical quality and reach of basic telephony service. The service neutrality aspect of cable television regulation was focused on ensuring adequate programming diversity. In the U.S., cable television providers are explicitly not regulated as common carriers.[13]

Table 3: Silo-based Cable and Telephone Networks Compared		
	Cable Television	Telephone
Service description	Television channels (each 6MHz)	Point-to-point telephone calls (each 4KHz)
Network characteristics		
Physical medium	Coaxial cable	Twisted-pair copper wire
Network architecture	Broadcast, one-way	Narrowband circuit, 2-way
Frequency range	~1GHz	~1MHz
Regulation	Monopoly franchise, common carrier, universal access	Monopoly franchise, programming diversity

Both telephone and cable television access networks were initially built and deployed, in most markets, as sanctioned monopolies. This was justified, in part, by the belief that the deployment cost of wired infrastructure made it a natural monopoly. The monopoly franchise eased the economic burden of financing (essentially) ubiquitous wired infrastructure in local areas by reducing the threat to future cost recovery from competition. In the U.S., over 90% of homes were passed by POTS telephony facilities as early as 1970[14] and by coaxial cable television networks as early as 1990.[15]

3.2. Convergence and regulatory response

Over time, the pull of new market opportunities and the push of lower costs drove wired providers to expand the range of services they offered. Network enhancements (capacity

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[13] See, for example, *Fact Sheet: Cable Television Information Bulletin,* Federal Communications Commission, June 2000 (available at: http://www.fcc.gov/mb/facts/csgen.html).

[14] Telephone penetration reached 90.5% of homes in 1970, and 97.6% by 2000. (Since then, penetration has been decreasing). Homes passed exceeds penetration. See Table 16.2 in *Trends in Telephone Service*, Federal Communications Commission, August 2008.

[15] *Annual Assessment of the Status of Competition in the Market for the Delivery of Video Programming (Second Annual Report)*, Federal Communications Commission, FCC 95-491, December 11, 1995, Appendix B, Table 1. Cable television services passed 89.9% of homes in 1989 and 53.5% of households subscribed; by 1996, the households passed reached 96% and subscribership 65.2%.

expansion, digitalization, packet-switching) made it increasingly clear that legacy silo operators could offer services that competed with each other. The wired telephone and cable television network operators' network architectures also converged, toward IP-based broadband, along with their markets.

Convergence has forced policymakers around the globe to reassess silo based regulatory frameworks that differentiated between telecommunication and broadcasting services, or between telephone and cable television services. Policymakers were confronted with the challenge of how to treat new services (e.g., interactive television, broadband Internet access, basic telephone service offered by cable providers, or video dial tone offered by telephone providers) and how to alleviate the market distortions arising from asymmetric regulatory treatment as the silos morphed toward competing platforms.

Policymakers have adopted different models to address this challenge. In the U.S., where duopoly wired competition already existed in most markets, regulators pursued further deregulation in the hope that facilities-based market competition between broadband platform providers would be sufficiently robust to deliver good outcomes in terms of service availability and pricing. Evidence of intermodal platform competition (i.e., similar service offerings in the market being provided via different technologies) has helped justify the movement toward deregulation and toward further dismantling of legacy regulatory controls for telephone and cable television providers. The actual or prospective emergence of service offerings over other platforms such as 3G, broadband-over-power lines (BPL), satellite, or fixed wireless (e.g., WiMAX) provides additional hope that intermodal competition will render markets for all local access communication services effectively competitive.

In Europe and other markets where the coverage of duopoly wired networks is less extensive, regulators have preserved open access regulations for the incumbent monopoly facilities-provider of wired access infrastructure.[16] The goal of this approach is to enable intramodal competition to emerge over time via the growth of resellers (non-facility-based providers that provide retail-level competition) and new facilities-based providers that rely on the open access rules while they grow to the operational scale needed to compete with the established incumbents.

The difference in the European and U.S. approaches highlights the tension between promoting intermodal facilities-based competition or intramodal competition (whether facilities-based or

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[16] In Europe, incumbent telephone providers were required to offer wholesale access to competitors under two frameworks at regulated rates and terms. Under local loop unbundling (LLU) access, the incumbent is required to provide competitors with access services analogous to provision of a basic copper loop (e.g., to provide competing voice or DSL services). Under bitstream access, the incumbent is required to provide competitors with a Layer 3 IP packet transport service for access (e.g. for backhaul or to provide a higher data rate access service). Roughly similar open access and unbundling rules were imposed on U.S. incumbent telephone operators via the Unbundled Network Element (UNE) and Total Service Resale (TSR) requirements that were adopted in the Telecommunications Act of 1996 (TA96). In the U.S., the open access/unbundling rules have been substantially discarded in favor of further deregulation and reliance on facilities-based competition.

otherwise).[17] The pro-intermodal competition policies are intended to maximize incentives to invest in network facilities. In this context burdensome regulations, including open access regulations, are generally perceived to pose an impediment to investment.[18] In contrast, the European approach, which relies more heavily on open access regulation to promote the emergence of intramodal competition, is designed to lower entry barriers for new intramodal competitors by allowing them to use the facilities of the incumbent operator. Lower prices for regulated open access to the incumbent's platform may encourage growth in service offerings based on that platform, while deterring investment in alternate technologies.

3.3. Current issues for wired broadband services

There is a major broadband policy debate in the U.S. known as "network neutrality" that is focused on whether additional rules are needed to ensure open and non-discriminatory access for applications and content over broadband Internet services.[19] Pro-neutrality advocates argue that intermodal competition is not adequate to protect the openness of the Internet. Further they argue that preserving non-discriminatory and open broadband access will provide a platform for intramodal over-the-top competition, improving both innovation and competitive discipline. The incumbents argue that such rules will reduce their incentives to invest in intermodal facilities platforms and that the rules will impose costly constraints on their ability to manage their networks efficiently.

In Europe, network neutrality has been less of an issue because of the continued reliance on strong open access regulations. The focus in Europe has been on formulating appropriate regulatory models for so-called Next Generation Networks. In the European context, this terminology is generally interpreted to refer to the fiber-intensive wired networks operated by incumbent telephone network operators that are capable of delivering a tripartite bundle of television, telephone, and broadband Internet access services to home users.[20]

While the regulation of evolving wired broadband platforms has varied by country, the overall trend has been to move from franchise monopoly regulation toward increased reliance on

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[17] Speta (2004) criticizes the Telecommunications Act of 1996 for failing to adopt a coherent framework with respect to the desire to promote intramodal or intermodal competition.

[18] Economic theory is ambiguous on whether regulation or asymmetric regulation deters or provides additional incentives to invest in intermodal facilities. For example, symmetric regulation may impose costs on both platform providers that deter investment. Alternatively it may limit the ability of platform providers to differentiate their services, and thus ameliorate the intensity of commodity competition. More intense competition may expand or retard industry investment depending on the context (e.g., will demand grow faster with commodity platforms competing more aggressively on price or with differentiated platforms?). On the other hand, asymmetric regulatory burdens may deter investment by the incumbent who bears the regulatory costs, while encouraging investment by the intermodal competitor. Economists disagree on the implications of regulation for investment and the relative merits of intramodal or intermodal competition. See for example, Crandall & Aron (2008), Distaso *et al.* (2006), Waverman *et al.* (2007), Sidak *et al.* (2003), or Spiwak (2004) for discussion of these issues.

[19] See Lehr, Peha, and Wilkie (2007) for a collection of articles on the network neutrality debate in the U.S. and Europe.

[20] See for example, Pupillo and Amendola (2008) or OECD (2007).

competition. Going along with this, there has been a general preference in favor of greater symmetry in regulating intermodal platforms, and toward neutral regulation (i.e., service regulation that is agnostic to the underlying technology).

3.4. Historical regulation of wireless services

From the start of mobile wireless service in the 1980s, regulators took a much lighter and less intrusive approach to mobile provider interconnection and service regulation than had been adopted for wired services.[21] This was enabled by the common view that wireless services are not a natural monopoly.

First, wireless technology and the markets for wireless services evolved decades later than the corresponding technology and markets for wired networks. As a result, there was no initial pressure to provide universal access via wireless services. Market introduction of voice-only mobile systems occurred in the 1980s, by which time wired telephony was already ubiquitous. Mobile services evolved to provide broadband data with the deployment of 3G networks starting in 2000. At that point basic (aka dial-up) Internet access was universally available and even broadband Internet access was widely available via wired networks. Internet access was clearly much cheaper to offer through wired than through wireless technology in densely settled areas. Without the need to assure universal access, regulators did not need to establish a monopoly that could cross-subsidize unprofitable service to some consumers through higher (noncompetitive) rates charged to others.

Second, deployment of wireless networks does not require digging trenches down streets or opening conduits into buildings. This dramatically affects network build-out economics, making it cost-effective to provide service in an area even when that service is not a monopoly. It also reduces community resistance to the deployment of multiple overlapping networks.[22]

Since wireless was not viewed as a natural monopoly, regulators relied on promoting competition. This was achieved primarily through spectrum management policies which governed the allocation and assignment of spectrum access rights. Historically, the policy was one of parsimony: regulators allocated the minimum amount of spectrum per licensee to allow a specific service to be delivered. This enabled licensing multiple operators in each geographic region, at the cost of strongly limiting the maximum capacity achievable within any one wireless network.

In the U.S. and in a number of other countries, two mobile operator licenses with spectrum allocations were allocated in each market to enable duopoly competition from the start. Later on in the U.S., the PCS auctions in 1995 expanded the number of mobile operators in each market.

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[21] This is not to say that the overall regulatory burden was minimal. Traditional “command & control” spectrum management imposed strong service limits and technology-specific regulation on wireless service providers.

[22] Community resistance to the build-out of wireless networking has focused on the siting of base station antenna sites, expressed as conflicts with local zoning authorities. In most cases, tower sharing has enabled deployment of multiple overlapping networks, with no additional community challenges compared to a single wireless network.

Spectrum licensing was managed to promote facilities-based competition among multiple wireless providers.

In the U.S., mobile providers were also initially subject to open access regulation in the form of mandatory support for service resale. The primary motivation for such rules was to facilitate broad geographic coverage before provider-owned networks were fully built out. Over time, as the number of facilities-based providers increased and the mobile market matured, the open access obligations imposed on mobile providers were relaxed. In any case, mobile operators never faced the sort of intrusive regulatory oversight imposed on wired operators during the days of monopoly regulation, nor the sort of open access obligations placed on wired network operators by the Telecommunications Act of 1996.

In Europe, policymakers have been willing to impose more intrusive open access regulations on mobile providers than is the case in the U.S. European policymakers have mandated support for Mobile Virtual Network Operators (MVNOs) and have regulated mobile carrier roaming agreements. Regulation of roaming agreements is a form of open access regulation in that it establishes a wholesale market where one provider can acquire another's services to help support its own customers.

3.5. Toward regulatory neutrality

The issues surrounding regulatory neutrality are different in the case of wireless and wired networks.

For wireless networks, regulatory neutrality has two distinct aspects: service and technical neutrality. Service neutrality refers to the flexibility to offer different services in a frequency allocation. For example, in the U.S., licensees are allowed to offer data services in spectrum originally allocated for voice services. In Europe, license rules restricted the use of 2G spectrum to the provision of voice services (requiring operators who wished to offer 3G data services to bid for additional spectrum allocations).[23] In this sense, the U.S. approach was service neutral and the European was not.

Technical neutrality in spectrum management discussions refers to restrictions in spectrum licenses on the signals that may be transmitted in a given allocation. In the U.S., PCS licensees were allowed to choose the network technology used to implement 2G voice services. This is a technically neutral approach. In Europe and many other places, policymakers required 2G voice service licensees to use GSM technology. This is a non-technically neutral approach.

In truth, service and technical neutrality are closely related and there is an inherent tension between them. For example, some argue that service neutrality is helped by regulations that precisely define which services are permitted or prohibited in a given allocation. A precise definition of a service, however, usually requires some level of technical specification (e.g., the minimum acceptable latency or dynamic frequency range to be considered a real-time telephony

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[23] CDMA2000 technology exploits the flexibility to use existing 2G spectrum via a channel band plan that can be overlaid on 2G allocations. In contrast, the UMTS 3G architecture requires additional spectrum.

service). Such technical specifications imply technical constraints that are inherently non-neutral (impact different communication technologies differently).

The tension between the two goals is most apparent in wireless networking. For example, mixing different services in a wireless channel (service neutrality) may reduce overall channel capacity.[24] Thus, in order to maximize flexibility with respect to the technologies that may be used in a band (technical neutrality), it may be better to limit the range of services that are offered (service neutrality restricted).

As applied to wired networks, the distinction between service and technical neutrality is less clearly articulated. This is due, in part, to the fact that wired networking evolved in an earlier age with an inherently non-neutral silo-based regulatory framework. Thus, telephone and cable television networks offered a single service via a single technology. Line of business restrictions and rate regulations that specified the technical characteristics of the service and that restricted what investments would be allowed into the rate base jointly imposed service and technology restrictions on wired operators.

Over time, as intermodal competition emerged, the service and technical neutrality of regulations increased as part of the general move toward deregulation and platform competition discussed earlier. Efforts to improve regulatory neutrality focused on the elimination of asymmetric treatment for telephone and cable television providers, and between legacy (incumbent) and new (e.g., competitive local exchange carriers) operators.

There are active current debates surrounding further increases in service neutrality of wired network regulation. For example, a primary question is to what extent the regulations covering traditional copper local loop telephony (access charges, universal service obligations, etc.) should carry over to other telephony services. Both fixed line cable telephony and VoIP are potentially affected. Operators of these networks naturally argue that they provide a different service from traditional local loop telephony.

There are also current debates over technical neutrality. An interesting case concerns open access rules for broadband Internet services. Open access rules normally must be specific in their mandates, since the incumbent provider can be expected to exploit any flexibility to the detriment of competitors. The need for specific mandates inherently conflicts with technical neutrality.

For example, mandates requiring an incumbent operator to unbundle facilities at Layer 1 are quite different for copper telephone and coaxial television networks. With a copper local loop network, a common form of unbundling is to require the incumbent to offer access to naked copper pairs at the main distribution frame in the incumbent's central office. With a coaxial television network, there is no easily implementable close analogy.

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[24] The need to manage interference from unaffiliated signals in the communication channel is a first order problem in wireless networking. The knowledge of the character of unaffiliated signals can help improve the signal-to-noise ratio and hence the performance of wireless networking. For example, carrier sensing technologies that attempt to sense the presence of other users to facilitate resource scheduling are more easy to implement if one knows what the other user's signals look like. Mixing different types of signals can make this and other strategies that might be used to manage congestion less robust.

Open access rules for next generation networks face similar challenges. Fiber to the home networks are being deployed with multiple architectures: homerun fiber, active star, or passive optical (PON). Layer 1 unbundling mandates such as wavelength or dark fiber sharing are specific to the architecture selected. Neutral regulatory treatment is only possible if the duopoly incumbents select similar architectures.

However, with convergence toward a common IP Layer 3 architecture for wired broadband platforms, it becomes feasible to implement a form of technically neutral “bit stream” access. In this scenario, all incumbent facilities-based wired providers may be required to offer to competitors a wholesale bit stream capability, specified as a basic IP transport service of some minimum data rate and QoS, that is suitable for supporting a broadband platform service. We do not engage in the debate here as to whether such open access rules are desirable or not, but merely notice that the goals of technical and service neutrality are rendered jointly more feasible and consistent as wired networks evolve toward a platform model. Meanwhile, a fundamental tension between these concepts remains for wireless networks.

3.6. Summary of regulatory review

There are clear differences in the evolution and current regulation of wired and wireless broadband services. At the same time, current regulatory trends are moving toward greater technical and service neutrality. Some might argue that wired and wireless regulation should or will converge in the future, through judicious regulatory reform enabled by ongoing technical evolution and maturing markets.

In the next sections, we argue against such a “super-convergence” view. We explain why wired and wireless networking represent fundamentally different cases that have different optimal endpoints and will continue to need different regulatory treatment.

4. Wired versus Wireless Networking

Table 4 summarizes the key features that underly persistent differences in wired and wireless networking and their appropriate regulatory treatment.

Table 4: Persistent Key Differences in Wired v. Wireless Networking

	Wired	**Wireless**
Capacity	Abundant	Scarce
Topology	Point-to-point	Broadcast
Reliability	Reliable	Unreliable
Mobility	Fixed	Mobile
Layering	Effective	Inefficient

4.1. Capacity

Wired networks have an inherent capacity advantage over wireless networks because of the significantly greater frequency range that is available via wired infrastructure. This is a simple matter of physics. For example, a single coaxial cable has a useful frequency range on order of 1GHz while a single optical fiber has a useful frequency range of over 1,000GHz.[25] The entire RF spectrum (3Hz to 300GHz) could easily fit in a single fiber. With multi-fiber bundles, each cable replicates many times more than the entire available RF spectral capacity.

The capacity advantage of wired networks is even larger because of variations in RF propagation characteristics at different frequencies. Non-line-of-sight (NLOS) transmission, which is necessary for wide-area mobile services and low-cost deployment, is normally considered economical only below 3 GHz.[26] This spectrum has been nearly completely allocated to existing uses and licensees in a patchwork of overlapping access rights that make it hard for any would-be wireless broadband service provider to assemble a large contiguous block of spectrum. Even the highly anticipated "digital dividend" at 700 MHz resulting from the digital TV transition has not freed up much spectrum. In the 2008 U.S. auction of this spectrum, the total bandwidth auctioned was only 62MHz. The D-block license that policymakers hoped might be used to provide a national broadband network was only 10MHz.

Within the below 3 GHz region where mobile services are economical, propagation differences at different frequencies drastically affect the cost of network deployment. Higher frequencies have shorter wavelengths that interact more strongly with objects in the transmission path (rain drops, walls, trees) and hence require a greater number of infrastructure sites to cover the same geographic region. Frequencies below 1 GHz are thus the most desirable for building out cost-competitive networks. Comparing again to optical fibers, there is 1000 times the useful frequency range in a single fiber as is available in the most desirable part of the RF spectrum that must be shared by all services in a given geographic area.

The comparison of raw frequency range availability is a good first-order indicator of the capacity differences of different technologies. To make the discussion complete, two second-order effects need to be mentioned. First, maximum data rate depends not only on frequency range but also on the encoding or modulation scheme that is used. More sophisticated modulation schemes can increase the bit rate, albeit at increased equipment cost. Second, data communications capacity depends on how the frequencies are allocated and utilized in addition to the frequency range and maximum data rate. For example, studies of RF usage have found that most of the desirable RF spectrum is not actively carrying transmissions most of the time in most places—which suggests that there is substantial room for the available frequencies to be shared more intensively.[27] We

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[25] See Goleniewski (2007).

[26] See Riback (2006) for path loss measurements taken in urban and suburban areas.

[27] A number of studies have measured RF spectrum occupancy. For example, in a series of studies conducted by Shared Spectrum Company for the US National Science Foundation (see http://www.sharedspectrum.com/measurements/), data showed that the average occupancy over all locations tested was 5.2% and that the maximum occupancy was in New York City at 13.1%. This suggests that even in

believe strongly (and have argued elsewhere) that such sharing is both desirable and necessary for the healthy evolution of wireless technology and services. However, neither of these second-order effects—the potential for improved modulation schemes and the potential for improved sharing—is nearly sufficient to overcome the massive capacity disadvantage facing wireless broadband services based on the simple physics of useful frequency range.[28]

4.2. Topology

Wired networks depend on the physical deployment of cables that go from one place to another. The cables focus all transmitted energy to the specific locations at either end of the wired link.[29] Therefore a wired network is inherently point-to-point. While physical layer broadcast is sometimes possible (e.g. in ring topologies or passive optical distribution networks) it is a secondary and limited operation mode normally suppressed rather than supported or exploited.

In contrast, wireless networks are inherently a broadcast technology. In the case of commonly used and inexpensive antennas, the energy will be radiated over a substantial fraction of a sphere. Newer smart phased array and beam forming antennas can focus RF energy to smaller radiation patterns, but the cost is high enough that these are not widely deployed. Moreover, even with advanced antennas, there are often multiple receivers within the geographic area covered by a transmission. As a result, interference is a major issue for wireless networks. Even worse, the range at which a signal causes interference (degradation in performance of an independent communication link using the same frequency) is substantially greater than the range at which it can be usefully received, further reducing efficiency.[30]

The topology difference further accentuates the capacity differences introduced in the previous section. Additional capacity may be provisioned in wired networks at low incremental cost, by installing additional wires to additional sites, or more commonly, by lighting additional fibers pre-installed to support growth. In contrast, spatial reuse of the limited frequencies available to a wireless network requires adding expensive base station sites, in order to shrink cell size and lower transmit power so that interference is reduced. As a result, capacity increases for fully built out wireless networks are expensive to deploy and offer relatively small benefit compared to easily achievable capacity increases for wired networks.

The topology difference also drives significant economic differences between the two network types. Deployment of wired infrastructure requires securing access to rights-of-way and

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the most congested markets, there are ample opportunities available to share the already allocated spectrum more intensively.

[28] Additionally, wired network utilization rates could also be significantly increased. See Odlyzko, Andrew (2000), "The Internet and other networks: utilization rates and their implications," *Information Economics and Policy*, Volume 12, Issue 4, December 2000, pages 341-365. Provisioning excess capacity has been cheaper than incurring the traffic management costs needed to achieve higher utilization rates.

[29] We are ignoring here the limited problems that arise as a consequence of wires acting like antennas that can contribute to interference in adjacent wire pairs (cross-talk) or may generate RF interference (as was the case with earlier BPL designs).

[30] RF-over-fiber technologies and distributed antenna systems represent an attempt to capture some of the benefits of wired infrastructure for wireless services. See for example, Jacobs *et al*. (2007).

conduits/outside structures (e.g., telephone poles). Once secured, the access supports virtually unlimited opportunities for capacity expansion at low incremental cost. Network investment is therefore dominated by the relatively large up front cost associated with wiring a neighborhood. Wires need to pass every home that might be served by the network. The high up front cost limits the number of wired providers that are likely to be economically viable in any local area.

Indeed, there are very few instances in the U.S. where there are more than two wired operators. With the significant excess capacity available over a fiber optic local access network, there are likely many local areas that previously had duopoly facilities-based competition (DSL over copper vs cable modem over coax) which may see the deployment of only one fiber optic network.[31]

Wireless networks have fundamentally different economics. Initial deployment and maximum capacity are gated by availability of spectrum licenses. Within those (significant) constraints, deployment is flexible. Coverage can be maximized at low up-front cost by installing a small number of high-power base stations, reaching all homes in an area. As market penetration and customer use grows, capacity may be expanded by shrinking cell sizes and adding base stations to increase spatial reuse of available spectrum resources.

This scalability in deployment means that wireless services are normally economically viable at lower take rates from covered population than would be required for wired services. As a result it is feasible to support more wireless providers than wired providers in the same geographic area. This helps explain why many local areas have four or more mobile facilities-based providers to choose from as well as other technologies such as Wi-Fi based networking options.

4.3. Reliability

Wired networks are generally much more reliable than wireless networks at layers 1 and 2. That is, at the transmit power and propagation distances necessary for a commercially viable system, a wired network has orders of magnitude fewer bit errors than a wireless network. Moreover, wired links offer 100% uptime except during equipment failures, whereas wireless links occasionally drop out for a period of time (due to variations in channel loss, mobility effects, and so on).

The reliability challenges of wireless networks are due, in part, to the much more challenging transmission channel characteristics of free-space radio propagation. A well engineered coaxial or fiber optic cable has consistent and easily predicted propagation characteristics along the transmission path. In contrast, wireless transmission paths are much more variable and unpredictable. Multipath, interference from unaffiliated transmissions, and obstacles (hills, trees, buildings, people, rain drops) all contribute to variability in the wireless transmission channel. Moreover the wireless channel has much higher attenuation than a well-engineered cable.

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[31] This seems especially likely in areas where wired duopoly is less prevalent, such as in Europe. This helps motivate the current interest in Europe in segmented geographic regulation (Pupillo & Amendola, 2009). In the U.S., even if one of the incumbents fails to upgrade to fiber in a given local market, this does not mean that retail-level competition will fail to be adequate in a fiber-intensive world, but it does raise valid regulatory concerns.

Transmitted energy is broadcast rather than channeled toward the receiver, reducing the received energy per bit and hence increasing bit error rate.

The fundamental unreliability of wireless networks further exacerbates their capacity constraint relative to wired networks. This occurs because overcoming bit errors requires the use of additional resources (spectrum or transmit power) to send redundant information. Coding overhead and retransmissions consume a substantial fraction of network capacity in most wireless networks.[32]

The high fraction of limited available network capacity used for error correction creates a strong incentive for network designers to specialize the error correction method to the service being supported. For example, key frames of compressed video can be sent with greater redundancy than incremental update frames, whose loss causes fewer visible artifacts to the end user. Voice sample retransmissions can be suppressed if the tight latency deadline imposed by a full duplex voice conversation has expired. SMS messages can be resent at a later time rather than immediately since the end user delay expectations are not stringent.

Specializing the error correction methods in ways like this requires that the lowest layers of the network design be adapted to the service being provided to the user. That is, inherent unreliability creates an incentive to make wireless networks service-specific that is not present in wired networks.

4.4. Mobility

Wired networks are installed in specific locations and inherently provide a fixed service. Wireless is of course inherently about mobility in all of its many flavors. This includes near ubiquitous coverage, communications availability when moving at high speed, and flexibility in choosing and changing service location. For example, Wi-Fi use in households facilitates the sharing of a single wired connection within the home and also makes it easier to configure even a single broadband access point (i.e. cable-free deployment). Wireless mobility also allows services to follow the individual rather than be fixed to a device in a specific location (i.e., support “personalization”).

Provisioning for mobility further limits the capacity of wireless networks compared to wired networks. For example, supporting a mobile phone call for a user who is traveling in a car at 100km/hour requires more spectral and transmission resources than if the user were sitting still in a fixed location.

More subtly, the difference in mobility affects user behavior and expectations. The interaction between a mobile user and the inevitably spotty coverage of a wireless service leads to a situation where the user is often disconnected. Users learn to manage their wireless service quality, in some cases at large scales (in which towns does the mobile device work) and in some cases at small scales (moving around a room to improve signal strength). A user actively seeking connectivity and better signal quality easily becomes a user exploiting multi-radio devices to combine services from multiple providers. The most common example of this today is the

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[32] For example, in the GSM voice network, 43% of the capacity allocated to each voice call (9.8 kbps out of 22.8 kbps) is used for error correction.

consumer expectation of using the Wi-Fi capability of a smartphone for low-cost or free coverage when in range of a hotspot, rather than always using a costly wide area network service.

Thus consumer behavior is very different in wired and wireless networks. In wired networks the user is normally a passive consumer. The user purchases one instance of a service and if it fails they wait for maintenance actions by the provider.[33] In wireless networks, the user is often an active consumer, juggling multiple devices and connection options to optimize cost and overcome service failures.

While today this difference is not particularly fundamental to broadband market dynamics, an imminent technological change will make it much more important. A growing fraction of the mobile device market consists of devices with high local flexibility and computing power (smartphones, netbooks, laptops) as well as multiple radios. A consumer with such a device is empowered to select different air interfaces and use different service providers based on dynamically changing needs and desire to pay. This trend will accelerate if open handset architectures prevail, or even further out, if cognitive radio technologies enable mobile devices to make these choices automatically on behalf of the user. This is quite different from the market dynamics of wired networks, where users rely on a single access network provider and select among various services offered over-the-top.[34]

4.5. Layering

Layered protocol design has proven to be a fundamental tool for architecting networks. The core benefit of layering is to delineate functional responsibilities and thus enable partitioning the complex interlinked design problems facing networks. Moreover, layering enables “mix-and-match” of technologies. Any of multiple technology options at one layer can be used with any at another, since communication between the layers occurs over well-defined interfaces. For example, routing algorithms at the network layer do not need to change whether the physical layer is a shared ethernet, a point-to-point leased T1/E1 line, or a wavelength on a fiber.[35]

The broadband platform concept as we have defined it represents virtualization just above the network layer in the Internet architecture. Different applications—by which we mean services such as voice telephony or video broadcast—use common networking services provided by the network layer to communicate their data. That layer in turn uses lower level resources to accomplish its tasks. As discussed in section 2.2, the core physical layer attribute of a network is

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[33] Observe that the fixity of the device (rather than the user) in wired operation changes the costs of providing customer service/maintenance. With wired networks, a truck rolls to a specific address, which is easier than sending a repairman to a mobile consumer. With wireless networks, the consumer goes to the provider's store. The costs of the “truck roll” are shifted from the provider to the consumer.

[34] Switching among wired access providers is feasible for mass market consumers, but usually with a longer cycle time. Wireless providers, who confront this risk much more directly, attempt to reduce customer switching through long-term contracts, often sold with the inducement of equipment subsidies.

[35] In the interests of brevity and accessibility to a non-technical audience, our discussion of Internet architecture is somewhat loose and imprecise. For further elaboration of the layered architecture of the Internet see Tannenbaum (2002) or Kurose and Ross (2007).

the collection of frequencies used for data transport. These frequencies are determined by the capabilities of the wires or fibers that comprise the physical infrastructure of a wired network, or by the collection of RF frequencies (spectrum access rights) associated with a wireless network.

The original Internet was designed to support only “best effort” packet delivery. It provided no explicit packet loss or delay guarantees. This service model enabled the Internet to easily interconnect a wide diversity of networks with very different capacities and service qualities. The mismatch in data rates at the boundary between networks potentially leads to congestion and packet loss, as does excess offered load. Resource management to overcome these problems is done by a transport layer protocol (TCP). TCP is implemented by the sources and consumers of data at the edges of the network. Each data sender limits its transmission rate in a way that avoids overloading the most congested router or link in the path between the sender and consumer.

The real-time requirements of newer multimedia services such as VoIP have challenged the traditional Internet model. Also, these services rarely use TCP, causing congestion problems. The most common way to work around this is to provision excess capacity so that the delays of “best effort” service end up meeting the real-time requirements. To support multimedia services in situations where overprovisioning is not possible, newer congestion control mechanisms have also been developed (e.g, DiffServ, MPLS).

TCP and the newer protocols all operate at Layer 3 and above. This resource management design works effectively in wired networks for two reasons. The underlying point-to-point topology means that packets transmitted by separate senders only interact at routers. As a result Layer 1 and Layer 2 design decisions do not affect congestion management. Furthermore, the capacity of any given point-to-point link is stable over long time periods. This gives TCP time to discover and respond effectively to capacity variations. Since TCP is an end-to-end protocol implemented between edge nodes, it takes multiple round trip times across the network to adjust transmission rates to a new optimal setting.

With wireless networks, neither of the attributes just described holds. The topology is broadcast rather than point-to-point, meaning that lower layer design decisions significantly affect resource management. The lower layers include a MAC (Media Access Control) protocol that has a dominant effect on the data rate available to each sender in a shared channel—a much greater effect than the allocation decisions made by Layer 3 mechanisms like TCP or DiffServ. Moreover, the unreliability of wireless channels combined with variations in channel quality caused by mobility mean that the available resources for communicating with any given wireless device change rapidly. A Layer 3 mechanism neither has sufficient information nor can it act quickly enough to discover and respond effectively to these physical layer changes.

Therefore, resource management in wireless networks cannot be delegated entirely to Layer 3 and above protocols. This challenge to the traditional Internet layered design is further exacerbated by the intense capacity constraints facing wired broadband services. The driving need to optimize capacity translates into a need to specialize MAC designs. MACs are specialized to physical layer characteristics such as frequency band (differing propagation characteristics), network architecture (mesh vs. hierarchical), and allocation plan (paired vs unpaired spectrum). MACs are also specialized to application layer characteristics such as expected packet size, delay requirements, loss tolerance, and relative fraction of broadcast vs point-to-point traffic.

Fundamentally, wireless networking requires close coupling between design decisions at the physical layer, network layer, and application layer to achieve the efficiency demanded by stringent capacity constraints. Consequently, the separation of layers that is effective for wired networks is inefficient for wireless networks.[36]

4.6. Summary of fundamental differences

This section has discussed fundamental and persistent differences between wired and wireless networks. The fundamental capacity of wired networks is orders of magnitude higher than wireless networks. This effect is accentuated by topology, reliability, and mobility effects that reduce the effective capacity of wireless networks.

Furthermore, topology differences change build-out economics, affecting the number of providers that can economically compete in most markets (one or two for wired networks, four or more for wireless networks). Reliability differences give advantages to service-specific wireless networks over general-purpose wireless networks that do not arise in the wired networks case. Mobility effects in wireless networks combined with multi-radio devices empower and encourage consumers to combine services from different wireless providers, whereas a consumer normally only relies on a single wired network provider. Finally, the isolation of layer designs that is effective in wired networks is much less efficient in wireless networks.

These differences are fundamental in the sense that they will not change as technology evolves. Therefore, it is important to avoid carrying concepts or regulatory approaches from the more mature wired networks world into the wireless networks world, without carefully considering whether those concepts or approaches apply to wireless networks. The next section focuses on one such concept, broadband platforms, whose compelling success in the wired world has led to a widely accepted but in the end incorrect assumption that it applies to wireless networks as well.

5. The case against wireless broadband platforms

The fundamental differences between wired and wireless networks discussed in the previous section lead to different optimal endpoints. More specifically, wireless networks do not now embody nor will they evolve to become broadband platforms.[37]

This section explains the reasons why the broadband platform model is not the optimal endpoint for wireless networks. We make the argument by first focusing on technical differences in how wireless and wired networks provide support for mixed media traffic, and then by considering the economic reasons for why the evolutionary trajectories will continue to diverge in the future.

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[36] Cross-layer protocol issues do not arise only in wireless networks. However, this is a problem that is much more common in wireless contexts, which is why we highlight it as an important distinction. For further discussion of some of these cross-layer issues see Lehr and Crowcroft (2005), Kawadia (2004), or Shakkottai, Rappaport and Karlsson (2003).

[37] Remember we are using the term "broadband platform" to refer to a specific network architecture. See definition in Section 2.

5.1. Technical case against wireless broadband platforms

As explained in section 4, wireless network design and market dynamics are dominated by capacity challenges, interference mitigation, and other effects. The capacity challenges put great stress on transmitting as little data as possible to satisfy the user's service needs. This data efficiency requirement drives networks away from a broadband platform model (section 5.1.1). The capacity challenge requires network designers to make data transmission scheduling as efficient as possible, minimizing wasted time in the valuable channel. Scheduling efficiency requirements also argue against implementing a broadband platform approach (section 5.1.2). Based on these efficiency drivers, we predict that new wireless networks specialized for voice will be deployed when current 2G voice networks are retired, rather than moving voice service wholly into 4G or beyond broadband data platforms (section 5.1.3). Finally, the combination of spectrum limitations and interference mitigation drives wireless networks toward small cell sizes, which is only economical if the broadband platform model of a single integrated network is fragmented into independent cell-size-optimized networks (section 5.1.4).

5.1.1. Data efficiency

A core aspect of the broadband platform model is that the network is general purpose. This is problematic for wireless networks because it increases the amount of data to be transferred. We can find multiple examples in current state-of-the-art deployments to demonstrate this.

Voice services over GSM vs. wireless broadband platform: GSM, a system dedicated to voice communications, supports 8 simultaneous voice streams in a 270 kilobits per second TDMA channel.[38] Compare this to a hypothetical broadband platform with the same raw capacity of 270 kbps and the same voice data stream of 13 kbps. Due to the many small packets sent to make end-to-end delay tolerable for full-duplex conversations, header overhead doubles the data rate consumed by the voice call to approximately 25 kbps.[39] Error correction designed for loss-intolerant data services further reduces efficiency compared to the voice-specific error correction used in GSM, leading to an uncoded rate requirement over 50 kbps. Assuming similar framing and synchronization technology, the same 270 kbps channel can carry only 3 voice calls. In other words the broadband platform approach has less than 50% the spectral efficiency of the voice specific network.

Video distribution over MediaFLO vs. wireless broadband platform: Qualcomm's MediaFLO is an example of a modern system dedicated to video. It delivers 13-30 video streams sized for display on mobile devices in a single 6 MHz UHF channel.[40] These streams are available

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[38] GSM allocates 22.8 kbps data rate for each of the 8 voice streams (the gap between 22.8*8 and 270 goes to framing and synchronization). There is 13 kbps available for each voice stream after forward error correction. The current state-of-the-art Advanced Multi-Rate (AMR) codec for GSM can reduce the required data rate substantially below 13 kbps. At the lower data rates the advantage of the dedicated GSM design over a VOIP broadband platform approach becomes even greater than is presented here.

[39] This includes RTP/UDP/IP headers. While header compression can help, header compression schemes developed for wired links often perform poorly in wireless contexts due to cascaded error effects after a single packet loss. This is an active area of research. See Suryavanshi (2008).

[40] PCCW (2008) reports on a field trial performed in Hong Kong.

simultaneously to all users in range of a single base station site. In contrast, a single user viewing a comparable 640x480 video stream over a broadband platform consumes 600-700 kilobits per second of bandwidth, at the compression levels and frame rates widely used by current internet video content providers. Making some reasonable assumptions regarding mobile device distance from the base station, a 6 MHz wide WiMax system, using a similar OFDM physical layer to MediaFLO, can support only around 10 such users simultaneously per antenna beam.[41]

Comparing equivalent base station technologies—both MediaFLO and WiMax operating with an omnidirectional antenna—the dedicated system is two to three times more efficient even if only one user is viewing each video stream. In normal operation the number of customers served simultaneously would be much higher than one per stream, leading to a corresponding increase in efficiency of the MediaFLO system from a business perspective. Moreover, MediaFLO requires fewer base station sites to provide video service than does a WiMax system designed to provide sufficient capacity for video over the same geographic region.

More generally, there are fundamental theoretical results showing that a general-purpose system will always be less data efficient than a service-specific system. Independent source and channel coding inherently requires sending more data than joint coding does, to achieve the same error rate for the same transmit power and channel characteristics, in almost all real-world situations.[42] The economic cost of this efficiency loss will only grow as usage growth makes wireless broadband systems ever more capacity constrained. This challenges the traditional model of layered design that supports the virtualization of the underlying resources, and thus, it challenges the viability of the platform model for wireless.

5.1.2. Scheduling efficiency

The general purpose nature of a broadband platform also reduces spectral efficiency through reducing opportunities to optimize data transfer scheduling.

In a broadband platform, different applications are handled identically by the underlying network infrastructure. This is inherent in the decoupling of service and network that is at the core of the platform model. In most cases, for example, the infrastructure is not even aware that some bits it carries represent voice while others represent video or web traffic.

Because any bit might be part of any service, the network must be engineered to a QOS (quality of service) sufficient for all services. That is, the network must provide the low latency required for full-duplex voice traffic. It must provide the high capacity required for video traffic. And it must handle short burst transmissions without substantial startup or teardown delays, to give a

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[41] The two services are somewhat different. A user can only choose from a few tens of video options with MediaFLO, whereas (as of August 2008) there are well over 100 million video clips available on YouTube. Operators have responded by offering both services. The greater spectral efficiency of MediaFLO enables it to be offered as a low-cost video service, while the greater choice offered through YouTube and other web video sources earns a premium. This may seem counterintuitive since users are asked to pay a monthly fee for the specialized video service. However, the data plan required for substantial web video consumption is substantially more expensive than the fee for specialized video service.

[42] See Vembu (1995).

good web surfing experience. Most challengingly, the network must provide all three of these desirable attributes simultaneously.[43]

Scheduling efficiency can be substantially improved by matching the underlying transport to the actual requirements of the service. Here are three examples.

GSM voice network—connection setup latency: The GSM voice network exploits the connection setup latency tolerance of telephony to reserve processing and communication resources in multiple parts of the radio access network. It can take a substantial fraction of a second to establish a connection, which would be unacceptable for web surfing. By the time the GSM call setup process has completed, the system has guaranteed a low-latency no-loss path all the way from the mobile device to the PSTN. Subsequent voice traffic between base station and mobile device occurs at scheduled intervals with no header overhead. As a result, the wireless link can be used at near 100% loading to carry voice data, needing only a small guard interval between transmissions to overcome clock drift and mobile device location uncertainty.

QualComm 1xEVDO—data transmission latency: The Qualcomm 1xEVDO network—named "DO" to emphasize that it is specialized for "Data Only"—boosts overall system efficiency by exploiting the increased latency tolerance of data traffic compared to voice traffic. 1xEVDO batches up data at the base station for transmission to each mobile. In each time slot it picks the mobile that temporarily has the highest available transmission rate. The base station uses all of its radio resources to burst queued data to that mobile as fast as possible. Mobility effects lead to continual change in which mobile has the highest available rate.[44] Assuming sufficient variation in channel quality and sufficient independence of channel variation across mobiles, the overall achieved downlink data rate is much higher than is achieved by systems using voice-oriented latency-minimizing scheduling algorithms.

Motorol iDen—push-to-talk voice latency: The Motorola iDen network exploits the increased latency tolerance of half-duplex voice compared to full-duplex voice to efficiently schedule push-to-talk traffic. Attempts to graft a PTT function into a 3G system that treats half-duplex and full-duplex voice bits the same—e.g. Qualcomm QChat—results in a system with substantially higher costs and lower performance than iDen. After the merger between Sprint and Nextel, the combined company tried to move its legacy Nextel PTT customer base to QChat so it could shut down iDen. The cost and performance advantages of iDen likely contributed to Sprint Nextel's eventual decision to continue operating both networks.

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[43] This problem can be partially solved by the DiffServ mechanism. In DiffServ, IP packets are marked with a QOS category such as real-time or bulk. Future wireless systems may be sophisticated enough to adjust radio-level scheduling (layer 1 and layer 2 behavior) based on DiffServ packet markings (layer 3 information). For a variety of reasons that would require too much space to describe here, the expected scheduling efficiency of a DiffServ-enabled general-purpose network still falls short of the scheduling efficiency of a service-specific network.

[44] Sophisticated scheduling algorithms in 1xEVDO base stations assure that no mobile is starved even if it is in a poor radio situation that prevents it from becoming the highest rate mobile for a long period of time.

5.1.3. A new voice network

GSM and equivalent second generation voice networks around the world are largely regarded as a low-tech legacy. However, if the metric is data and scheduling efficiency, they are amazingly well designed. They have relatively low spectral efficiency compared to more recent systems simply because of the low level of modulation and signal processing technology that could be implemented in mobile devices 20 years ago.

Hence, a prediction: The second generation voice networks are scheduled to be decommissioned between 2015 and 2020. We predict that operators will deploy a new network specialized for voice and associated services rather than providing these services on top of general-purpose 4G or 4.5G data systems. If this occurs it will strongly support our contention that a general-purpose broadband platform is not the appropriate model for wireless broadband services.

Our prediction of a new network specialized for voice is not a prediction that separate hardware units will be deployed to base station sites or in handsets for the new network. Software defined radio technology will enable the voice network to operate simultaneously with a 4G or 4.5G data network on top of shared hardware. Furthermore, cognitive radio techniques will likely be used to reallocate physical layer resources such as spectrum, transmitter power, and processing capacity between the networks as user demand changes. At the application layer, if the specialized voice network is temporarily overloaded when the user initiates a voice call, that call may be carried transparently to the user as VOIP over the data network. What characterizes the voice service as a separate network will be a specialized air interface, with different scheduling and robustness characteristics from the 4G data air interface, occupying an identifiable (but dynamically changing) set of spectrum resources distinct from those allocated to 4G data.

5.1.4. Small cell sizes

In the earlier parts of this section, we discussed the general-purpose aspect of the broadband platform model. Another aspect of the platform model is that the service provider operates a single integrated network. This substantially reduces costs in wired broadband systems.

In wireless, the need to reduce cell size for high capacity and high coverage has driven operators away from a single network model. Instead, some 3.5G networks today and all planned 4G networks follow an aggregated network architecture. This is different from the service-specific networks described in previous sections. Each of the subnetworks discussed in the following support the same services and may run the same air interface.

The two subnetworks used today are a *macro* network, consisting of powerful base stations at towers or on poles, and *customer-deployed infrastructure* (CDI), consisting of low-power access points in homes or offices. There are two types of CDI devices. Some are “femtocells” that operate in the cellular spectrum, e.g. Sprint AIRAVE.[45] Others are “hotspots” that operate in unlicensed spectrum, e.g. T-mobile hotspot@home.[46] Both types rely on the customer’s wireline internet link to connect to the broadband wireless provider’s core network.

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[45] http://www.nextel.com/en/services/airave/index.shtml

[46] Pogue (2007)

The macro network and CDI are properly viewed as autonomous networks, rather than a single integrated network forming a broadband platform, for the following reasons.

- Technical: The CDI device or centrally controlled network of CDI devices makes decisions regarding spectrum access and transmit power largely independently of macro network frequency planning. Moving a mobile device from the macro network to coverage provided by a CDI device is technically similar to roaming from one cellular network to another.
- Economic: The customer either owns or leases the CDI device. The customer provides a location, heating/cooling, electricity, any labor associated with initial installation or replacement of defective units, and an internet data connection. All of these attributes are different from operator-owned macro network base stations.
- Operational: Operators charge different prices for service when a mobile device is supported by a CDI device than when it uses the macro network. Use of services provided by the CDI device is often limited to mobile devices authorized by the CDI owner, whereas the macro network serves all customers.

The use of CDI is driven by critical capacity problems that arise in broadband macro networks. Under extant real-world spectrum limitations, each broadband customer consumes a significant fraction of the provider's spectral resources. The only way to offer sufficient capacity to a large number of customers is aggressive spatial reuse of spectrum. As wireless broadband market penetration and use grow, operators face the prospect of massive, unaffordable investment requirements to dramatically increase the number of sites or increase the use of smart antenna technology, or both.

Similarly, achieving the coverage expected by customers—that is, providing broadband capacity even inside buildings—requires excessive investment to increase the link power directed to each customer. Per-customer link power increases are particularly challenging to achieve in spectrum constrained situations where links are interference limited rather than noise limited. The only solution is to deploy many more sites, enabling shorter link distance and path loss to each customer.

The business case for customer-deployed infrastructure is compelling compared to aggressively subdividing macro cells to achieve the equivalent capacity and coverage. CDI provides coverage precisely where it is needed, inside the customer's home or office. The provider avoids the site acquisition and zoning costs of erecting new outdoor sites. Ongoing costs for the data connection back to the core network, which are a significant operational expense, are paid by the customer rather than by the provider. The low transmit power of CDI devices reduces both device cost and network management costs.

Because of the strong business case, there has been major investment to develop, trial, and begin deploying CDI devices.[47] The strong push toward customer-deployed infrastructure is

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[47] Press releases and vendor announcements showing the breadth of this investment are collected by the Femto Forum and available at http://www.femtoforum.org/femto/. As of a 5 February 2009 press release, Femto Forum membership includes all of the top 5 mobile network infrastructure vendors and 17 of the world's top 20 operators.

confirmation that a single integrated 3G/4G macro network cannot by itself provide a cost-effective wireless broadband service. We see again that the broadband platform model is not optimal for wireless.

There is no reason to expect this situation to change in the future. In fact, we may see yet a further division of the broadband service. For example, substantial spatial reuse gains may be possible if pedestrians (slow-moving, densely packed, unpredictable trajectories) are segregated from vehicles (fast-moving, low density, predictable trajectories) into independent, geographically overlapping cells. If this proves to be the case, operators will have incentives to deploy autonomous subnetworks for different user categories. Software-defined radio and cognitive radio technologies will help, as previously discussed in section 5.1.3. SDR and CR will enable deploying multiple networks without significantly increased capital or operating costs, while allowing dynamic resource sharing between the networks, particularly of critical spectrum resources.

5.2. Economic case against wireless broadband platforms

The broadband platform model is inappropriate for wireless services for economic reasons. It is higher cost than an aggregation of specialized networks and is also inconsistent with the market dynamics for wireless services.

5.2.1. Higher cost

The earlier discussion makes clear the technical reasons why adopting a platform architecture for wireless services would reduce effective capacity. The reduction in effective capacity may be viewed, equivalently, as an increase in the economic cost of the wireless network. On top of this, there are other economic reasons why a platform architecture would contribute to higher costs for wireless broadband networks.

Inherent specialization of wireless users: There is a fundamental need for specialization to achieve cost economies in wireless networks. Specialization helps reduce cost because of the heterogeneity of wireless applications and usage scenarios. For example, there is wide variation in available power, form-factor, and expected deployment locations across applications such as sensing, cable replacement, and personal communications. Each of these end device characteristics strongly affects the optimal design of the lower wireless network layers such as choice of frequency band, modulation, and media access control protocol. Furthermore, exploiting the available cost reductions through specialization is critical because of the sheer number of devices to be connected wirelessly (e.g. “the Internet of things”).[48]

In contrast, the economic advantages of the platform model depend on the cost economies achieved through constructing and operating a single network to support a range of users, end devices and applications (i.e., a “one-size-fits-all” design approach). The need for specialized designs to realize performance goals at acceptable cost will drive wireless solutions away from a platform approach.

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[48] While the capacity per end-point for a wired connection may expand without limit, the number of potential end-nodes per unit of wireless capacity may expand without limit.

Incremental vs. upfront deployment: As already noted, from a service feature perspective, the killer application for wireless is mobility, which includes the notion of ubiquity or "everywhere availability." To deliver this via wireless, it is necessary to provide coverage over a sufficiently wide area before it is possible to sign up any customers.[49] This argues for a deployment strategy of one-service-at-a-time across the minimum sized critical region, rather than a broadband platform sufficient to support all services, which has to be built out across that whole region before you can earn a single dollar. This is especially true if some of the services (e.g. video broadcast) can be built out for far less than others (high-speed web surfing) when those services are segregated into autonomous subnetworks.

5.2.2. Market Dynamics

Overlapping network lifetimes: The wireless services market has historically evolved as a series of deployments of geographically overlapping networks by each provider. As a result, different networks and services are at a different stage of their life cycle at any given time, ranging from high value added services for early adopters through mass market use and finishing with low-value (and in some cases regulatorily mandated) support for a small number of legacy users.

For example, we observe that the major wireless broadband providers rely on multiple networks of different ages. A current wireless broadband service usually incorporates a 7–10+ year old dedicated mobile voice system (GSM or CDMA2000), a 3–5 year old dedicated mobile data system (3G HSPA or 1xEVDO) and in some cases a 1–3 year old video distribution system (DVB-H or MediaFLO).

This history shapes future growth directions. The current situation of overlapping network lifetimes makes it economically advantageous to continue with a heterogeneous collection of networks in the future, rather than to fold all service offerings into a broadband platform. Mid-life networks earning healthy revenues are not turned off when new ones are installed. Technology maturity and high production volumes significantly reduce mobile device prices for older networks, creating a strong business case to continue operating those networks to support cost-sensitive market segments. The capital investments in recent networks have not been fully depreciated, creating high switching costs for reallocating their spectrum and other resources to support a new broadband platform network.

In a sense, this is simply the argument that because wireless broadband is not currently implemented using broadband platform networks, the costs of switching to a single integrated broadband platform make that solution suboptimal. While this argument is somewhat a tautology, the path dependence of future growth on the current situation is a strong effect that cannot be neglected.[50]

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[49] Fixed wireless broadband via WiMAX is an exception to this rule. As we explained earlier, this is a niche application that is not expected to have major impact, and we do not focus on it in our analysis. See footnote 6.

[50] The path dependence of networks is re-enforced by a number of economic forces including network externalities (that can result in lock-in, see Besen & Farrell, 1994, or Arthur, 1989), regulatory inertia, sunk costs and other sources of irreversibility. While such effects are undoubtedly important, we do not emphasize them in this paper because we do not want to say that wireless and wired will be different in

Competition by specialized network providers: As previously discussed in section 4.4, end-users of wireless broadband systems play a more activist role than they do in wired systems. Technical trends and equipment markets in wireless are evolving to facilitate user selection among multiple networks or providers on a service-by-service or transaction-by-transaction basis. A current smartphone user, for example, has at least two telephony options: using minutes from their voice plan with the mobile provider, or using Skype or a similar application on top of the 802.11 Wi-Fi capability built into the phone.[51] This type of choice controlled by the user will increase to a range of services with future trends toward more flexible radios (SDR), smarter control mechanisms (Cognitive Radio) and decentralized user-provided infrastructure (mesh networking, wireless grids).

Giving the end user this type of choice shifts market power from the service provider to the user. In particular, it enables users to optimize the mix of networks and service providers they use to meet their needs. As this trend develops more fully, it changes the economic attractiveness of broadband platforms. A platform network, because of its generality, is inevitably less efficient at providing any particular service than a specialized network, for all the reasons described earlier. In an ecosystem where users are enabled to mix and match services, a provider with a specialized network may be able to cherry-pick customers for that service from a one-size-fits-all platform network provider, by offering a lower price. The result is that the platform network is left providing services that are relatively less profitable, normally because they consume a high amount of resources or have stringent QoS demands. The effective market response by the general service provider is to provide its services using a heterogeneous collection of specialized networks, rather than a general platform network, enabling service-by-service competitive offerings.

6. Policy Implications

In the preceding, we have explained why we believe wireless (in contrast to wired) will not evolve toward a broadband platform. The earlier discussion highlighted some of the likely implications for technical designs and industry economics. In this section we consider what our conclusions mean for communication policy in several important domains, including:

- Regulatory neutrality goals
- Interconnection and universal service regulations
- Open access rules (to enable resource sharing of potential “bottleneck” access facilities)
- Spectrum reform

The following sub-sections address each of these in turn.

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the future simply because they have been different in the past. Instead we emphasize the additional reasons for why the evolutionary paths will vary.

[51] Stone (2009).

6.1. Regulatory neutrality goals

Regulatory neutrality goals that would eliminate asymmetric rules for wired and wireless are one obvious casualty of the divergent evolutionary paths for wired and wireless. Since wireless is unlikely to evolve toward a broadband platform, it makes little sense to try and extend regulatory frameworks crafted for a wired broadband platform to wireless networks. Today, regulatory frameworks for the two worlds are different. Our analysis suggests that these differences will persist into the future. Regulatory agencies like the FCC will continue to need separate bureaus (with different specialized expertise) to track and regulate wired and wireless services, and will need to invest resources in harmonizing rules where policy concerns overlap.

6.2. Interconnection and universal service regulations

Policies for managing carrier interconnection and for promoting universal service are two specific areas impacted by the need to address wired/wireless differences.

The FCC has long been engaged in trying to rationalize the inconsistent landscape of differential intercarrier compensation policies that are a legacy of an earlier age. Under current rules, there are different regulatory rules and charges for intrastate and interstate long distance telephone service (access charges), for traffic exchanged between local telephone companies (reciprocal termination rates), and for telephone calls carried as a traditional “circuit”-switched traffic or as VoIP. Differing regulatory-mandated rules and pricing that systematically deviate from the underlying costs distort market behavior.

In 2001, the FCC initiated a proceeding to investigate options for developing a unified intercarrier compensation regime to address these problems.[52] It was generally recognized that the incremental (usage-based) costs for terminating traffic, at least to wired networks, are quite low. Further, traffic flows between similar operators are likely to be approximately balanced.[53] For this, and some other reasons, policymakers considered moving to a bill-and-keep model in which intercarrier interconnection fees are eliminated.[54]

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[52] See *Notice of Proposed Rulemaking (NPRM), in the Matter of Developing a Unified Intercarrier Compensation Regime, Before the Federal Communications Commission,* CC Docket No. 01-92, April 19, 2001.

[53] Above-cost fees for terminating traffic induce operators to seek unbalanced traffic for arbitrage benefits. In the 1990s, a number of competitive local exchange carriers (CLECs) in the U.S. sought to exploit this opportunity by signing up disproportionate numbers of ISPs as customers because of the asymmetric traffic they generate. That is, when dial-up Internet customers dialed in to their ISP, the call looked to the network like a telephone call that originated on the incumbent operator's network and terminated on the CLECs. Therefore, the CLECs claimed they were owed termination fees under the terms of the reciprocal compensation rules. Moreover, because of the much longer holding times typical of Internet access (as opposed to regular telephone calls), the number of terminating minutes and associated termination fees grew quite large.

[54] Bill-and-keep simplifies the regulation of intercarrier compensation since it gets the regulator out of the role of price monitoring. It also replicates the approach employed in most peering arrangements between Internet backbone providers (i.e., revenue neutral traffic settlements), although even in the Internet, interconnection has grown more complex in recent years (see Faratin *et al.,* 2007).

Because of the inherent scarcity issue for wireless networks, however, it is not clear that the assumption of near-zero or symmetric incremental terminating costs applies. It is reasonable to believe that, in general, terminating to a device on a wireless network is more expensive than terminating to a wired network and the costs are more variable (congestion- and local RF environment-dependent). Interestingly, this systemic difference may be used to argue either against a bill-and-keep model or for it. The argument against bill-and-keep is that wireless termination costs are not close to zero and traffic flows are asymmetric, so non-zero termination rates are needed. Conversely, some may argue that the variability of wireless termination costs makes it inefficient (from a regulatory implementation perspective) to do anything other than bill-and-keep. According to this perspective, wireless carriers should look to their own subscribers for cost recovery of usage-sensitive termination costs. In either case, the situation is sufficiently different from wired networks that it requires special consideration.

Universal service is a closely related problem. Much of the justification for intercarrier compensation regulation derives from the need to subsidize service to high-cost customers. However, there are additional considerations. Mobile telephony is now so important, especially in the developing world, that universal service goals are being reconsidered. It may be desirable to treat consumers whose sole telephony service is mobile identically to those who use a fixed line.[55] This has obvious implications for how funding obligations are applied and subsidies distributed. For example, it forces consideration of whether (and how) mobile or perhaps even VoIP service providers should contribute to universal service funding pools.

The rise of wireless networks as a potential delivery mechanism for basic, universal service also accentuates the need to reconsider what basic services should be universally available to consumers. For example, should universal service include broadband Internet access? If so, the rules need to take into account the fundamental differences in wired and wireless Internet broadband access services. A regulatory mandate to offer a certain bit rate and quality of service at a specified price has substantially different impacts on wired and wireless service providers. Additionally, wireless services offer mobility which may be argued to add value compared to fixed services, and thus deserve higher subsidies.[56]

Taken together, the challenges that wireless networks pose for universal service (as well a those posed by other forms of intermodal competition) further increase the pressure for an overhaul of the entire universal service system. They make it increasingly difficult to rely on service-provider-centric mechanisms and increase the merits of shifting to a framework based on end-user portable, competitively neutral, and more narrowly targeted subsidies.[57]

Finally, there is the question of whether a national wireless broadband network offers the best solution for universal broadband Internet and telephone access. Hopes for the creation of such a network motivated, in part, the design of the recent 700 MHz auctions in the United States and

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[55] Ward and Woroch (2005) provide evidence of the substitutability between fixed and mobile telephony.

[56] Some have suggested that mobile telephony can benefit the homeless by allowing them to keep employment even when they have no residence (see Graham, 2007).

[57] For example, see Crandall & Waverman (2000) or Dawson (2000).

have prompted a number of proposals from industry.[58] All of these plans assume that a single integrated broadband platform, operating within a relatively small spectrum allocation on the order of 10–25 MHz, can offer a cost-effective universal service solution.

Our analysis of wireless broadband network fundamentals suggests that such proposed solutions to the national universal service challenge need to be examined carefully and with great caution. The key issues surrounding universal service effectiveness are device cost and service cost. The question is whether a wireless broadband platform would minimize these costs and thereby simplify the challenges of providing access to underserved consumers.

In the area of device costs, providing multiple services using a single virtualized network inherently increases the raw network capacity that user devices must interoperate with. In turn this requires wider channels and/or a more sophisticated coding/modulation scheme. Compare for example a GSM voice-only device that only needs to transmit and receive 200 kHz of spectrum at a time, versus a 1xEVDO or UMTS data-capable device that must transmit and receive multiple MHz at a time, within which the data rate is many times faster than the GSM system. These effects tend to increase device cost, as does the increase in higher layer processing required to multiplex the desired data into a transport link shared with other services. The device volumes associated with even a nationwide universal access network (notionally in the tens of millions of units) are too small to achieve the same scope and scale cost economies provided by international standard units that are sold worldwide.

In the area of service costs, specialized networks are clearly superior to a combined broadband platform approach. This was discussed in the previous sections on technical and economic issues surrounding wireless broadband platforms. The more optimized design possible with a specialized network enables reducing the number of base stations and the amount of spectrum required to provide a specific service such as voice or video distribution. This translates directly into lower provider cost, which simplifies the challenge of achieving universal access objectives.

Looking only at the data service that is the focus of hopes for a nationwide broadband network, the question is whether the spectrum allocations discussed are sufficient to meet broadband Internet access requirements. The inherent capacity limits of wireless, combined with the high cost of achieving high spatial reuse through small cell sizes or smart antennas, suggest that capacity offered to each individual user in the proposed schemes would be limited and potentially offer poor QoS. The result would be a noticeably second-class service, especially in the likely event that the lowest data rate commonly considered to be broadband rises over time from the current 1 megabit per second per user. An effective broadband platform requires a higher underlying capacity than may be able to be provided given the amount of spectrum that could potentially be allocated to a new universal service oriented network. Regulators may need to consider how to leverage both wireless and wired Internet access methods, combining the differing strengths of each into a universal service offering, rather than relying exclusively on one or the other.

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[58] See http://www.cyrencall.com/ or http://www.m2znetworks.com/ which offer competing proposals for how to meet universal service needs with wireless broadband.

In sum, the divergent trajectory for wireless and wired services complicates the formulation of interconnection and universal service subsidies. Appropriate policies in both domains would be ill-served by arguments that presume wireless will or should evolve toward a broadband platform.

6.3. Open access rules and the promotion of competition

A key goal of communications policy in recent decades has been to promote competition. Pursuit of this goal is challenged by a history of monopoly public utility regulation which has not yet been fully left behind. The transition to managed competition is made even more complex by changing technology and market dynamics.

6.3.1. Prospects for facilities-based competition

The differences between wired and wireless networks imply systemic differences in the prospects for facilities-based competition. This leads to fundamental differences in the regulatory policies appropriately employed to promote competition.

In the context of traditional wired networks, there is almost no intramodal facilities-based competition. The move to fiber optic next generation architectures makes it even less likely. In general, it seems reasonable to expect the number of intramodal facilities-based wired competitors to be strictly limited. As a result, regulation needs to focus on promoting robust intermodal facilities-based competition among existing wired networks.[59]

We do not offer a judgement here on what constitutes adequate facilities-based competition, or whether open access rules are needed or desirable if competition is inadequate. Instead we simply note that if there is suitably robust facilities-based competition, mandatory rules for sharing of wired networks would be unlikely and unnecessary. Facilities resale and active wholesale markets for wired network services are likely to naturally emerge in competitive markets.

In contrast, wireless broadband services promise much stronger prospects for intramodal *and* intermodal facilities-based competition. This is due in part to the economics of wireless systems discussed earlier. In most markets we have multiple 2G or 3G mobile network operators (intramodal competition).[60] There are also a growing range of newer wireless architectures (e.g., Wi-Fi, WiMAX, mesh, end-user deployed wireless infrastructure) in development or deployment that offer the promise of further proliferation of facilities-based wireless networking. Moreover, as noted above, many of these networks are adopting very different technologies and are specialized in ways that substantially differentiate them. Classifying this situation as intramodal competition (because they are all wireless technologies) seems misleading. Perhaps these networks should more reasonably be considered additional intermodal wireless competition. In any case, regulators should consider the different circumstances of wireless networks and wired networks when evaluating the level of competition and determining appropriate remedies.

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[59] In some markets, new wireline networks based on broadband-over-power line (BPL) or municipally-owned fiber may offer additional sources for intermodal competition.

[60] Intramodal competition among Wi-Fi is also common, including from “free” Wi-Fi.

6.3.2. Partitioning of communications resources

Depending on the market and one's assessment of current and prospective service competition and the economics of facilities deployment, one may reach divergent conclusions about whether there remains an access bottleneck in last-mile networks that gives rise to the potential for market power or otherwise restricts access to downstream competitors.[61] For those who conclude that a last-mile bottleneck remains a problem, it is worthwhile considering whether open access rules should be mandated, and if so, how best to accomplish that goal. Open access rules may take many forms including structural remedies,[62] facilities unbundling, or wholesale service obligations that are imposed on the incumbent facilities provider to enable downstream competitors to share the network facilities of the incumbent's network. In general we call all of these options "partitioning" the available resources among multiple competitors.

The goal of partitioning is to promote intramodal downstream competition. Without engaging in the debate over whether open access rules are needed or desirable, it is worth considering how the challenge of designing an open access regime differs for wired and wireless providers. Moreover, even if open access rules are not imposed, consideration of how network facilities are most naturally partitioned provides insight into how wholesale and resale markets might evolve in the future.

There are systematic differences in how partitioning is best accomplished in wired and wireless networks. Referring back to the analysis in section 4.5, it is more desirable to partition wired network communication resources above Layer 3 (e.g. competitors sharing a common data transport), while wireless communication resources may be partitioned at either Layer 3 or at Layer 1 (e.g. competitors operating separate networks, each allocated independent frequencies).

Partitioning above Layer 3 may be called application layer partitioning. There is a long tradition of application layer partitioning in wired networks. Examples include reseller provisions such as those that were common in long distance telephone markets and have also been used with mobile operators to promote 2G competition. One type of partitioning is a pure resale obligation that provides competitors with a wholesale price discount (relative to the retail offering by the incumbent). Another is the European mandate for incumbents to provide "bit stream" access, which allows downstream competitors more scope for service modification. That is, the incumbent is obligated to offer a wholesale IP transport service to competitors. They may use the wholesale service to offer an Internet broadband access retail service over the incumbent's network that differs from the incumbent's offerings.

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[61] The access bottleneck may be a result of monopoly ownership (e.g., in some markets FTTH may be a natural monopoly) or inadequate capacity availability (e.g., a market imperfection resulting in inadequate investment).

[62] Structural remedies include such strong measures as mandated structural separation which may involve splitting the company into two separate entities (e.g., as occurred with the divestiture of AT&T in 1984) or adoption of operational or accounting separation which involves some level of separating the business operations of the entity into regulated and unregulated services. The logic behind such remedies is that it helps simplify regulation and mitigates incentives for the network operator to discriminate against unaffiliated competitors of the network operator's own retail offerings.

Partitioning at Layer 1 may be called physical layer partitioning. Multiple partitioning methods are possible based on different selections of the communications resources to be shared. There may be independent wavelengths (colors) in a single fiber running to a customer's home, or independent radio frequencies in the geographic area surrounding the customer's home. Alternatively, there may be independent fiber strands within a cable bundle or independent bundles within a shared conduit.

In wired networks, it is more natural to employ application layer partitioning. Application layer partitioning is inherently easier to achieve than physical layer partitioning once the local infrastructure has been deployed. Physical layer partitioning raises risks of damage to the existing network and also depends on the details of the network architecture (e.g., wire plan) which makes it difficult to impose in a neutral way (that does not have asymmetric implications for intermodal competitors). Application layer partitioning is effective at promoting downstream competition in large part because of the very high capacity potential of wired platforms. Even with limited facilities-based broadband platform competition, there is plenty of opportunity for value-added and competitive services operating "over-the-top."

In contrast to wired networks that favor application-layer partitioning, wireless communications resources may be partitioned at either the application layer or at the physical layer. Application layer partitioning is done exactly the same as is done in wired networks. An example of this is Mobile Virtual Network Operator (MVNO) regulations. Within the limited scope of wireless networks such as 3G to provide a "platform"-like capability, MVNO regulations have been used to encourage price competition for existing services and certain specialized value-added services like alert services or gaming. Capacity constraints on wireless networks restrict the amount of over-the-top competition that is possible, but this constraint does not discriminate between the facilities-based provider and downstream competitors.

Physical layer partitioning of wireless communications resources involves allocating portions of the RF spectrum to independent competitors. This has traditionally required competitors to deploy their own wireless network infrastructure. Open access rules in this context included mandates to allow competitors to install additional antennas on existing towers.[63] More recently, software defined radio infrastructure systems have been introduced that support multiple independent competitive networks, each running a different physical layer air interface, on top of a single virtualized hardware platform.[64] Such equipment significantly reduces the infrastructure build-out required for a competitor to light up a new network.

Given that open access obligations may be imposed either at the application layer or at the physical layer for wireless communications resources, the question becomes which is more desirable from a policy perspective. Application layer open access rules reduce the investment required for a downstream competitor to introduce a new over-the-top service. Physical layer open access rules reduce the barrier to a competitor introducing a new network design, for

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[63] This issue has largely been rendered moot with the recent emergence of third-party tower companies that have acquired most of the towers from incumbent wireless operators. The tower companies' business plans assume that multiple operators will share tower space, and they actively seek new tenants.

[64] See for example the Vanu, Inc. MultiRAN virtual base station product (see http://www.vanu.com/solutions/multiran.html).

example with a new air interface, MAC or data transfer scheduling algorithm. The choice between these two types of rules is a choice whether to favor the establishment of new over-the-top services or the establishment of entirely new networks.

Put in these terms, it is clearly desirable to pursue both approaches in parallel. Some level of encouragement of network-level innovation is needed, because the primary constraints in wireless broadband are physical layer constraints (spectrum availability, attenuated channels and multipath, interference). Improving overall service levels requires ongoing improvements at the physical layer, which can only be delivered through deploying new networks. On the other hand, the barrier to deploying a new network is still relatively high, so it is beneficial to facilitate easy deployment of innovative over-the-top services through application-layer partitioning.

6.4. Spectrum reform challenges

Increased RF spectrum sharing is required for future growth of wireless broadband, since there is not enough unallocated spectrum available to meet growth projections for even the next decade. Fostering increased sharing of the RF spectrum will require further policy reforms and the building of an ecosystem. At the root is the goal of unbundling (not by regulatory mandate, but by reforming technical designs and industry structure) the RF spectrum from the wireless infrastructure networks that use the RF, and ultimately, the applications and retail services that are delivered via the wireless networks.

Elsewhere we have discussed the importance of moving toward more flexible spectrum sharing, including Dynamic Spectrum Access (see Chapin & Lehr, 2007). We reserve further discussion of what is involved from a policy perspective to a companion paper.[65]

7. Future of Wireless Broadband is Not a Platform but a Hybrid Network

The conclusion of the above arguments is that the broadband platform model is neither a good description of current wireless broadband systems nor does it describe an optimal endpoint for future evolution. The fundamental technical differences between wired and wireless networks, the different economic issues surrounding network deployment and operation, and the different regulatory treatment arising from different histories mean that the broadband platform model which dominates wired networks is inappropriate in wireless.

An alternate model called *hybrid wireless broadband* is a better description of current wireless broadband services and a better guide to future evolution and policy making. A detailed analysis of this model and its policy implications is provided in a companion paper. Briefly, a hybrid wireless broadband service is a high-capacity general-purpose service implemented via multiple overlaid wireless networks, some of which share resources with other systems. Such a service is hybrid in two senses. It integrates multiple wireless networks to serve the user's needs, for example a voice specific network and a data-only Internet access network. It also combines multiple economic models to serve the user's needs, for example dedicated resources (e.g. exclusively licensed spectrum) and shared resources (e.g. unlicensed or dynamic spectrum access).

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[65] See “Hybrid Wireless Broadband,” forthcoming.

While current wireless broadband services make only limited use of shared resources, and only for non-core aspects of the service, the increasing squeeze of spectrum capacity limitations as market penetration and per-user demand grow will make resource sharing a critical requirement for the future success of wireless broadband. Some combination of provider policies and user decisions will split traffic on a per-service or per-transaction basis between transport mechanisms that exploit dedicated resources—with associated better QoS but also higher cost—and those that exploit shared resources—with potentially higher delay or congestion but also lower cost. We see this effect operating to a limited extent today, for example with smartphones that give the user the option of acquiring some services via 802.11 Wi-Fi hotspots (shared resources) or via the macro cellular network (dedicated resources).

Over time, users of wireless broadband services will gain increasing control over network, service and pricing options. Enablers for this include increasing device flexibility, open handset architectures not controlled by service providers, and hybrid wireless services where individual subnetworks compete on cost and efficiency, all of which tend to reduce switching costs for users and thereby increase the level of competition among providers. This situation is fundamentally different from wired broadband networks, in which the user has little control over service options on a day-to-day basis. Multihoming does occur in wired broadband networks, for example some businesses connect to multiple providers. However, even with a substantial increase in business use and some mass-market uptake, multihoming will still cover only a tiny fraction of the wired broadband market and is therefore unlikely to significantly affect the playing field. We expect limited and slow customer switching among facilities-based wired broadband providers.

The fundamental differences in appropriate network architecture and competitive dynamics between wired and wireless services have significant policy implications. Different trajectories are likely to lead to systematically different industry and market structures, as well as different service provider business models. Therefore the optimal regulatory treatment will continue to be asymmetric rather than evolving toward full regulatory neutrality.

Asymmetric regulatory treatment is optimal even though convergence will continue. We can expect increased intermodal competition among wireless technologies and between wired and wireless broadband services. This is a first-order effect that renders all forms of silo-based regulation suspect. There is a strong argument against regulations that assume or promote the persistence of clear industry boundaries within which there is close coupling between technology, infrastructure, and services. Instead there will be strong cross-market interaction effects. For example, mobile 3G/4G will compete with wired platform technologies in offering telephony, video, and data services (either separately or as bundles), while wired service providers will seek to deliver at least some of the benefits of mobility and personalization. Over time this competition will lead to increased interoperability and integration of multiple wired and wireless platforms.

Even with ongoing convergence, regulators must be cautious when applying policies developed for the broadband platforms characteristic of next generation wired networks to broadband wireless services. We have discussed several areas of concern in this paper. Open access regimes must differ since bitstream unbundling has fundamentally different impacts on wired and wireless networks, given both the underlying technical issues involved and the critical issues surrounding capacity limits of wireless networks. Intercarrier compensation reform is also affected, for example the viability of bill-and-keep for wireless services and the economic differences in termination costs that prevent uniform termination charges for wired and wireless infrastructure. Finally, goals of service and technical neutrality must be shaped appropriately for the structural and legacy differences between the two service types, in particular for the difference between broadband platforms and hybrid wireless systems.

Future technical innovation in wireless systems will only exacerbate the differences between wired and wireless broadband services. Increased device flexibility through maturation of software defined radio technology will reduce barriers to greater specialization of wireless networks to specific applications and services. Increased deployment of cognitive radio technology will enable fine-grained reallocation of spectrum and other resources to optimize performance and economic returns within complex hybrid wireless systems. Finally, open handsets and growth of dynamic spectrum access may lead to proliferation of infrastructure-less (mesh or ad-hoc) networks.

Whatever form the innovation takes, it seems likely that wireless broadband services will evolve significantly over the coming decades. Their evolution should not be constrained by a regulatory framework derived from more mature wired broadband networks and ecosystems.

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