Riding the Data Tsunami in the Cloud: Myths and Challenges in Future Wireless Access

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ABSTRACT

Data rates of mobile communications have increased dramatically during the last decade. The industry predicts an exponential increase of data traffic that would correspond to a 1000-fold increase in traffic between 2010 and 2020. These figures are very similar to ones reported during the last Internet boom. In this article we assess the realism of these assumptions. We conjecture that wireless and mobile Internet access will emerge as a *dominant technology*. A necessary prerequisite for this development is that wireless access is abundant and becomes (almost) free. A consequence is that the projected capacity increase must be provided at the same cost and energy consumption as today. We explore technical and architectural solutions that have realistic possibility to achieve these targets. We ask if Moore's law, which has successfully predicted the tremendous advances in computing and signal processing, will also save the day for high-speed wireless access. We argue that further improvements of the PHY layer are possible, but it is unlikely that this alone provides a viable path. The exponential traffic increase has to be matched mainly by increasing the density of the access networks as well as providing a modest amount of extra spectrum. Thus, the future research challenges are in designing energy- and cost-efficient short-range architectures and systems that support super-dense deployments. A non-technical complication is that such infrastructures are likely to lead to highly fragmented markets with a large number of operators and infrastructure owners.

INTRODUCTION

The commercial success of mobile and wireless access to the Internet has been monumental. Initially thought of as a way to sell excess capacity of third generation (3G) networks or provide some simple "value added services," it has, together with the proliferation of smartphones, created an explosion of traffic volumes (often referred as the "Data Tsunami"). This trend is already threatening to overrun many networks. The heavy investments in new technologies — fourth generation (4G), Long Term Evolution (LTE) — will not provide immediate relief, since the terminal market is still dominated by 3G devices. More seriously, the first deployments of LTE systems do not exhibit radically higher spectral efficiency (bits per second per Hertz) compared to existing high-speed versions of 3G. At the same time, customer-installed non-mobile networks such as Wi-Fi networks are similarly becoming congested due to increased interference and demand. Eventually, LTE will buy the operators some time, but what can be expected in the medium- to long-term future?

The widely cited Cisco Virtual Networking Index Forecast Study[1] [1] predicts a 25- to 30-fold increase in global mobile data traffic until 2015. There is an industry consensus that wireless access technology has become viral, and is likely to continue so over the following five-year period. Some extrapolations even project a 1000-fold increase in total wireless data traffic by 2020. As exponential growth usually requires an exponential increase in resource consumption, there is reason to remain somewhat skeptical toward such traffic predictions. We scrutinize what lies behind this rapid growth in demand and what is needed to keep it going. We are particularly interested in understanding what makes wireless access viral.

Such a growth rate in a short period of time is a formidable challenge for system designers and operators. However, one should note that one could sustain exponential growth, such as described in [1], only while there is a demand and "while supplies last." The wireless access also has to be affordable to large consumer groups or the demand will saturate. In this sense wireless Internet access is no different from the original Internet boom. However, there are specific wireless challenges. First, the infrastructure costs (capital expenditure, CAPEX) for wireless wide-area coverage scale much less favorably. Second, the operating expenditure (OPEX) of today's wireless networks also scale strongly with the increased infrastructure and number of users. In fact, a significant part of OPEX is attributed to energy consumption. Hence, we formulate the overall challenge as

> *1000 times more capacity at today's cost and energy consumption*

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[1] *A recent "Traffic and Market Data Forecast" from Ericsson paints the same picture [2].*

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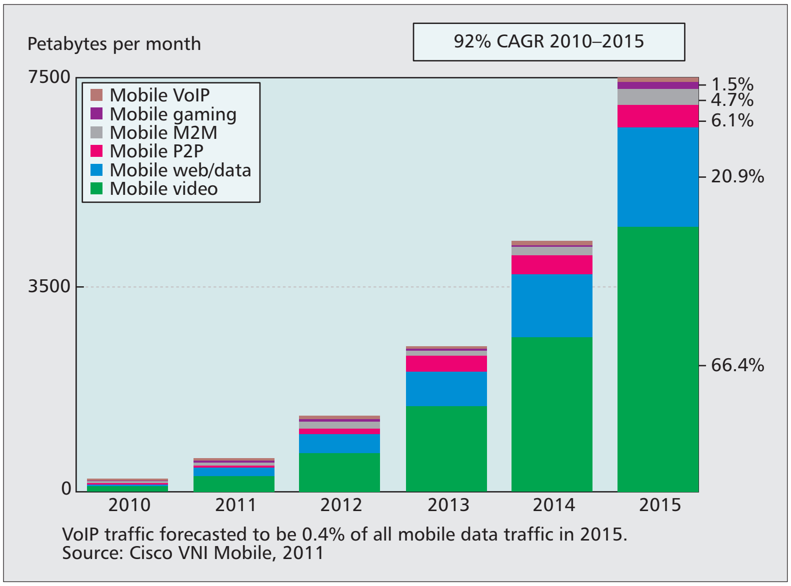

VoIP traffic forecasted to be 0.4% of all mobile data traffic in 2015.
Source: Cisco VNI Mobile, 2011

Figure 1. *Mobile traffic predictions according to Cisco Virtual Networking Index Forecast Study [1].*

THE TRAFFIC TSUNAMI: DRIVERS AND LIMITS TO EXPONENTIAL GROWTH

Although it is a historical fact that mobile data traffic has roughly doubled over the last few years in most markets, we should be somewhat skeptical toward the prediction that this will continue uninhibited in the coming years. One reason for skepticism is that many of the predictions are based on simple extrapolations and market trend analysis. Moreover, most analyses are presented by major telecom vendors that have vested interests in the projections. There are, however, also arguments that support the claims, at least in the short- to mid-term perspective.

The main underlying driver of current development is that IP access is also rapidly becoming the dominant design in wireless communication. The concept of *dominant design* dates back to 1975, when Utterback and Abernathy [3] introduced the term to describe a technology that enforces or encourages standardization. Prior to the emergence of a dominant technology there are many rivaling products and technologies; following it there is a wave of exits and consolidation. IP technology has had this impact in fixed networks. IP networking and access took over completely not because of its technical superiority but mainly due to its high degree of flexibility. The abundance of optical fiber capacity has further strengthened this trend. The end-to-end principle of the Internet, which allows new services and communication models to be easily introduced by third parties, has effectively obliterated walled-garden approaches and rival "intelligent network" architectures.

The mobile industry was slow to recognize this trend as an inevitable force. The only successful pockets of resistance against the victory march of IP access have been various wireless systems where the poor efficiency of IP-based systems coupled with legacy entrenchment has allowed some systems to survive. Examples of such "one-trick ponies" include, for example, telephony and broadcast TV and radio systems. Many of these services are also increasingly provided over fixed lines using IP. When 3G networks were designed a decade ago, there was heated debate over what would be the "killer application" that would single-handedly pay for the new infrastructure. Now we know that skeptics against "design for killer applications" were right. The access itself is the key, and the days of dedicated systems are also numbered in wireless: special solutions inevitably lose the race for economies of scale. Wireless IP access with its increasing data rates is becoming the dominant design. Although there are a number of rival and complementary physical access technologies (e.g., cellular, WiFi, and fixed wireless broadband techniques), they all provide the user an IP access. Other wireless architecture proposals, such as peer-to-peer and multihop/mesh systems, have fallen victim to the dominant design, and they can, at the best, take niche positions.

Being a provider of an efficient bit pipe for Internet access is still an attractive business position, if it is provided cost efficiently, for network operators. The Internet and its cloud services are winning through the scale and sheer convenience of the service. Many of the "apps" in our smartphones are also becoming cloud-based. Cloud computing is a consequence of efficient and virtually free communication. We compute and store information wherever in the world it may be cheapest and most effective, neglecting the marginal cost of communication. The physical terminal we are using is of no consequence. In mobile access this has not really been the case — poor coverage, high cost, latency, and limited data rates have been limitations that have prevented service mobility and convergence. If and when the mobile and wireless networks provide better connectivity and access speeds, cloud computing will inevitably also become the ruling paradigm in wireless. A striking example of this is when two friends meet in the street and would like to exchange digital content, say photos. In principle, short-range peer-to-peer radio connectivity (e.g., Bluetooth) would be the most effective from an engineering perspective. However, instead of wasting time and effort for peering, you simply email your photo to your friend or put it on a service like Flickr using a cellular or WiFi access. The reason for this is that even though this operation may consume significantly more network resources, the marginal cost for the user is zero. And there is an abundance of generic applications to do this without wondering how to do peering.

The convergence of mobile and fixed networks is thus driven by dominant design and shared cloud applications. Because of this, and if the costs and complexity can be efficiently managed, we argue that the data tsunami can, in the short term, even exceed the estimates. In fact, it is likely that cloud service access will dominate streamed media and consumption of YouTube-type content. The cloud paradigm adds a number of additional traffic sources:

- Content generated and kept in our mobile devices are regularly uploaded to the cloud to share between others and the different devices of the user.

- Semantically cached content [4] (i.e., content that is predicted to be used) can overcome temporary poor connectivity and enhance the perceived performance. This will lead to increased proactive traffic for caching.
- Application and cloud synchronization traffic: Future services are likely to keep the status and state of the different applications up to date with very low latency (e.g., email, messaging, social media traffic).

Another factor to consider is the growth in the number of users. In the industrialized countries, we may suspect that many "active data subscriptions" are not used to their full potential. Globally, recent International Telecommunication Union (ITU) estimates [5] show that although the penetration of cellular subscriptions worldwide is about 87 percent, active mobile data subscriptions reach only 17 percent penetration worldwide. The differences between the industrialized world and the developing countries are still large in this category. Only 20 percent of households in developing countries have computers with Internet connection, and only 8 percent of the inhabitants have a mobile data subscription (compared with 71 and 56 percent in industrialized countries, respectively). Hence, there is a large reserve of potential new users that can increase the data networking traffic by an order of magnitude. However, in the developing nations and the "near industrialized countries" (NICs), the average revenues per user (ARPU) are significantly lower than in the developed nations. As an example the monthly ARPU in Western Europe is on the order of €20, whereas the corresponding figure for India is only about €2 (2011). This means that any realistic data offering thus sustaining a data avalanche in new economies requires new innovations that lower access costs even further.

We emphasize that the usage patterns described above and the dramatic increase in traffic are not inevitable and governed by fate. They will only occur if the "price is right." History has shown a constant shift between computational paradigms that has adapted to computing and computational bottleneck. We have gone from the mainframe era in the 1960s, when both communication and processing were expensive, to the PC era in the 1980s and 1990s when processing became cheap, but communication still was a bottleneck. Now we are moving toward the cloud paradigm, when communication now is virtually free, and remote computing can be the most effective solution.

If the wireless and mobile systems will not be able to deliver similar services with low flat rates, the data tsunami will eventually be stifled and the exponential growth will come to an end. In the following we now explore to what extent and how this capacity expansion can be achieved.

Why Moore's Law Is Not Coming to the Rescue

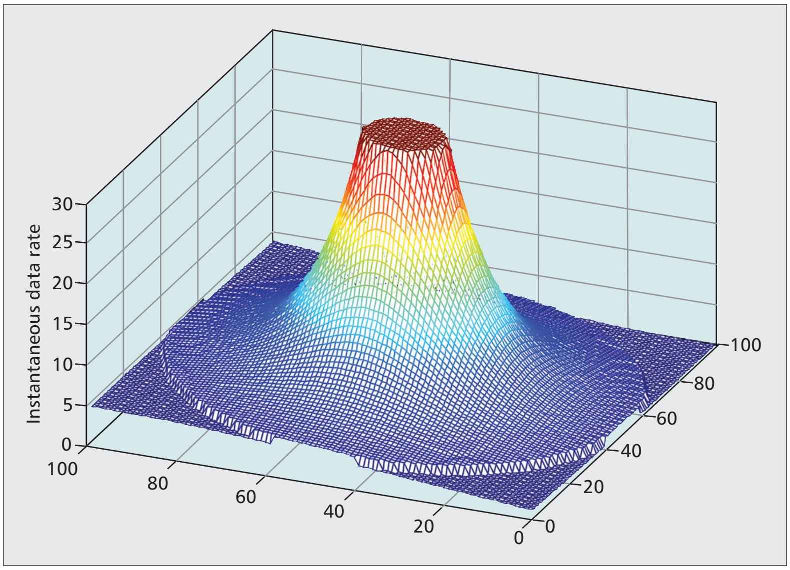

Figure 2. *Data rates in a cellular (mobile) data systems.*

Let us start by estimating the cost of a wireless infrastructure. A common assumption is that the total cost is dominated by factors proportional to the number of base stations (we simplify by neglecting core network costs). The total cost can in this case be given by [7]

$$C_{\text{infra}} \approx C_{BS} N_{BS} = C_{BS} c_A \frac{N_{user} R_{user} A_{service}}{\eta W_{sys}} \qquad (1)$$

where $A_{service}$ is the size of the service area, W_{sys} is the available (spectrum) bandwidth, and η is the effective reuse factor. The number of base stations, and thus the system cost, will almost linearly follow the provided capacity. If we want to increase the capacity $N_{user} R_{user}$ significantly while maintaining the same total cost, we need to either:

- Increase the effective reuse η, that is, improve the physical (PHY) layer of the system
- Increase the available spectrum W_{sys}
- Lower the cost per base station C_{BS}
- Reduce the coverage area $A_{service}$

The usual way to deal with exponential growing demand is to employ an improved technology. The achievable data rates in standardized mobile systems have increased dramatically over the last 10 years. In the Third Generation Partnership Project (3GPP) domain we have seen 3G/Universal Mobile Telecommunication System (UMTS) systems being enhanced by high-speed packet access (HSPA) that are now by many operators being replaced or complemented by LTE systems. Driven by tremendous advances in signal processing capabilities, peak rates have risen from a few hundred kilobits per second to approach 100 Mb/s in the latest LTE releases. Higher peak rates have been partially driven by better signal processing techniques that have benefited from the rapid advances in electronics over the last decades, described by Moore's law. These advances are likely to continue in the years to come to provide faster processing, more memory, more compact designs, lower equipment cost, and lower power consumption. However, this may have led to the common misunderstanding that future capacity/cost prob-

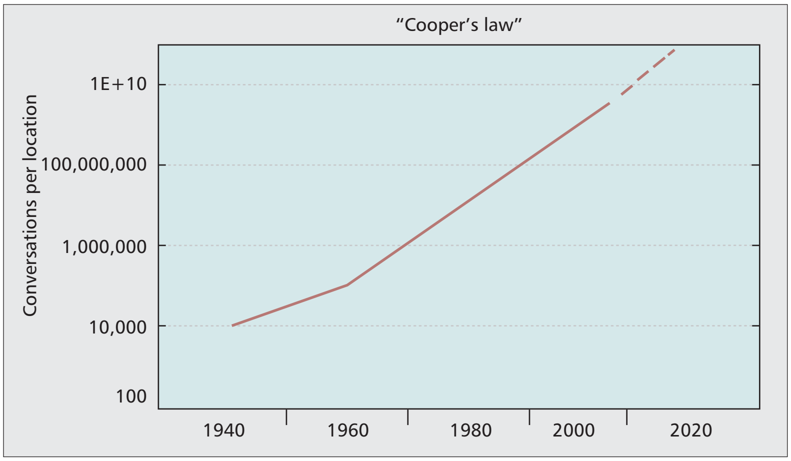

Figure 3. *Martin Cooper's assessment of spectral efficiency of wireless systems (in "conversations per location"). Adapted from [10].*

lems can be solved by simply replacing current equipment with new models with higher peak rates at lower cost. The equipment itself is, as we will see, not the dominating cost item. Furthermore, current systems already operate very close to the Shannon bound that corresponds to using "infinite" computational power. There is therefore little to be gained by even more computationally intensive PHY-layer schemes. The price for higher peak rates in the same spectrum is an(exponentially) increasing energy consumption [6].

The problem is compounded by the fact that what is important is not the peak rate of the system (marketing) but the actual data rate the user experiences (reality). Virtually all modern wireless standards adapt the data rate to the received signal quality. Figure 2 shows the so-called rate volcano, that is, the data rate for a modern adaptive rate system operating close to the Shannon bound for various locations around a single base station in the middle of the graph.

The cell capacity (i.e., the average user data rate) is considerably lower than the peak rate. This means that the average user data rate is largely determined by the density of base station deployment, rather than the peak rate. Another issue is that the available data rate is shared by all users. Under heavy load conditions the available user rate will thus drop even more. In marketing talk it is often conveniently forgotten to mention that the theoretical peak rates are only available in a small area very close to the base stations and when the user is alone in the cell.

The literature today is full of ingenious digital signal processing (DSP) schemes that use multiple-input multiple-output (MIMO) antenna systems, base station cooperative multipoint (COMP) and interference control (intercell interference coordination, ICIC) techniques to increase efficiency. These techniques are often facilitated through centralized radio resource management, where processed digital baseband waveforms are sent to simple "radio heads" (up-converters, power amplifiers and antennas) by means of optical fibers. The ultimate objective of these schemes is to effectively eliminate the co-channel interference caused by frequency reuse. Ideally, this could result in a two- to seven-fold improvement in capacity. The gain, of course, will vary due to the amount of actual interference. In open areas with little environmental protection from interference, these schemes are likely to excel. In an indoor environment with plenty of walls to shield interference, the benefits are likely to be limited [12]. Recent results from 3GPP standardization [8] show that such schemes seem to be very sensitive to estimation errors and delays in the channel state information (CSI) that has to be passed around between the base stations. Under realistic conditions a factor of 2–3 improvement seems to be a plausible maximum benefit. Improvement, no doubt, but a rather modest one, introducing very high complexity. Finally, medium access control (MAC)/link layer schemes, such as packet scheduling, may also provide some advantages. Such schemes work well in larger cells with many users, but they tend to have less gain when there are few users, each with high capacity demand, as may be expected in the very dense indoor scenarios we discuss below.

If signal processing and clever MAC and PHY-layers will not solve all our problems, what can be done? Surprisingly, the answer might be that we have to use the same old solution that has been saving us time and again. Looking at capacity improvements in a historical perspective, Martin Cooper found that "wireless capacity" measured in "simultaneous conversations" has doubled every 30 months. This observation is often referred to as *Cooper's Law* [10] (Fig. 3). Compared to 1945, we can today provide more than a million more mobile phone connections for a fixed area. Cooper lays out the basic ingredients for this advancement: *allocation of more spectrum, use of more efficient PHY-layer techniques, and densification of the base station grid*. He estimates that the increased capacity is due to 25 times increase in spectrum and 25 times more efficient use of the spectrum (PHY-layer techniques).

The remaining 1600-fold increase, however, is attributed to more efficient spatial reuse, mainly having more base stations in significantly denser spatial configuration, but also to some extent by use of efficient directional antennas.

The above basic ingredients for capacity improvement remain intact also for the coming years. In Table 1 we show how some of the major vendors of wireless infrastructure equipment view the relative contributions of the various techniques. Based on the reasoning above, a spectral efficiency gain of 10–24 seems quite unrealistic as well as finding 10 times more spectrum for exclusive mobile use. What cannot be achieved in PHY/MAC layer efficiency and additional spectrum, has to be made up by deployment architecture. We argue that a more than 60-fold densification is a more reasonable assumption, both technologically and economically. The only other possibility would be to find more spectrum. That this proposition is not realistic at the required scale, we demonstrate later.

HETNETS: DEPLOYING CAPACITY AS NEEDED

To build an affordable infrastructure according to Eq. 1, we need to minimize the number of base stations while keeping cost of deployment low for each base station. The problem of providing some required capacity with a minimum number of base stations has a straightforward and well-known solution: make sure to provide capacity where it is actually needed [9]. This is illustrated in Fig. 4, which shows the strong variations in capacity demand for various locales, ranging from small areas indoors and in "hot spots" where the user densities are very high all the way to large rural areas with low capacity demands. Providing "blanket coverage," that is, a capacity corresponding to the peak demand everywhere (red dashed line), would require a very large number of base stations. The green dashed line corresponds to heterogeneous network (HetNet) deployment where the service area is subdivided according to the demand. Very high capacities can be provided in small areas with very high demands at moderate costs since the corresponding $A_{service}$ in Eq. 1 is small. In larger and larger areas, less and less capacity is required. HetNet deployment tailors the provided capacity to the traffic demand, and can include several cellular tiers meshed together. As the demand is expected to increase most where the majority of users are (i.e., indoors), this is also where most of the deployment is going to occur as we meet the demand.

Not only do well designed HetNets minimize the number of base stations; the cost per base station and required energy consumption are also significantly reduced in the very small cells. Equation 2 shows the base station cost broken down in its major components

$$C_{BS} = C_{site} + C_{backhaul} + C_{equipment} + C_{deployment} + C_{maint} \tag{2}$$

For conventional outdoor wide-area systems, all five components are in play. Site costs are high due to high masts, housing for the equipment, and roads for maintenance. Backhaul is also expensive since a "macro-site" often requires new installation of a dedicated fiber connection. Finally, equipment is high-power industry-grade equipment that often requires cooling; all this leads to a high price tag (tends of thousands of dollars). Moreover, the deployment, planning, and installation require skilled personnel and maintenance; due to costs, there is only limited redundancy built in for the wide-area coverage.

Indoor systems are deployed on-premises, usually by the facility owners, which results in negligible site costs. The equipment is consumer grade and low cost (hundreds of dollars). If the capacity is too low, a few more access points can easily be deployed. Coverage is not a problem; and when a base stations breaks, it will only cause a minor degradation in capacity. The equipment can be replaced by the electrician at some later time, resulting in much lower maintenance costs. If the network is deployed indoors, where in most cases there is already a fiber or Ethernet outlet, the backhaul cost also vanishes — provided that the base stations can use standard IP access. If the network has the capability to self-organize, the dominant remaining cost is that of the (physical) deployment of the base stations.

Company	Spectrum	Spectral efficiency	Densification	Total capacity increase
Nokia Siemens	10X	10X	10X	1000
Huawei	3X	3.3X	10X	100
NTT DoCoMo	2.8X	24X	15X	1000
Our projection	3X	5X	66X	1000

Table 1. *How significant market players strategize about achieving the target and the authors' take.*

The analogy with lighting is striking: outdoor public lighting is provided by large high-power floodlights on high towers, whereas indoor lighting is provided by an abundance of simple lamps. This analogy also demonstrates another point: no one would dream of providing indoor lighting using street floodlights. Most of the energy would be wasted and absorbed in walls, and the indoor illumination results would be poor. This is, on the other hand, exactly the solution we still see in mobile data operation today, causing poor energy efficiency, high transmission power, and low indoor data rates.

The reason for this is not technical. Instead, we have a clash of business models. Public outdoor access is provided by mobile operators as a subscription-based service, whereas indoor (WiFi) systems are provided as part of the services provided when renting an office, similar to electricity and ventilation. The public operators cannot hope to deploy their own systems in every building, but still a user wants seamless transitions from the outdoor public system to the indoor private system. A key research question is thus to find efficient techniques and business models for sharing the indoor systems. A majority of the traffic growth will be carried by indoor low-cost base stations, which will certainly have an impact on the manufacturing industry. WiFi is certainly not the solution to all local access problems. WiFi may work in many homes, but in very-high-density deployment, there are significant capacity shortcomings with the simple carrier sense multiple access with collision avoidance (CSMA/CA) access protocol. Regardless of the technical advanced content of a future indoor base station, it will still eventually be a $100 ollar box that someone puts on the wall.

MORE SPECTRUM: WHERE IS IT TO BE FOUND?

Allocation of extra spectrum is a cost-efficient way to provide extra system capacity (Eq. 1). Surprisingly, this strategy can be competitive against other approaches even when spectrum licensing costs are high. In addition, increased

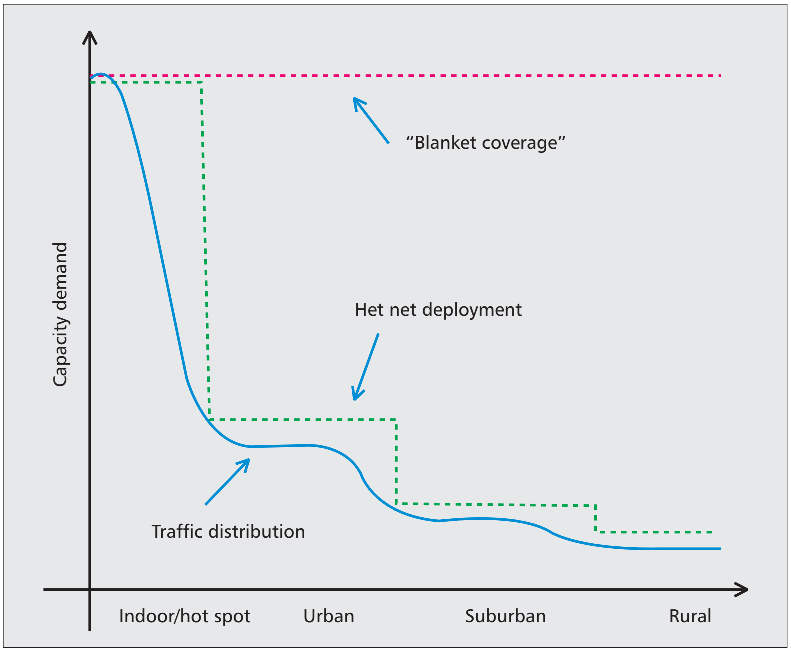

Figure 4. *Capacity demand and deployment strategies for non-homogenous traffic.*

spectrum allocation creates possibilities for energy savings [6] as both energy as well as infrastructure costs can be saved. Thus, it is no wonder that there has been active lobbying for extra spectrum allocations.

However, the spectrum is a limited natural resource, and there are competing services. Moreover, there is a trade-off between the properties of different spectral bands. Roughly speaking, we have a lot of spectrum available for exclusive licensing above 10 GHz, but radio propagation conditions are not making these bands attractive for current stakeholders and operators. Although very-high-frequency systems can be built, there are still severe questions on cost efficiency and usability for mobile devices. If we want to build customer installable systems for mobile data purposes, the spectrum bands below 6 GHz are still significantly more attractive. Although there are some possibilities for refarming of lower spectrum bands below 2 GHz (e.g., by reallocating terrestrial broadcast and military frequencies), it is unlikely that several hundreds of megahertz could be made universally available for *exclusive licensing*.

Efficient spectrum use requires balancing different approaches carefully. The higher-frequency systems (> 2 GHz) can provide superior capacity in the femto-cellular segment of HetNet architectures. For large-area coverage and when good wall penetration is important, the lower frequencies (< 2 GHz) become a better way to provide low-cost coverage, but at the expense of lower capacity. It is a still a complex research question how to balance the trade-offs between coverage and capacity in the most cost-efficient way while maximizing the public good.

Dynamic spectrum access (DSA) has also been proposed as one way to provide more spectrum. Although we believe that DSA can be an efficient way to provide rapid market entry possibilities and temporary solutions, it is not a permanent answer for handling the data tsunami. Several projects, the European Union funded QUASAR project [13] among them, have more carefully studied the various DSA propositions. First, allowing secondary use of WiFi-type systems with uncoordinated CSMA-like media access is unlikely to produce large capacities below 1 GHz channels. This is due to the fact that if we use simple shared medium access methodology, such as CSMA, the interference between secondary users will limit the achievable data rates significantly [13]. The availability of so-called TV White Spaces for outdoor use in locations where additional capacity is needed is likely to be less than 100 MHz (in Europe) even if we allow non-disjoint channel aggregation. Building wide-area national cellular systems using only white spaces does not appear to be a viable alternative in general [13]. For strictly indoor use the availability is significantly higher. However, as discussed above, the TV spectrum is appropriate to provide low-cost indoor coverage, but is not well suited to provide the higher capacities. Here, radar bands (3–6 GHz) provide a better opportunity. Our conclusion is that although more spectrum can be refarmed or provided through DSA-mechanisms it is unlikely to be more than few hundreds of megahertz for outdoor usage and, say, 1 GHz for indoor usage at frequencies below 6 GHz can be made available in DSA or a licensed manner. This has to be compared with the 200–300 MHz already allocated for wide-area cellular and an additional 500–600 MHz for WiFi use. This is hardly enough to be an answer for the described exponential traffic growth. Certainly a 1000-fold traffic increase cannot be matched by spectrum allocations alone. The architecture solution (i.e., increasing density of base stations) seems to be inevitable. However, the good news is that there are enough spectrum opportunities available for both exclusive and shared licensing, using either dynamic or static allocation, to enable smooth deployment of HetNets with small cells. Thus, we estimate conservatively that maybe at most a three-fold spectrum increase is possible, and definitely a 10-fold increase looks impossible to achieve below 10 GHz in the short to medium term.

DISCUSSION: A NEW BALL GAME FOR THE WIRELESS INDUSTRY

The rapid traffic growth as projected by industry is a real challenge due to increasing popularity of wireless and mobile Internet access. The growth can continue only "while supplies last," that is, as long as we can keep on providing abundant capacity for mobile access with very low user costs. In order to sustain such growth even in the short to medium term, we need to provide an order of magnitude more capacity at today's cost and power consumption levels, which in turn requires fundamental changes in the evolution of our networks. The classical game of the "next generation standardization" with better signal processing and new spectrum allocations will not work. The good news is that most of the traffic growth will occur in densely populated areas and indoors, for which there are promising solutions, spectrum is abundant, and most fixed infrastructure is already in place.

	Exclusive < 6 GHz	Shared < 6 GHz	Secondary < 6 GHz	Exclusive > 10 GHz
Availability	Very low	Low (100 MHz)	Good (> 1 GHz) for <u>indoor use</u>	Very good
Advantages	• Guaranteed QoS • Long-term investments • NLOS propagation	• Spectrum available • Low cost equipment • "Ad hoc" deployment (NLOS)	• Spectrum available • Low cost equipment • "Ad hoc" deployment (NLOS	Very high capacity Low interference Advanced antennas
Disadvantages	• High spectrum cost • Low availability	• No QoS guarantees • Low availability	• Limited QoS guarantees • Regulatory uncertainty	LOS propagation Planned deployment

Table 2. *Spectrum options for future wireless access.*

The research challenges lie in facilitating massive deployment of high-performance "plug-and-play"-type (self-organizing network, SON) network hardware. This is the way to not only lower the cost of the access infrastructure, but also a way to share and integrate wireless infrastructure investments into real-estate investments similar to electricity, plumbing, and fixed network access. There will be a significant impact on the industry — the need for wide-area systems will not go away, but most of the traffic increase will occur in the short-range indoor domain. In this domain, the game is played by different rules. The customers are not as easily identified, and a transition from moderate-volume expensive industry-grade equipment to large-volume consumer-grade equipment will leave its mark onn the industry.

Some of the research questions that have been identified:

- What should the architecture and design of ultra-dense networks look like?
- What are the business/technical models for operator spectrum/infrastructure sharing?
- Is it worthwhile to do PHY-layer intra-operator coordination [12]?

Interestingly enough, this will also be a survival game for existing operators and vendors as the business realities and alliances are likely to shift radically. Continued business success depends on the ability to adapt to the new rules It also seems that technology and capability to provide efficient "bit pipes" is becoming a crucial competitive edge. A. Odlyzkos' claim that "Content is not king" [15, 13] could be proven to be truer than many have expected — we venture to say that at least content is not the only king; efficient bit transfer capabilities are worthy of a kingdom in the future, too.

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BIOGRAPHIES

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