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Expanding mobile wireless capacity: The challenges presented by technology and economics[☆]

Richard N. Clarke[*]

AT&T, Suite 400 North, 1120 20th Street NW, Washington, DC 20036, USA

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ABSTRACT

As demand for mobile broadband services continues to explode, mobile wireless networks must expand greatly their capacities. This paper describes and quantifies the economic and technical challenges associated with *deepening* wireless networks to meet this growing demand. Methods of capacity expansion divide into three general categories: the deployment of more radio spectrum; more intensive geographic reuse of spectrum; and increasing the throughput capacity of each MHz of spectrum within a given geographic area. The paper describes these several basic methods to deepen mobile wireless capacity. It goes on to measure the contribution of each of these methods to historical capacity growth within U.S. networks. The paper then describes the capabilities of 4G LTE wireless technology, and further innovations off of it, to further improve network capacity. These capacity expansion capabilities of LTE-Advanced along with traditional spectrum reuse are quantified and compared to forecasts of future demand to evaluate the ability of U.S. networks to match future demand. Without significantly increasing current spectrum allocations by 560 MHz over the 2014–2022 period, the presented model suggests that U.S. wireless capacity expansion will be inadequate to accommodate expected demand growth. This conclusion is in contrast to claims that the U.S. faces no spectrum shortage.

1. Overview

Demand for mobile wireless services continues to explode. Cisco's latest *Visual Networking Index* (*VNI*) reports that “global mobile data traffic grew 70% in 2012,” driven by average connection speeds that more than doubled from 248 kbps to 526 kbps (Cisco, 2013, p. 1). Further, Cisco estimates that by 2017, global mobile data traffic will exceed its 2012 level by a factor of 12.6. While in many parts of the world, significant portions of expansion in mobile wireless network capacity will continue to be due to expansions in the geographic coverage of wireless data networks, in developed countries such as the

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[☆] The analyses and data presented in this paper are intended to portray the U.S. mobile wireless industry on a national average basis. They may not be representative of any particular U.S. geographic region or mobile operator, including AT&T. No proprietary AT&T data were used in performing these analyses. The conclusions developed in this paper are those of the author, alone, and should not be construed as representing any official position of AT&T. I am indebted to my colleagues at AT&T and Peter Rysavy for valuable assistance in preparing this paper. Very useful suggestions were also received from two anonymous reviewers. All remaining errors are my own. An earlier version of this paper was presented at the 19th Biennial Conference of the International Telecommunications Society in Bangkok on November 20, 2012.

[*] Tel.: +1 202 457 2130.
E-mail address: rnclarke@att.com

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U.S., advanced mobile broadband networks already cover 98.5% of potential subscribers (FCC, 2011, ¶ 46). Thus, the network expansions necessary to accommodate demand growth in developed countries will focus most greatly on *deepening* network capacities. Technically and economically, this presents a different set of challenges from simply expanding coverage scope – a topic that has been addressed extensively in universal service research.[1]

The purpose of this paper is to describe and quantify the challenges particularly associated with wireless network deepening. This includes an analysis of the technical issues concerning what techniques for capacity deepening are feasible, and also consideration of the costs of these techniques to determine the economic capability of these techniques to keep up with growing demand. While certain parties have suggested that improvements in technology to increase throughput capacity per megahertz (MHz) of spectrum and increased geographic reuse of spectrum will be adequate to address wireless demand growth in the U.S. over the next five to ten years, this analysis finds otherwise.[2] Although methods to improve throughput capacity per MHz or increase spectrum reuse may be technologically feasible, and are expected to be used intensively by wireless providers, by themselves they are likely to be inadequate or to become uneconomic absent significant increases in mobile wireless pricing. Thus, even under the conservative modeling assumptions of this paper, substantial quantities of additional spectrum (on the order of 560 MHz) will need to be deployed for mobile wireless use if currently forecasted demand is to be satisfied over the next decade without significant service quality degradation or rationing from price increases.

This finding is consistent with the conclusions developed by several other studies in the literature that have examined the ability of current or expected spectrum assignments and technologies to accommodate forecasted demand.[3] The analysis presented in this study will differ from these prior efforts both by improving on the accuracy of their analyses and by projecting certain enhancements in the ability of evolving wireless technologies to carry more mobile traffic.

This paper begins by describing the basic techniques that may be used to expand mobile wireless capacity. These include increasing raw amounts of available radio spectrum, increasing the absolute carrying capacity of each MHz of spectrum, reducing the bandwidth required to carry popular applications, and increasing the utilization of each MHz of spectrum or unit of infrastructure through cell-splitting, sharing or multiple use. In Section 3, this history of technological evolution is contrasted with both the growth in available mobile wireless spectrum and the growth in mobile wireless demand. The paper goes on to catalog the possible forward-going capabilities and economics of several of the most well-known potential Fourth Generation (4G) Long Term Evolution (LTE) wireless technology innovations, including innovations whose effects remain highly speculative. By comparing the joint capacity expansion capabilities of these new and old techniques with demand growth estimates, it is possible to evaluate their ability to accommodate demand growth and to reduce upwards pressure on current wireless pricing. In the end, the analysis demonstrates that by themselves, these methods will be inadequate to accommodate fully expected demand growth at today's prices. Thus, increased assignment of radio spectrum to mobile wireless will be essential. This is in contrast to suggestions from certain parties that spectrum scarcity should not be a terribly significant concern for government policymakers.

2. Mobile wireless capacity expansion techniques

Methods for expanding mobile network capacity divide into three general categories: the deployment of more radio spectrum; more intensive geographic reuse of spectrum; and increasing the throughput capacity of each MHz of spectrum within a given geographic area.

The carrying capacity of a mobile wireless system is the total amount of data or voice traffic that the system is able to transfer to and from customers.[4] Wireless data are carried by modulating or distorting radio waves. The quantity of waves (or amount of spectrum) a wireless system is allowed to modulate each second is called its bandwidth, and is measured in hertz (Hz). Everything else equal, a signal with a higher bandwidth (i.e., more Hz) can carry more data per second than a signal of lower bandwidth (i.e., less Hz).

The total amount of data that a network may transfer over a given period of time relates closely to the rate at which it transfers data bytes. All things equal, a faster network will transfer more bytes than a slower network. Rates of data transfer are measured in terms of bits per second (bps).[5] Note, however, that in addition to raw transmission speed, the total amount of data transfer will be higher on a network that operates as a higher usage/fill factor (i.e., transfers data during more seconds of the measurement period). This can be achieved if a network has traffic offered more uniformly to it over the measurement period – either because the network serves multiple users whose patterns for offering traffic to the network

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[1] See, for example, Williams et al. (2011).

[2] See Bazinet and Rollins (2011), Bode (2012), Burstein (2011), Chen (2012a,b) and Reardon (2010) for arguments suggesting that the U.S. faces no serious shortage of mobile wireless spectrum.

[3] See FCC (2010b), Feldman et al. (2011), Lawson (2012), Rysavy (2011) and Rysavy Research (2010, 2011a,c) for analyses suggesting that mobile wireless spectrum will become critically scarce.

[4] In general, the capacity of the total network will be limited by the capacity of its last-mile radio access network (RAN). Although congestion on fixed backhaul links may possibly occur, increased availability of fiber backhaul facilities should allow backhaul bottlenecks to be engineered away.

[5] By convention, data transfer rates are typically measured in terms of bits (b), and data quantities in terms of bytes (B). Because there are eight bits in a byte, a transfer rate of 8 bps corresponds to transferring one byte per second (1 Bps).

are less than perfectly correlated, or because the network employs packet scheduling protocols that efficiently divide traffic into different queues based on the immediacy of their need for transmission.[6]

Perhaps the most well-known way for cellular networks to increase the amount of data they carry is by dividing or splitting cells to reduce cell size, and thus increase the number of cells serving a given area. This is done by deploying more radio towers/antennas and shrinking the reach of each tower by reducing the radiated power of its radio transmissions. This allows radio spectrum to be *reused* for multiple simultaneous transmissions within the geographic area. Thus by subdividing cells, the amount of traffic that a Hz of spectrum can carry within an overall geographic area (measured by bps/km^2) is increased. But while very effective at deepening wireless network capacity, this method is also expensive – requiring the construction of extra towers/antennas, deploying more radios and base station equipment; as well as extending additional backhaul links to link new towers back into the mobile operator's core network.[7]

Over the past thirty years, mobile wireless networks have evolved from First Generation (1G) to Fourth Generation (4G) technologies that make increasingly efficient use of available radio spectrum. In the following sections, the contributions of 4G technical enhancements are developed – and compared with contributions to capacity growth from raw spectrum growth and increased reuse of available radio frequencies.

3. Analysis of historical demand and spectrum growth

3.1. Growth in mobile usage

The history of U.S. mobile services demand has been one of continuous and increasingly rapid growth. If voice minutes are converted into data traffic equivalents, it is possible to chart historical rates of total mobile demand growth. This is shown in Fig. 1. As can be seen, U.S. data usage outstripped voice usage by the end of 2009, and by 2012 data usage exceeded voice usage by a factor of 7.5.[8]

This explosive growth in data demand has been the product of two forces: increasing numbers of subscribers adopting advanced mobile data devices and increasing monthly use of mobile data services by the subscribers that are using these devices. Because adoption of smartphones is now nearing 70% in the U.S., it is possible that the first force driving mobile usage growth may begin to stabilize, but the latter shows no hint of flagging.[9] Cisco estimates that while current mobile data growth rates may be the maximum that may be seen in the advanced countries, these growth rates will decline only slowly.[10] Total mobile traffic growth is shown in Fig. 2.[11]

3.2. Growth in spectrum resources

In contrast to the exponential growth in mobile bandwidth demand, U.S. mobile spectrum has been doled out at a far more moderate pace. Table 1 illustrates the significant assignments of wireless spectrum by the Federal Communications Commission (FCC) for U.S. mobile use.

While Table 1 lists current mobile wireless spectrum allocations by the approximate year the assignments were made, it does not give an accurate indication as to the amount of spectrum actually built-out by mobile wireless operators. Build-outs typically lag spectrum assignment dates by a number of years (Rysavy, 2012). There are several reasons. First, some of the spectrum bands were not cleared of their previous occupants as of the date of their reassignment to mobile wireless. This was particularly true of the EBS/BRS and AWS-1 bands. Second, build-outs, especially of new technologies, take planning and time. Thus, for the purpose of evaluating the actual amount of spectrum available to meet customer demand, the analysis shall employ a rough rule that build-outs of spectrum in new frequency bands do not start until a year or more following its assignment, and that its full deployment into the market then takes place over an interval of four

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[6] Not all traffic requires immediate handling. If data bytes supporting a voice conversation are not transferred immediately, the conversation will become broken up and unintelligible. But data bytes supporting certain file transfers may tolerate delays quite well. Indeed, the speed at which a file is transferred is best indexed by how soon its last byte is transferred, and not by how quickly any of its intermediate bytes arrive. Thus, if file transfer bytes are held briefly and interspersed into gaps in a voice transmission, it is quite possible for a joint-use wireless channel to operate far more efficiently than if separate channels were used to satisfy each demand. See Yuksel et al. (2010).

[7] Reuse techniques may also be slow to implement – as regulatory approvals may need to be obtained before new cell sites are deployed or additional equipment is placed at pre-existing sites.

[8] Similar global figures are shown in Ericsson (2012a, 2012b).

[9] See Credit Suisse (2012, p. 65) and Ericsson (2012b). Although smartphone penetration may be close to saturation, customers are adding still additional mobile devices like tablets to their portfolio. Further, widescale adoption of machine-to-machine devices is just beginning (OECD, 2012). As the "Internet of Things" evolves, there may be no limits to how many new data devices will seek to be connected to mobile networks.

[10] Cisco (2013) projects figures to 2017. To continue the projection out to 2022, Cisco's projected 2016–17 growth rate of 42% is reduced by 10% each year to reach a growth rate of 25% in 2021–2022. This latter growth rate matches reasonably current growth rates in wireline broadband use per subscriber (Cisco, 2012b).

[11] The presented traffic growth assumptions may be conservative. Qualcomm believes that mobile data growth from 2010–2020 will be a factor of 1000 × . This figure is much higher than Cisco's assumption of a 103 × data growth factor over this period. See http://www.qualcomm.com/media/blog/2012/08/09/heard-1000x-challenge-hint-it-s-about-mobile-data-growth. Note too, that Cisco's mobile traffic projections include only traffic passing over mobile carrier RANs. Traffic that mobile devices transmit over Wi-Fi connections, while large and growing, is considered by Cisco to be fixed traffic and included its *VNI* fixed traffic estimates (Cisco, 2013).

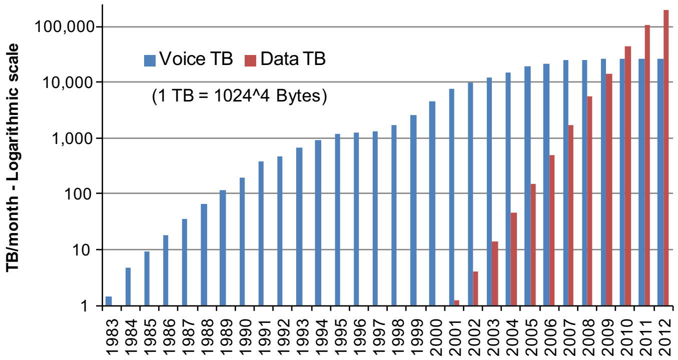

Fig. 1. History of voice and data demand growth. *Notes*: Voice TBs calculated from CTIA (2013) data on mobile minutes, adjusted to data equivalents assuming 20 kbps encoding for digital networks (2G+) and 60 kbps for analog networks (1G). Data TB from Cisco (2009–2011, 2012a and 2013) for 2008–2012, and extrapolated backwards for 2001–2007.

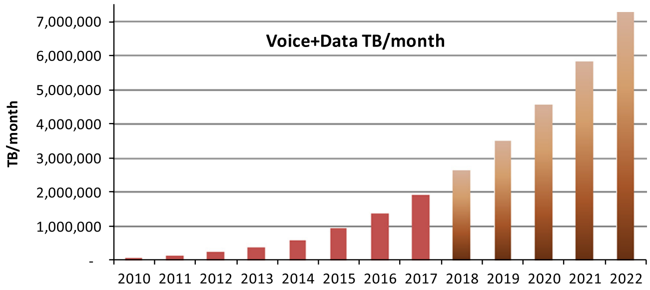

Fig. 2. Forecasted growth in mobile demand. *Notes*: Voice and Data TB figures for 2010–2012 are from Fig. 1. Forecasted 2013–2022 Voice demand growth assumes Voice TB remain flat at 2012 levels. Cisco (2013) figures for Data TB are used for 2013–2017 Data demand. These Data TB figures are extrapolated forward for 2018–2022 assuming that Cisco's forecasted demand growth rate for 2016–17 decays by 10% each year over the 2018–2022 period.

Table 1
Timeline of U.S. mobile spectrum allocations.

Year	Allocation (MHz)	Band (MHz)	Name
1983	40	850	Cellular
1989	10	850	Cellular
1993	14	800	SMR
1995	130	1900	PCS
2005	194[a]	2500	EBS/BRS
2006	90	1700/2100	AWS-1
2008	70	700	700 MHz
Total	548 (assuming all EBS/BRS spectrum to be usable) 409.5 (assuming only 55.5 MHz of EBS/BRS spectrum)		

Notes: Data in this table are assembled from Bazinet and Rollins (2011), FCC (2011, ¶¶ 270–275) and Feldman et al. (2011). Different data sources may suggest slightly different quantities for U.S. mobile wireless spectrum and allocation dates. These small quantity or timing differences are inconsequential for the purposes of the following analysis.

[a] Most EBS/BRS spectrum is leased by Clearwire from its primary licensees, who are educational or religious institutions and providers of wireless CATV services. Because current FCC rules require certain portions of this spectrum to remain in educational use and may involve other encumbrances, the FCC currently considers only 55.5 MHz of this spectrum to be immediately deployable for mobile wireless use. See 〈http://wireless.fcc.gov/services/index.htm?job=service_home&id=ebs_brs〉; 〈http://wireless.fcc.gov/services/index.htm?job=licensing_1&id=ebs_brs〉 and 〈http://wirelessspectrumreview.com/wireless-spectrum-bands/brsebs/〉.

years.[12] Based on these assumptions it is possible to better compare growth in mobile traffic versus spectrum resources. This is presented in Fig. 3. It is important to emphasize the difference in the scales used on this chart to measure spectrum growth versus traffic growth. The former is on the left, the latter on the right. Thus, if one looks at 1994 as a base, since that time

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[12] The exceptions made to this general rule are as follows. Buildouts of the initial Cellular allocation are assumed to have begun in the year of assignment. For the extra 10 MHz added to the Cellular band in 1989, deployment is assumed to have begun in the same year as assignment and completed the following year. For the AWS-1 and 700 MHz spectrum bands, it is assumed that buildouts did not commence until two years after the year of assignment. Note that these assumptions are quite rough, but even moderate changes to them will not alter general patterns in any significant sense.

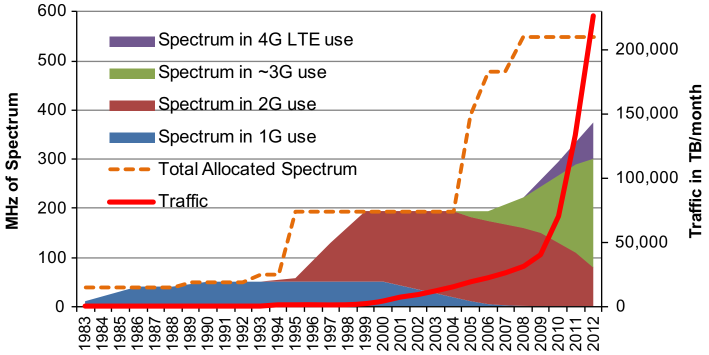

Fig. 3. Spectrum growth versus traffic growth. *Notes*: Gross spectrum quantities based on Table 1, with author's estimates from note 15 to divide by technology deployed and date of build-out. Traffic data are from Fig. 1.

allocated spectrum has increased from 64 MHz to 548 MHz (assuming all of the EBS/BRS spectrum will be usable) – a factor of 8.6. But over the same 1994–2012 period, total traffic has risen from 900 TB/month to 226,916 TB/month – a factor of 256.

To be sure, while Fig. 3 provides information about the amounts of spectrum licensed and built out to provide mobile services, it does not inform directly as to the amount of this lit spectrum that was actually being used to carry the mobile wireless demands that were offered to these networks in the given years. Such an estimate is essential to determine the amount of *headroom* that may exist in built-out U.S. mobile networks – and may remain available to accommodate increases in customer demand. For the purposes of evaluating the ability of U.S. mobile networks to accommodate increasing future demand, it is most useful to have a relatively recent estimate for this headroom. For several reasons, 2010 is chosen. Not only is 2010 recent, but it is a year that just precedes significant rollouts of services provided over AWS-1 or 700 MHz spectrum. Further, it is relatively soon after Clearwire began deploying small quantities of service over its EBS/BRS spectrum. Thus, in 2010 it is assumed that the amount of spectrum that was actually being consumed to offer mobile services was 194 MHz (=50 MHz Cellular+14 MHz SMR+130 MHz PCS).[13] But to be especially conservative in estimating needs for additional spectrum, an additional assumption is made that the 194 MHz of spectrum consumed in 2010 was not used as intensively (i.e., with as high a fill factor) as may be the case in the future. Based on analyst reports that lit U.S. mobile networks are operating at only 80% of their capacity on average, the figure this analysis employs for 2010 baseline spectrum usage is adjusted down to 155.2 MHz (=0.80 × 194 MHz).[14]

From 2009 through 2011 there were no significant additional allocations of mobile wireless spectrum by U.S. regulatory authorities.[15] But this began to change in 2012 as 12 MHz of unpaired lower 700 MHz spectrum that was previously used for broadcast fixed or mobile TV was transferred to mobile wireless;[16] and further FCC rule changes enabled 20 MHz of 2300 MHz WCS spectrum and 40 MHz of 2200 MHz S-Band MSS spectrum to be used for terrestrial mobile services.[17] As a result, 72 MHz of additional spectrum may be forthcoming for U.S. mobile wireless – and several other bands are also under study by the FCC and other government authorities for conversion to possible mobile wireless use.[18] While these reallocations or potential reallocations are promising, the effective capacity augmentations they may offer remain speculative as successful repurposing of these spectrum bands for two-way terrestrial mobile wireless is by no means assured. Technical or regulatory roadblocks may occur. Thus for future analysis, the analysis assumes, alternatively, that: (a) no additional spectrum to the 2011 figure of 548 MHz is able to be built out in time to serve customer demand over the

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[13] While it was likely that in 2010 some service was being provided over EBS/BRS and AWS-1 spectrum, these quantities were quite small. Further, it is also likely that there was still some modest amount of headroom remaining within Cellular, SMR and PCS spectrum as of that date. The effects of these two over-simplifications are assumed to roughly cancel each other. This assumption of 194 MHz occupancy in 2010 is also somewhat consistent with the estimate of 170 MHz occupancy in 2009 assumed in FCC (2010b) and the assumption of 192 MHz use in 2011 by Bazinet and Rollins (2011).

[14] See Credit Suisse (2011) for survey results that North American mobile networks are operating at 80% of capacity. Reducing this baseline figure for effectively utilized spectrum implies that a greater amount of past FCC spectrum allocations remain available to serve future demand – thus reducing implied future needs for additional spectrum.

[15] Certain attempts were made, however. In January 2011, the FCC issued an Order permitting LightSquared to repurpose 66 MHz of L-Band Mobile Satellite Service (MSS) spectrum to terrestrial mobile use. See http://hraunfoss.fcc.gov/edocs_public/attachmatch/DA-11-133A1.pdf. This spectrum, however, was adjacent to spectrum used by Global Positioning System (GPS) satellites and use by LightSquared of this spectrum was ultimately adjudged to interfere with neighboring GPS services. As a result, in February 2012 the FCC withdrew LightSquared's conditional authorization to use this spectrum for terrestrial mobile wireless. See http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-312479A1.pdf.

[16] See FCC Order approving the transfer of unpaired 700 MHz spectrum from Qualcomm to AT&T at http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-11-188A1.pdf.

[17] See FCC Orders approving terrestrial mobile use of the WCS band at http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-12-130A1.pdf and approving terrestrial mobile use of the MSS S-band at http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-12-151A1.pdf.

[18] These include up to 120 MHz in the 600 MHz UHF band currently used by broadcast television service and a portion of the 95 MHz in the 1750–1850 MHz band currently used by government agencies. More immediately, it is possible that 20 MHz of government spectrum in the 1755 MHz band could be paired with 20 MHz in the 2155 MHz AWS-3 band. For a fuller discussion of these future possibilities, see http://transition.fcc.gov/statelocal/presentations/Incentive-Auctions-MB.ppt, NTIA (2012), and more generally FCC (2010a, pp. 85–89).

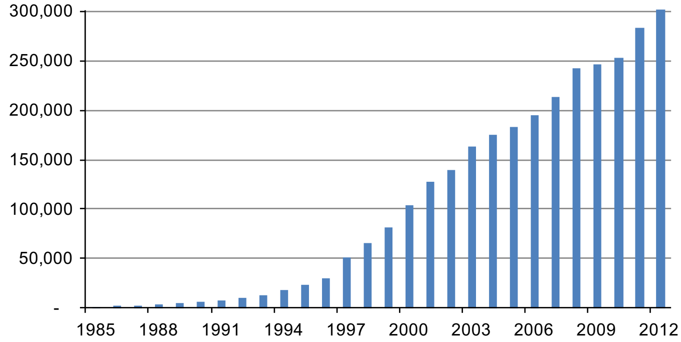

Fig. 4. Number of U.S. cell sites. *Notes*: CTIA (2013) count of cell sites. Note that CTIA's count is by network technology by physical location.

2012–2022 period;[19] and (b) the FCC is successful in reallocating a total of 300 additional MHz of spectrum to mobile wireless and this spectrum is built out over the 2014–2022 period.[20] The former may be considered a pessimistic assumption and the latter an optimistic one.[21] It is likely that actual effective spectrum additions will range somewhere between these two figures.[22]

3.3. *Intensity of spectrum reuse*

Fig. 3 shows that mobile usage has grown orders of magnitude faster than available spectrum, thus provides telling evidence that so far the largest contributor to increased mobile capacity in the U.S. has been investment by mobile operators to evolve networks to more spectrally-efficient technologies and to erect more cell towers that enable more intensive reuse of the radio frequencies that have been allocated to mobile wireless. When one examines the data, it is clear that most of this capacity uplift has been due to more intensive reuse. From 1985 to 2012, cell site counts have grown by a factor of 330. This history of cell site expansion is displayed in Fig. 4.

While this may suggest that capacity reuse has also risen by a factor of 330, the capacity effects of this proliferation of cell sites are hard to quantify precisely. For example, in the early years of a mobile technology's deployment, it is likely that most new sites were deployed to extend coverage of that technology, and not simply to increase the capacity of that technology within already covered areas. In the later years of a technology's deployment, capacity increases are more likely to be the purpose of new sites. But, because later deployments may be disproportionately of micro or pico cells, which are designed to serve smaller areas and traffic quantities, incremental capacity expansion per-site may decrease as cell site counts rise.[23] But if it is generously assumed that all recent site deployments have been strictly to improve capacity, and that these deployments provide an effective uplift in network capacity in direct proportion to their number, this suggests that if site deployment rates observed over the last six to ten years continue, traditional reuse will provide about an 8% per year increase in capacity to serve demand growth.

4. Spectral efficiency and unfolding 4G LTE technological capabilities

4.1. *Evolution of U.S. spectral efficiency and reuse*

Over the past thirty years there have been two sources of improved spectral efficiency of U.S. mobile networks: deployments of wireless technologies that are more spectrally efficient; and increasing the quantity of spectrum used by

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[19] Note that while this assumption may appear to neglect the contribution of the 72 MHz that has been newly provided in 2012, it also presumes that all 194 MHz of EBS/BRS spectrum previously assigned to mobile wireless (most of which still remains fallow) will be deployed over the 2012–2022 period.

[20] The FCC's *National Broadband Plan* (issued in March 2010) calls for an additional 300 MHz of spectrum to be allocated to mobile wireless by 2015, and for a total of 500 MHz to be added by 2020. See FCC (2010a, p. 84).

[21] Realistically, given that only 72 MHz has been added since the date of the *National Broadband Plan*, without significant changes in U.S. spectrum regulatory policy there is very little probability that a further 228 MHz of spectrum could be provided and built out within the 2014–2022 timeframe to meet even the *National Broadband Plan's* 2015 target of 300 MHz in additional spectrum. Lead times for identifying, auctioning, clearing and building out spectrum are generally on the order of 8–10 years. See FCC (2010a, p. 79).

[22] A recent U.S. government report (PCAST, 2012) recommends that 1000 MHz of government-controlled spectrum within the sub-4000 MHz bands be made available for shared, secondary use by commercial mobile wireless. While ambitious, it is extremely unclear as to whether this proposal is practicable from a technical or economic point of view, and even if it is, whether it can have any appreciable effect within the 2014–2022 time period. As noted earlier, North American mobile networks already operate at 80% utilization within their exclusively licensed bands. Thus, the opportunity to share, on an idiosyncratic secondary basis, some additional spectrum, poses substantial economic challenges. New network equipment and cell sites would need to be deployed, only to be able to make partial unassured use of these new bands. This suggests that the additional costs of using these shared bands may be disproportionate to their effective capacity uplift. Further, it is unlikely that all frequencies would be available throughout the country – or in the particular locations most in need of additional capacity.

[23] See Chapin and Lehr (2011, p. 32), FCC (2010a, p. 77), Goldstein (2012) and Paolini (2011).

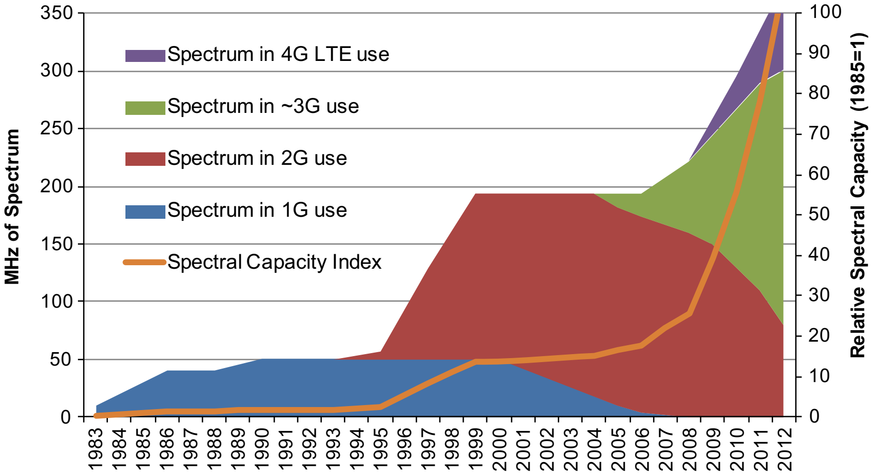

Fig. 5. Capacity expansion from spectrum expansion and migration of users to more spectrally-efficient technologies. *Notes*: Division of spectrum by technology and dates of build-out are from Fig. 3. Spectral efficiency factors used to compute spectral capacity are from Rysavy Research (2012b, p. 55).

these more efficient technologies relative to the quantity of spectrum used by older, less efficient technologies. For the purposes of the analysis presented here, 1G technologies are assumed to have a spectral efficiency of less than 0.1 bps/Hz on a sector basis; 2G technologies have an efficiency of 0.25 bps/Hz; ~3G technologies an initial efficiency of 0.5 bps/Hz – rising to between 0.90 bps/Hz and 1.0 bps/Hz for advanced implementations such as EV-DO, Rev. A or 4G HSPA+;[24] and current 4G LTE technologies 1.4 bps/Hz.[25] Based on these spectral efficiency figures and estimates of the quantities of U.S. mobile spectrum deployed to different technologies, it is possible to map the evolution of the potential capacity of U.S. mobile networks to handle voice and data traffic. This is displayed by the Spectral Capacity Index in Fig. 5 (scale on right side of the chart). As can be seen, the deployment of more spectrum and the implementation of more efficient ~3G and 4G technologies have provided a substantial uplift in mobile network carrying capacity.

But in addition to capacity growth due to spectrum expansion and the migration from older technologies to newer ones, there has also been increased reuse of frequencies due to the deployment of additional cell sites (Reuse Index). These two capacity expansion factors can be combined to estimate the total growth in U.S. mobile network capacity (Total Capacity Index).[26] This index is displayed in Fig. 6 where it is compared against an index of past traffic growth.

While mobile network capacity expansion has been impressive in its ability to roughly match past rates of demand growth, mobile capacity expansion faces an even more daunting task in keeping up with the projections for future demand growth displayed in Fig. 2. Whether or not it will be successful will depend importantly on future contributions to capacity growth from advances in 4G LTE technology. These will be discussed in the following section.

4.2. *Efficiency improvements from future 4G LTE innovations*

While current LTE networks are significantly more spectrum-efficient in carrying mobile traffic than earlier network technologies, LTE is capable of even further improvements as its technology progresses to LTE-Advanced (LTE-A or 4G+).[27] These improvements divide into three categories: increasing the raw transmission throughputs over LTE radio links; further increasing the possibilities for spectrum reuse; and packing offered traffic more efficiently into available transmission capacity.[28]

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[24] EV-DO stands for Evolution-Data Optimized and HSPA stands for High Speed Packet Access. Although HSPA+ technology has very high speed performance (21 Mbps and above) and is therefore recognized as a 4G technology by the International Telecommunications Union (ITU, 2010); its spectral efficiency is similar to that of 3G technologies. Therefore, for the purposes of the spectral efficiency analysis (not speed analysis) used in this paper, 4G HSPA+ is included in the ~3G category.

[25] See Rysavy Research (2012b, pp. 54–55) and Rysavy Research (2011b). These figures represent the consensus view of 4G Americas contributors of the actual mobile spectral efficiencies expected under real-world network conditions. As such, they are lower than other estimates developed under simulated ideal network conditions. While these efficiency figures may be imprecise, all that is absolutely necessary is that they provide a reasonably accurate picture of the *relative* spectral efficiencies of the presented technologies.

[26] Note that the presented capacity growth index is illustrative only. This is because this index does not account for possible changes in network packing over the 1985–2012 period. See Section 4.2.3 for a further discussion of network packing as a possible source of effective capacity growth.

[27] The progression of LTE technology is indexed by different releases of 3GPP specifications – with initial LTE-A specifications in Release 10. See Rysavy Research (2012b, pp. 24–26). It is possible that certain of the enhancements termed "4G+" are part of Releases earlier than 10, but since they are only now in the process of first implementation in networks, they will, for convenience, be called "4G+."

[28] Lawson (2012) and Real Wireless (2010) also provide catalogs of capacity expansion techniques. See Bhat et al. (2012) for more technical discussions as to how LTE-A achieves these improvements.

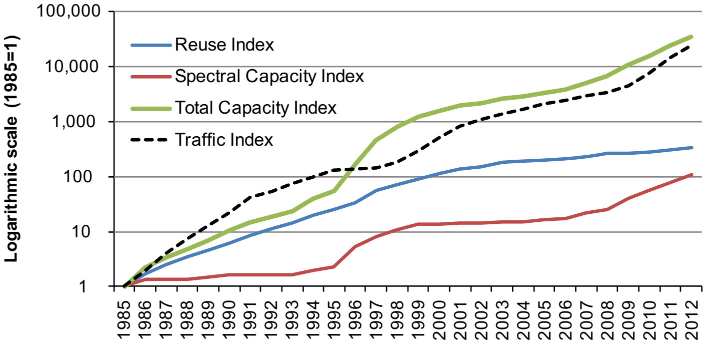

Fig. 6. Contributions of increasing spectral efficiency and frequency reuse to overall mobile network capacity. *Notes*: Reuse figures from Fig. 4, spectral capacity figures from Fig. 5 and traffic figures from Fig. 1. Total capacity index is the product of these two component indices.

4.2.1. *Improved transmission throughputs*

Perhaps the most dramatic potential improvements in LTE's capacity to handle traffic derive from higher-order Multiple Input Multiple Output (MIMO) implementations.[29] Current LTE deployments use 2 × 2 MIMO. This places two antennas at the base station and two antennas in the user device.[30] Because of the slight physical displacement of each transmitting antenna from the other transmitting antenna(s) and of each receiving antenna from the other receiving antenna(s), each sent and received signal will be subject to different multipath characteristics.[31] By examining the four signals together, more of the originally encoded information may be extracted. In addition, MIMO technology may be used to send multiple concurrent transmission streams between the base station and user device. This too may increase throughput over a given amount of spectrum[32] Implementations of 4 × 2, 4 × 4, and even 8 × 8 MIMO are already part of LTE-A specifications. While theoretically, 4 × 4 MIMO should provide twice the throughput of 2 × 2 (although at higher power usage), and 8 × 8 MIMO four times the throughput of 2 × 2, field tests suggest that actual uplifts are substantially less (Rysavy Research, 2012b, p. 56). However, these important advances come with their own challenges. First, mobile user devices generally are quite small. Although it has been possible to place two diverse antennas within their form factor, placing four or eight diverse antennas is much more problematic. Indeed, it may be that throughput advances from higher-order MIMO will only be won at the cost of physically larger and more power-hungry mobile devices. Second, placing additional radio transceivers at cell sites also bears increased costs for equipment, tower structure and electric power.

Another technology being developed is called Coordinated Multi-Point transmission/reception (CoMP). This technology leverages what would otherwise be undesirable interfering transmissions from adjacent cells or sector antennas by having user devices purposefully communicate with several cell sites (or sector antennas at a single cell site) simultaneously. Because CoMP coordinates these transmissions, what was previously interference from adjacent cell sites or sector antennas is actually converted into useful information-carrying bandwidth, and a more robust total signal received (Rysavy Research, 2012b, pp. 103–105). While potentially valuable, CoMP is expected only to enter LTE-A specifications via 3GPP Release 11 in late 2012, and its potential implementation in commercial networks is at least several years in the future.

However, these two significant throughput-improving advances associated with LTE-Advanced are not achieved just through software tweaks. Higher-order MIMO requires new antennas at base stations, and completely new user devices that incorporate both the increased number of antennas and the chipsets necessary for the more complex processing of received and sent signals. New chipsets will also be needed for advanced versions of CoMP. As a result, it is unlikely that commercial networks fully incorporating these advances will be seen until 2016 or beyond.

Taking all of these potential enhancements together, LTE-A technology is expected to achieve a spectral efficiency of 2.25 bps/Hz – a lift of nearly 61% over the 1.4 bps/Hz efficiency of current 2 × 2 MIMO LTE deployments (Rysavy Research, 2012b, p. 55).

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[29] MIMO technology employs multiple antennas on cell towers and within user devices to enable two or more parallel radio links connecting a tower to a user device. See Korowajczuk (2011, Chapter 14) and Rysavy Research (2012b, pp. 74, 102–103).

[30] The first figure in A × B MIMO represents the number of antennas at the network base station. The second figure represents the antenna count at the user device. 2 × 2 MIMO results in four effective signals: one from transmitting antenna 1 to receiving antenna 1; a second from transmitting antenna 1 to receiving antenna 2; a third from transmitting antenna 2 to receiving antenna 1; and a fourth from transmitting antenna 2 to receiving antenna 2.

[31] Multipath interference is perhaps the greatest reason why mobile technologies fail to attain throughput rates that match their theoretical maxima. This interference results from environmental obstacles like trees, buildings or mountains reflecting radio beams so that all of a signal's energy does not take the same path from its source antenna to its destination antenna. Because the whole signal does not take the same path (multipath), portions of the signal arrive at the destination both faded and slightly delayed, creating a less intelligible received signal. This becomes most acute when the signal is of high bandwidth because the portion of a data symbol whose receipt is delayed by multipath may interfere with the portion of a subsequent data symbol that arrives "on time."

[32] There are even more reasons why MIMO technology may improve throughputs between two points. Their discussion is beyond the scope of this paper. For further information, see Korowajczuk (2011, pp. 262–281).

4.2.2. Increasing spectrum reuse

As noted earlier, the prevalent form of spectrum reuse in mobile networks has been from *cellularizing* their served geographies into smaller and smaller units, and reusing radio frequencies in adjacent units. While this technique is certainly expected to continue, there are special ways in which LTE can foster even more intensive cellularization.

When mobile cellular networks were first deployed, cells were placed primarily for coverage purposes. Such cells are often called macro cells. As wide coverage was achieved and service demands in dense areas grew, macro cells were split into smaller cells, sometimes called micro cells. New micro cells were also simply overlaid on dense areas within the coverage of a previously-place macro cell. But macro and micro cells are expensive. They require a tower or rooftop to place their antennas, their own managed backhaul facilities, a substantial equipment hut, DC power supplies and possibly backup batteries or electric generating equipment. As individual cell tower service areas grow smaller, it may become less sustainable economically to continue spectrum reuse by the placement of more micro cells. Instead, the possible solutions are even smaller cells, known, variously, as pico cells, Distributed Antenna Systems (DAS), or femto cells.[33] The first two are cell systems designed to serve only a single office building in a complex, or even just a floor of a particular building. They may be located in closets or alcoves rather than on rooftops or towers. Their demands for electric power and electronics rack space are low. But these cells still require their own engineered backhaul to the core network and are managed from base station controllers so that they can take and give soft handoffs to other cell sites as a subscriber device moves in or out of their service area.

Femto cells are more basic. Typically they are designed to serve only devices located within about a dozen meters. But because they operate at very low power, many of them can be packed into a tight geography – all reusing the same frequencies. These devices generally are not managed by a base station controller and do not accept handoffs from other cell sites.[34] Despite these technical deficiencies, femto cells may be attractive to mobile network operators because, typically, they do not bear the full cost of these cells' deployment. Rather, the femto cell device is commonly purchased by a subscriber, perhaps at a discount from the operator. The subscriber is then responsible for furnishing electric power to the device, and most importantly, the subscriber must also provide a broadband backhaul line (commonly DSL or cable modem) to the Internet. Thus, signals from femto cells enter and leave the mobile operator's core network via the Internet and not via dedicated managed backhaul. But note, too, DAS or femto cells have typically been placed in mobile networks to improve signal coverage within homes or commercial buildings, not necessarily to deepen traffic capacity. Further, because of issues related to use of the broadband backhaul line furnished by the subscriber such as capacity, security and liability, femto cell access has commonly been restricted to just a predetermined list of subscriber devices – and is not open for general use.

Another method of spectrum reuse by which mobile networks may be able to accommodate demand growth is to offload certain of their traffic onto Wi-Fi networks – which are connected by fixed broadband access lines directly to the Internet. While similar to femto cell offload, Wi-Fi offload differs in several important respects.

The first is in traffic routing and processing. Femto cells direct all traffic through the Internet to reach the mobile operator's core network where it is processed and subsequently routed (possibly back into the Internet). In contrast, Wi-Fi offload allows the portion of data traffic emanating from the mobile device that is destined directly for the Internet to be injected immediately into the Internet for routing to its final destination. This traffic never touches the mobile operator's core network. The second difference is spectrum. Femto cells generally use spectrum allocations that are licensed to mobile wireless networks – thus their use consumes assigned mobile wireless spectrum.[35] In contrast, Wi-Fi offload uses unlicensed spectrum. Further, Wi-Fi has access to a very substantial amount of spectrum – with allocations of several hundred MHz in the 2400 MHz and 5000 MHz bands. Because of the low permitted power of Wi-Fi signals, it is possible to make very substantial reuse of these frequencies. To take advantage of this, many mobile wireless devices are capable of connecting to local Wi-Fi networks in addition to signals from cell towers. But while use of Wi-Fi offload is highly salutary because substantial amounts of traffic emanating from mobile devices is data traffic destined for the Internet, it may not affect the analysis presented here. This is because Cisco's *VNI* forecasts for Global Mobile Traffic which are used to measure mobile demand capture only traffic flowing across a mobile operator's managed RAN – and not via Wi-Fi or femto cell links backhauled across fixed broadband lines (Cisco, 2013).

Future implementations of LTE-A are expected to support soft handoffs of connections between femto cell or Wi-Fi access and licensed cellular spectrum access – which may cause the amount of mobile wireless traffic offloaded to Wi-Fi or femto cell access to accelerate.[36] Further, these LTE-A specifications are expected to support more dynamic load-balancing across the pico or femto cells that may exist within macro or micro cell coverage areas and to better integrate Wi-Fi access with managed cellular access.[37] If these are implemented successfully, Het-nets are likely to proliferate and the effective

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[33] See Chapin and Lehr (2011) and Goldstein (2010, 2012).

[34] See Chen et al. (2010) for a discussion of femto cell architectures and issues.

[35] In the future, this may not always be the case. Recently, the FCC proposed permitting U.S. operators to provide “small cell” mobile services in 100 MHz of spectrum in the 3550 MHz band. Their access to this shared spectrum would be opportunistic – with priority that is tertiary to existing licensed users and to a new class of protected users. See FCC (2012).

[36] It is also possible that other enhancements to Wi-Fi access from increased unlicensed spectrum allocations or other technical improvements may permit it to handle increased quantities of traffic destined to and from mobile devices. See PCAST (2012).

[37] Networks that more gracefully manage and distribute loads across different access configurations (i.e., macro, micro, pico and femto cells, and possibly Wi-Fi) are called “heterogeneous networks” or “Het-nets.” See Bhat et al. (2012), Qualcomm (2012) and Rysavy Research (2012b, pp. 106–111).

reuse of available radio frequencies will be intensified. Because of the very important capacity-expansion capabilities of this LTE-A innovation, the analysis assumes that it results in an annual growth rate for effective LTE-A cell sites of 16%[38] – a figure double the historic 8% growth rate for non-LTE-A sites – thus implying a highly accelerated growth rate for LTE-A frequency reuse.

4.2.3. *More efficient data packing*

Opportunities to pack data more efficiently into total available radio access spectrum are limited in mobile networks. Perhaps the greatest source of inefficiency in data packing is due to geography. In less populated areas of the country, portions of assigned mobile wireless spectrum may be fallow because local demand is insufficient to exhaust its carrying capacity. In contrast, in dense urban areas there are concentrated sources of demand that exhaust available mobile network capacity. While it is possible (and economic) for large users of resources like electricity (e.g., aluminum smelters) to locate close to remote hydroelectric dams, subscribers using mobile devices want to use mobile services where they are currently located (which generally is in denser population areas) and not in areas where they are not located.[39]

One way to gain packing efficiencies is to optimize data content sought by mobile subscribers into lower bandwidth format (e.g., stripped down web pages or video files downconverted to resolutions more appropriate for smaller format mobile devices).[40] Efficiency can also be gained from providing different mobile data applications with Quality of Service (QoS) that is tailored more precisely to their individual needs. For example, Voice over Internet Protocol (VoIP) or videoconferencing needs a consistent low-latency stream of data bytes. Errored packets, while they may create some degradation, can typically be accommodated by these applications without retransmission. In contrast, web browsing may function best if intermittent bursts of data packets arrive at high speed. Finally, file transfer bytes may be unforgiving of packet errors, but accommodate latency quite well. If a mobile network is offered a variety of these different application types by its subscribers, then by using QoS-based packet scheduling it can accommodate simultaneously these diverse demands using less total bandwidth than if each application is provided with the same QoS. By incorporating QoS-based packet scheduling into its specifications, newer releases of LTE will be able to allot bandwidth to different applications in a more efficient manner than earlier mobile technologies. This will permit operators to offer high quality Voice over LTE (VoLTE) service – and eventually to decommission their separate 2G and ~3G voice networks. By enabling increases in the total amount of service customers can be offered through a limited amount of spectrum, it is possible that LTE QoS and packet scheduling could improve effective throughput by up to 20%.[41]

In addition to more efficient data packing enabled by advanced technology, it is important to note that ordinary changes in subscriber use patterns may result in more or less efficient network fills. For example, as mobile data services evolve from ones with a business focus to consumer focus, it is possible that tomorrow's data will be offered to the network more evenly throughout the day than in prior years. Thus, if a significant amount of the new video traffic flooding U.S. mobile networks is off-peak load – it may be carried with reduced requirements for increased network capacity. Of course, the opposite may occur, too.

5. Overall ability of technology and spectrum to meet forecasted demand

To measure the ability of these various expected enhancements to mobile network capacity to meet forecasted growth in demand, the analysis employs a model similar to that used in FCC (2010b). This model is assumes that if U.S. mobile networks have successfully used a particular set of technologies, number of cell sites, and amount of spectrum in a recent *base year* to serve that year's level of demand, then it is possible to use these base year ratios to project the capability of future networks incorporating additional amounts of spectrum, an evolved set of technologies and an expanded number of cell sites to serve forecasted demand.[42] To accomplish this, the analysis compares an index of forecast demand growth against an estimated index of overall capacity expansion. This latter capacity index is itself the multiplicative product of separate estimated indices for: (a) growth in raw spectrum resources; (b) customer migration to more spectrally-efficient higher-G mobile technologies; (c) growth in effective spectrum reuse; and (d) additional capacity improvement due to more efficient network packing enabled by LTE and LTE-A technologies.

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[38] "Effective" LTE-A sites are sites that are equivalent to traditional macro or micro cells in their capacity uplift. But note that because each small cell is expected to handle less traffic than a large cell, this implies that actual small cell counts will be substantially larger than the effective cell counts that are estimated here.

[39] Of course the classic exception to this rule is when a mobile customer is in an area of poor reception and moves a short distance (say, to a higher floor of his house or out of a sheltered building alcove) to get a better signal.

[40] Transcoding video traffic and limiting streaming buffer sizes is an optimization technique already employed by certain mobile operators. See Verizon Wireless: "Data Plans & Features – Terms and Conditions," retrieved from: http://support.verizonwireless.com/terms/products/vz_email.html and "Optimization Deployment – Terms & Conditions," retrieved from: http://support.verizonwireless.com/terms/network_optimization.html.

[41] See Yuksel et al. (2010) for a more in-depth explanation for why multi-use networks incorporating QoS require less bandwidth for equivalent service quality than multiple single-purpose networks. LTE-A carrier aggregation may be an additional source of packing efficiency. By permitting non-contiguous spectrum blocks to be aggregated into wider channels, and by permitting asymmetric uplink and downlink block sizes, it will be possible for mobile operators to increase the throughput capacity of their spectrum holdings. This uplift is also considered in the proposed 20%.

[42] Note that this model abstracts from a location- or time-specific analysis by assuming that future demand will resemble base year demand in terms of its location and temporal profile. To the extent that this profile of demand characteristics changes over time, the model will be less precise.

Table 2
Contributions of raw spectrum to mobile capacity growth.

(a) Year	(b) Currently allocated spectrum (built-out MHz)	(c) Baseline Spectrum Index	(d) Additional built-out allocations (MHz)	(e) Augmented spectrum quantity (MHz)	(f) Upper bound Spectrum Index
2010	294.5	1.90			
2011	334.5	2.16			
2012	374.5	2.41			
2013	426.6	2.75			2.75
2014	478.8	3.08	30	508.8	3.28
2015	513.4	3.31	30	573.4	3.69
2016	548.0	3.53	30	638.0	4.11
2017	548.0	3.53	30	668.0	4.30
2018	548.0	3.53	40	708.0	4.56
2019	548.0	3.53	40	748.0	4.82
2020	548.0	3.53	40	788.0	5.08
2021	548.0	3.53	30	818.0	5.27
2022	548.0	3.53	30	848.0	5.46

Notes: Time pattern for deployment of already allocated spectrum assumes that substantially all of Clearwire's EBS/BRS spectrum is built out by 2016 (see note 13). Deployment pattern of the 300 MHz of additional spectrum assumes that WCS and unpaired 700 MHz spectrum will be built out in 2014 and PCS H-block and MSS S-band spectrum begin to be deployed in 2015 (see notes 18 and 19). Spectrum deployed from 2016 to 2022 will consist of 600 MHz UHF spectrum, AWS-3 spectrum and additional MSS spectrum or small cell 3550 MHz spectrum (see notes 20 and 35).

The first capacity index component addressed is raw spectrum growth. Two alternative indices for growth of raw spectrum are developed, one as a baseline and another as an upper bound. The baseline is an index of built-out spectrum that assumes that no more spectrum allocations are forthcoming to the U.S. mobile wireless industry beyond the 548 MHz already allocated – and that all of this spectrum is usable. The upper bound index assumes that an additional 300 MHz of usable spectrum will become available to the industry and built-out over the 2014–2022 time period. The year 2010 is assumed to be the model's base year. Although the analysis estimates that networks employing 294.5 MHz of allocated spectrum were built-out as of that year, it assumes that 2010 demand required only 155.2 MHz of this spectrum to be filled. This implies an initial Spectrum Index value of 1.90 (=294.5 MHz/155.2 MHz) to reflect the headroom available in 2010 spectrum deployments.[43] The baseline index is shown in column (c) of Table 2. Column (d) shows the assumed timeline for building out the additional 300 MHz that may be offered to the industry.[44] An upper bound Spectrum Index incorporating these additional allocations is given in column (f).

The next component of the capacity index developed are two alternative indices for effective spectral efficiency. They are presented in Table 3 and constructed by weighting the relative spectral efficiencies of each available mobile wireless technology by estimates of the fraction of total built-out spectrum that will be in use by these different technologies in each year. The baseline index assumes that only already-allocated spectrum will be available over the 2014–2022 period. The upper bound assumes an additional 300 MHz of spectrum will be released to the industry and that nearly all of it will be built out as LTE-A – thus raising the industry's average spectral efficiency. Column (g) of Table 3 shows the baseline index for capacity growth resulting from migration of use to higher G technologies assuming current total spectrum allocations.[45] Column (m) shows the upper bound index assuming spectrum allocations are augmented by 300 MHz over the 2014–2022 period.

Table 4 displays forecast growth in spectrum reuse. Column (b) shows forecasted cell site counts assuming continued 8% annual growth and current raw spectrum allocations. The index associated with this is in column (c). But as noted, LTE-A (4G+) enables Het-net development, thus facilitating accelerated growth of small LTE-A cells. This acceleration is assumed to double the annual growth of effective LTE-A cells to 16%. This is shown in columns (d), (e) and (f). If an additional 300 MHz of spectrum is supplied, this changes upwards the fraction of cell sites that will be deployed as LTE-A. Adjusted reuse growth figures to represent this are provided in columns (g), (h) and (i).

The final source of increased capacity is more efficient network packing. As noted, QoS-based packet scheduling, carrier aggregation and VoLTE implemented in LTE are assumed to permit a phased-in 20% improvement in LTE and LTE-A throughputs. This is shown in Table 5 – assuming LTE and LTE-A service prevalence both with current spectrum allocations (columns b and c) and with 300 MHz of additional spectrum (columns d and e).

Fig. 7 shows the contributions of each of the above-developed sources of capacity growth – with solid lines assuming the baseline of no additional spectrum and dashed lines assuming an additional 300 MHz of spectrum. As can be seen,

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[43] See Section 3.2, supra.

[44] See Rysavy Research (2012a) for a discussion of time paths and technical and business considerations governing mobile network build outs.

[45] This migration of customers to higher G technologies (principally from 2G to ~3G, 4G or 4G+), assumes no government regulations restricting U.S. mobile operators from migrating their customers. In fact, it was not until 2002 that the FCC issued an Order permitting U.S. networks to retire their 1G networks in 2008. See http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-225216A1.pdf and Lawson (2008).

Table 3
Contributions of migration to more spectrally-efficient higher G technologies to mobile capacity growth.

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)
	With currently allocated spectrum						With upper bound spectrum					
Year	2G share	~3G share	4G LTE share	4G+ share	Weighted average efficiency (bps/Hz)	Baseline Spectral Efficiency Index	2G share	~3G share	4G LTE share	4G+ share	Weighted average efficiency (bps/Hz)	Upper Spectral Efficiency Index
2010	44%	46%	9%	0%	0.57	1.00						
2011	33%	54%	14%	0%	0.70	1.23						
2012	21%	59%	20%	0%	0.86	1.52						
2013	12%	60%	28%	0%	0.99	1.75						1.75
2014	7%	54%	39%	0%	1.07	1.89	7%	53%	40%	0%	1.08	1.90
2015	4%	46%	39%	11%	1.24	2.19	3%	47%	40%	10%	1.24	2.18
2016	2%	40%	37%	21%	1.37	2.42	2%	39%	36%	23%	1.40	2.46
2017	1%	38%	37%	25%	1.43	2.52	1%	35%	35%	29%	1.48	2.61
2018	0%	33%	35%	32%	1.52	2.68	0%	30%	31%	39%	1.60	2.81
2019	0%	28%	32%	39%	1.61	2.83	0%	25%	28%	47%	1.69	2.97
2020	0%	23%	28%	49%	1.72	3.02	0%	18%	25%	56%	1.80	3.17
2021	0%	16%	23%	61%	1.85	3.26	0%	13%	22%	65%	1.90	3.34
2022	0%	8%	19%	73%	1.98	3.49	0%	7%	17%	77%	2.02	3.56
	0.25	0.95	1.40	2.25			0.25	0.95	1.40	2.25		
	Efficiencies (bps/Hz)						Efficiencies (bps/Hz)					

Notes: Spectrum deployment dates are from Table 2. Fractions of total spectrum used by different technologies are forward projections from Figs. 3 and 5 and assume aggressive migration to the most efficient technologies consistent with limitations outlined in Rysavy Research (2012a). Spectral efficiencies of different technologies are estimates from Rysavy Research (2012b, p. 55). Because of migration to 4G HSPA+, blended efficiencies for ~3G technologies are assumed to be 0.7 bps/Hz in 2010, 0.8 bps/Hz in 2011, 0.9 bps/Hz in 2012 and 0.95 bps/Hz afterward.

Table 4
Contributions of additional spectrum reuse to mobile capacity.

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
	Basic Reuse		Reuse with 4G+ Het-net lift					
Year	Cell sites	Cell site Reuse Index	With currently allocated spectrum			With upper bound spectrum		
			Reuse lift from 4G+ Het-nets	Number of effective sites	Baseline Reuse Index with Het-net lift	Reuse lift from 4G+ Het-nets	Number of effective sites	Upper Reuse Index with Het-net lift
2010	253,086	1.00		253,086	1.00			
2011	283,385	1.12		283,385	1.12			
2012	301,779	1.19		301,779	1.19			
2013	325,921	1.29		325,921	1.29			
2014	351,995	1.39		351,995	1.39		351,995	1.39
2015	380,155	1.50	1.0891	383,361	1.51	1.0882	383,025	1.51
2016	410,567	1.62	1.0967	420,424	1.66	1.0981	420,595	1.66
2017	443,412	1.75	1.0997	462,360	1.83	1.1034	464,079	1.83
2018	478,885	1.89	1.1055	511,154	2.02	1.1111	515,621	2.04
2019	517,196	2.04	1.1114	568,083	2.24	1.1174	576,166	2.28
2020	558,572	2.21	1.1194	635,913	2.51	1.1252	648,283	2.56
2021	603,258	2.38	1.1289	717,876	2.84	1.1323	734,060	2.90
2022	651,518	2.57	1.1383	817,173	3.23	1.1413	837,763	3.31
			Basic site CAGR:	8.0%				
			4G+ Het-net effective site CAGR:	16.0%				

Notes: Assumption for reuse increase from LTE-A Het-net support is author's estimate that effective 4G+reuse growth is double that historically observed for non-LTE-A technologies.

migration to higher G technologies and reuse growth including Het-nets each have an individual effect of increasing total capacity by a factor of close to 3.5 over the study period. These factors are roughly equal to the baseline spectrum growth factor offered by completing build-out and filling of already allocated spectrum (assuming all EBS/BRS spectrum is usable). Adding an extra 300 MHz of spectrum will raise raw spectrum's contribution to a factor of nearly 5.5.

Table 5
Contributions of improved network packing to mobile capacity.

(a) Year	(b) With current spectrum	(c)	(d) With upper bound spectrum	(e)
	Lift due to 4G and 4G+ packing efficiency	Baseline Network Packing Index	Lift due to 4G and 4G+ packing efficiency	Upper Network Packing Index
2010		1.00		
2011		1.00		
2012	1.0%	1.01		
2013	2.8%	1.03		
2014	5.9%	1.06	6.0%	1.06
2015	10.0%	1.10	10.0%	1.10
2016	11.5%	1.12	11.8%	1.12
2017	12.3%	1.12	12.8%	1.13
2018	13.4%	1.13	14.0%	1.14
2019	14.3%	1.14	15.0%	1.15
2020	15.4%	1.15	16.3%	1.16
2021	16.9%	1.17	17.4%	1.17
2022	18.3%	1.18	18.7%	1.19
		Ultimate 4G and 4G+ packing efficiency lift:	20%	

Notes: Improvement in LTE and LTE-A network packing is assumed to be 5% in 2012, 10% in 2013, 15% in 2014 and 20% thereafter. These effects are weighted by the prevalence of 4G and 4G+ technologies in overall U.S. mobile wireless networks. Assumption for ultimate effect of QoS-based packet scheduling is author's estimate based on VoLTE implementation, carrier aggregation and Yuksel et al. (2010).

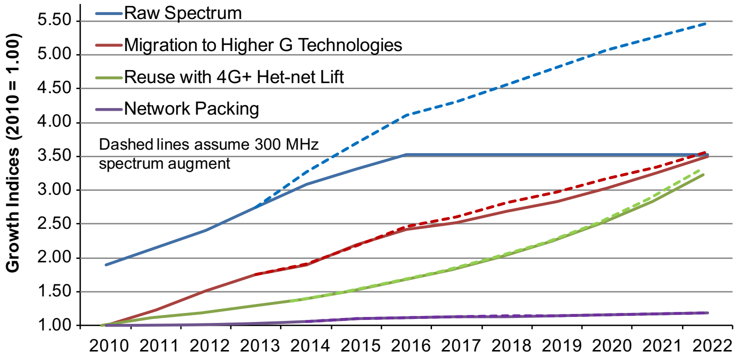

Fig. 7. Contributions to mobile capacity growth. *Notes*: Solid lines assume baseline of no additional spectrum allocations. Dashed lines show contributions if 300 MHz of additional spectrum is allocated.

Thus, if the U.S. mobile industry is successful at: (a) deploying all of the raw spectrum assumed; (b) increasing its reuse intensity of this spectrum; (c) achieving all of the stated LTE and LTE-A efficiency lifts; and (d) quickly migrating customers to these higher G technologies; these individual contributions may be multiplicatively combined and their joint lift on mobile capacity compared with forecasted traffic demand. This is done in Fig. 8. The solid red line shows baseline capacity growth assuming current spectrum allocations. The dashed red line shows the upper bound estimate of capacity growth assuming an extra 300 MHz of spectrum. This capacity growth is in comparison to the Cisco *VNI*-based demand forecast for U.S. mobile traffic shown in solid blue.

As can be seen, assuming baseline mobile capacity growth, the U.S. goes into capacity deficit in 2014; and by 2020 demand will be more than double available capacity. While beginning to add 300 MHz of additional spectrum in 2014 narrows somewhat the capacity gap, even this is inadequate to keep the U.S. out of deficit beyond 2017. Indeed, to keep the U.S. out of deficit through 2022, the modeling suggests that total spectrum additions over the 2014–2022 period need to amount to roughly 560 MHz – for a total of 1108 (=548+560) deployed MHz.[46] The index figures underlying Fig. 8 are provided in Table 6.

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[46] This figure, while large, is smaller than certain other estimates of incremental spectrum needs. In 2009, CTIA projected the U.S. to require an additional 800 MHz of allocated spectrum off of a base of 410 MHz – for a total of 1210 MHz (CTIA, 2009). Note, however, CTIA employed more conservative assumptions about potential increases in spectrum reuse than the aggressive (and possibly unrealizable) assumptions employed in the present model.

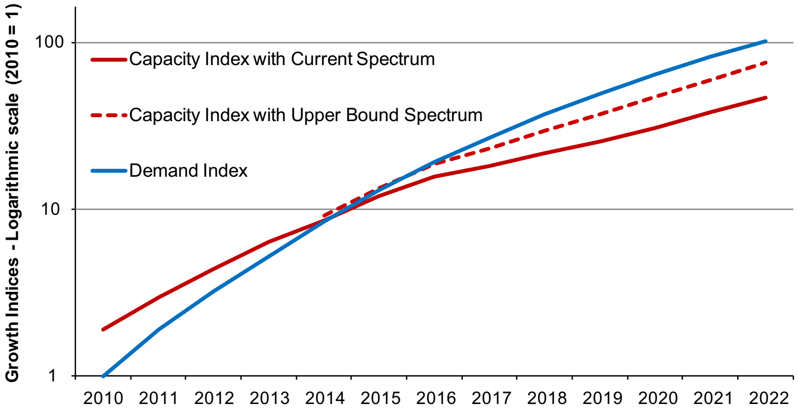

Fig. 8. Comparing mobile capacity growth to demand growth. *Notes*: Capacity indices developed from Fig. 7 and demand indices from Fig. 2.

Table 6
Mobile capacity growth versus demand growth.

(a) Year	(b) Total indices	(c)	(d)
	Capacity Index with current spectrum	Capacity Index with upper bound spectrum	Demand Index
2010	1.90		1.00
2011	2.98		1.91
2012	4.40		3.23
2013	6.38		5.24
2014	8.60	9.19	8.47
2015	12.09	13.41	13.08
2016	15.85	18.80	19.22
2017	18.26	23.24	27.13
2018	21.71	29.82	37.26
2019	25.64	37.51	49.82
2020	30.96	47.90	64.97
2021	38.15	60.04	82.79
2022	47.13	76.49	103.25

While this analysis suggests that evolving demand for U.S. mobile wireless services is likely to be stymied by inadequate capacity growth, it is also useful to consider possible reasons why this may fail to occur – or if it does occur, how the market will equilibrate.

One possibility is that the forecasted demand figures are wrong and mobile service usage will not expand at the rates forecasted by Cisco. While this is certainly a possibility, it should be noted that until 2012, Cisco's updates of its Global Mobile Data Traffic Forecast generally found actual Total Global Mobile Data Traffic to be larger than what its forecast from the previous year predicted (Cisco, 2009–2011, 2012a). While Cisco's 2013 forecast was a revision down from its earlier forecasts, it is also this more conservative forecast that is used by the analysis to project future demand.[47]

Another possibility is that far greater load-shifting, and thus improved network packing, will take place than suspected. To the extent that disproportionate amounts of new customer demand are for mobile services at times-of-day and in geographical locations where network capacities are not at their limit, it is possible that networks could absorb increased traffic without requiring proportional capacity reinforcements. Absent very granular network traffic data, it is impossible to know the extent of this possible mitigating effect.

On the other hand, it is more likely that reductions in service quality or price increases will end up being the principal forces for equilibrating the market. When wireless capacities are tight, data connections will slow down. Either customers will accept slower performance of their mobile applications, or they will discontinue their use, or transfer their use to off-peak periods or locations. It is also possible that they will eschew particularly data-hungry applications in favor of less-desirable substitute applications that have the virtue of reduced data use. Either way, the effective service quality that customers receive will be reduced. Further, it is quite certain that prices will also be a major equilibrator of the market.

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[47] See Cisco (2013). Also remember that Qualcomm projects 1000 × data traffic growth from 2010–2020 – far greater than the 103 × growth factor for data traffic and the 65 × growth factor for total traffic implicit in the analysis' Cisco *VNI*-based figures for 2010–2020. See note 11.

This is because Cisco's demand forecasts are predicated on customer adoption and use trends that assume a continuation of today's price trajectory – which has been sharply declining prices per byte of traffic. As such, Cisco's *VNI* should be considered to provide forecasts of notional demand. To the extent that capacities go into deficit, this will attenuate, and possibly reverse, current downward price trajectories. If this occurs, future demand will be repressed to match more closely to available supply.

6. Conclusions

Expanding mobile wireless capacity in an economic and effective manner requires multifaceted efforts. The analysis presented in this paper has demonstrated the techniques that have been used to deepen mobile wireless networks. These include the allocation of additional spectrum; the development of more spectrally-efficient wireless technologies and the migration of customers to these technologies; increased reuse of available radio frequencies enabled both by cell site splitting and LTE-A support for enhanced small cell and Wi-Fi integration; and by tighter packing of offered data into available transmission capacity. But even though the analysis has tried to be generous in its projections of capacity growth and cautious in its projections of demand growth, it appears that U.S. mobile wireless markets will face capacity deficits possibly as early as 2014, and after 2016 these may be significant. In order to keep these deficits to manageable proportions, it will be essential for U.S. regulatory authorities to allocate quickly all of the 300 MHz of increased spectrum that was proposed in the *National Broadband Plan* for exclusive mobile use. If less than this sum is allocated, or if allocations are delayed until towards the end of the decade-long prospective study period, shortfalls will be especially severe. Indeed, in order to keep U.S. wireless markets fully on their current trajectory of virtuous growth, the presented model suggests that 560 MHz of additional spectrum will need to be deployed over the 2014–2022 period.

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