IMT-Advanced: 4G Wireless Takes Shape in an Olympic Year

4G

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It has been well over a decade since the International Telecommunications Union (ITU) launched its International Mobile Telephony-2000 (IMT-2000) third-generation (3G) framework for mobile wireless communications. In more recent times there has been much anticipation of the fourth generation (4G) with development of so-called 3.5G, 3.75G and 3.9G standards. However, in this Olympic year, it was perhaps appropriate that China was the venue for a landmark workshop on 4G wireless that took place in Shenzhen following the April meetings of the working groups from the Third Generation Partnership Project (3GPP).

The purpose of the workshop was to start planning 3GPP's response to the ITU's 4G program, which the ITU has named "IMT-Advanced." There were around 200 delegates in attendance from all the major wireless industry players. Nearly 60 technical papers were presented espousing corporate views on the provisional 4G requirements and potential 4G solutions.

The article "What Next for Mobile Telephony: Examining the trend towards high-data-rate networks" in Issue Three of Agilent Measurement Journal introduced some of the concepts further developed in this article. From here forward, the terms 3G and 4G will be used interchangeably to refer to IMT-2000 and IMT-Advanced.

Putting 4G in context

Reviewing previous wireless generations will help put 4G in context. The first generation came of age in the 1980s, offering for the first time a relatively affordable (though expensive by today's standards) mobile wireless telephony service. 1G was characterized by a multiplicity of incompatible regional analog standards that kept the market fragmented, expensive and without international roaming.

In the early 1990s, GSM, the first of the digital second generation, arrived to provide telephony plus text messaging and limited circuit-switched data services. For GSM, everything lined up: technology; demand; supply; pricing; value; and delivery costs. The result remains an enormous international industry that in 15 years grew from nothing to being owned by more than half the people on the planet, revolutionizing the way the world communicates. GSM's success can be traced back to a few key factors: sufficient scale (17 European countries); the focus of basic telephony (text messaging was an unexpected bonus); and value (providing affordable services people wanted to use). The other main 2G system was CDMA, which offered services similar to GSM but in different geographies. In essence, 2G wireless brought the niche 1G to the mass market.

Following the phenomenal and unexpected success of 2G there was heightened anticipation of what 3G would bring, but 3G's contribution to date is a very mixed bag. On a technical level, 3G met the increased single-user data rates mandated by the IMT-2000 requirements, but the uptake of much-hyped 3G services such as video telephony has been poor.

One key challenge in moving from telephony to data services has been the complexity and diversity of the possible services, compounded by the difficult issue of pricing. Also, services requiring higher data rates are less available than 2G voice: radio conditions mean that it is normal to experience a 10:1 variation in data rates across a cell, even before loading is considered. This largely explains why 3G in mobile phones has not lived up to expectations. 3G subscriptions are just over 7 percent of 2G subscriptions and many of these are primarily using telephony and basic messaging rather than 3G-specific data services.[1]

Real uptake of data services didn't start until the c.2005 introduction of the so-called 3.5G packet-based data services (HSDPA on UMTS and 1xEV-DO on cdma2000). Dedicated data-only devices with flat-rate tariffs (e.g., USB dongles used with laptops) are showing strong growth in some markets with good performance, at least for early adopters. Whether there is demand backed by network coverage, capacity and sufficient revenue to allow such services to become mainstream is yet to be seen, meaning 3G's impact is currently much less significant than the step from the first to the second generation.

Given the experience so far with 3G, how should we evaluate the targets being set for 4G? Will 4G make mobile broadband a reality for the masses? This should surely be the hope of the industry and is the reason why it is so important to correctly define the fourth generation. At this stage in the planning process, opportunities still exist to identify those critical elements that will make 4G a success.

Scanning the IMT-Advanced timeline

The ITU's 3G program took some 12 years to complete, with work having started as far back as 1985 under its original project name of Future Public Land Mobile Telephone System (FPLMTS). Not so with IMT-Advanced, which has a much contracted timeline — and a pronounceable name. The 4G work started in 2005 and Figure 1 shows the projected ITU timeline and links into 3GPP.

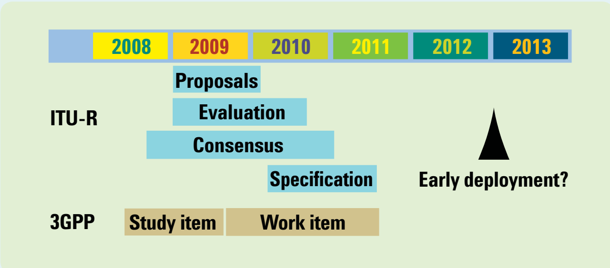

Figure 1. Overall IMT-Advanced timeline

The ITU's goal is to approve candidate 4G technologies by the end of 2009 with standards development and implementation to follow. This puts 4G about two years behind 3GPP's Long Term Evolution (LTE) project, suggesting that 4G commercial service will be available no earlier than 2012. By any standard, and particularly by 3G standards, this is an aggressive timeline. It is made possible, however, because the two most likely 4G candidate technologies — IEEE's 802.16e standard (Mobile WiMAX™) and 3GPP's LTE — are already considered 3.9G technologies and the enhancements required to meet 4G's requirements are not considered major. This is a significant point: Unlike with 3G, the advent of 4G is not going to result in a major rethinking of existing air-interface technologies.

In some ways, IMT-2000 led the development of 3G standards; however, in the case of IMT-Advanced, it is playing catch-up with the many developments that have taken place since the IMT-2000 requirements were established in 1997. 3GPP's submission to the ITU, planned for September 2009, will be a backwards-compatible enhancement of LTE Release 8, to be known generally as LTE-Advanced, and will probably be fully specified in 3GPP release 10.[2] For the IEEE, it is likely any submission will be based on the 802.16m standard, which is an evolution of 802.16e.

What's in a 4G name?

In naming its 4G initiative IMT-Advanced, the ITU has consciously reused the first part — "IMT" — from the 3G IMT-2000 program. This naming is significant because it has been agreed that spectrum currently allocated for exclusive use by IMT-2000 technologies will now be known as just "IMT" spectrum and will also be made available for IMT-Advanced. Crucially, there are no plans for exclusive IMT-Advanced spectrum. This is pragmatic since spectrum is scarce and largely occupied.

Reviewing IMT-2000 (3G) requirements and deployment

The requirements for 3G systems can largely be summarized by the following peak single-user data rates:

- 2048 kbps: indoor office
- 384 kbps: outdoor to indoor and pedestrian
- 144 kbps: vehicular
- 9.6 kbps: satellite

It is unfortunate that 2 Mbps dominated early 3G marketing and it was a long time before the limited reality of early 3G deployments became clear. Since the emergence of HSDPA in 2006, the original 3G data rates have long been surpassed. Even so, these figures have always lacked the caveats that translate headline rates into typical end-user experience. The two biggest culprits are coverage and capacity. Coverage falls into a couple of categories: locations where, for commercial reasons, there is simply no 3G service; and performance within the coverage area, which is highly dependent on radio conditions (indoor performance being particularly challenging). The other major issue is capacity. The IMT-2000 figures represent single-user peak data rates and say nothing about the number of users who can expect to see such performance in any given cell. The requirements may have ignored coverage and capacity factors but the end-user certainly cannot because these directly drive quality of experience (QoE). Shortcomings with coverage and capacity — along with difficulty in pricing and presenting value-added services — are the main reasons why the uptake of 3G has been much slower than predicted.

There are similar differences between peak and average performance in other industries where claims are designed to grab the eye and the wallet — but a growing list of caveats in the small print speaks more to the QoE. For example, getting the quoted performance out of a modern laptop battery requires tactics such as slowing the CPU to a fraction of its peak performance, dimming the display and switching off wireless features. Without regulations such as those that control claims about automobile gas mileage, the reality of wireless will continue to lag the hype. Peak-rate marketing in telecommunications is not unique to cellular wireless — as many DSL and Wi-Fi users will testify — but the gap between the peak and average for cellular is larger and growing faster than for wired or hotspot services.

Another point worth noting about 3G, as evidenced by its now six members*, is that it would be easy to conclude that 3G was a happy family of specifications. However, the ITU chose to define 3G only in terms of performance requirements and did not provide guidance on any technical implementation that might have created a stronger bond between the technologies. Thus, although 3G technologies share a common minimum performance level, the 3G label did not ease interworking between them.

When we consider the scope of the 4G requirements it will be interesting to see what they say about interworking and the factors limiting 3G in the areas of capacity and coverage.

Sketching preliminary IMT-Advanced requirements

The preliminary requirements for IMT-Advanced are shown in the sidebar Key features of IMT-Advanced and can be found on the ITU's IMT-Advanced website.[3] The first seven of the eight requirements are "soft," largely being pursued by the industry already. However, when it comes to defining what 4G is all about, the final target for data rates leaves no room for doubt: 100 Mbps high mobility and 1 Gbps low mobility. Thus, the headline requirements for 4G are nailed to the same mast as that of 3G: the continued growth in single-user peak data rates.

The intent of most of the softer requirements is to create a more integrated family of technologies than was ever the case for 3G. These good intentions, however, will always be subject to commercial reality and it seems evident from 4G contenders LTE and WiMAX™ that they will have little in common by the time the electromagnetic waves hit the air. Consequently, we are likely to end up with a repeat of 3G where interworking within the 4G "family" may still feel more like The Simpsons than The Waltons.

The 1-Gbps headline figure is likely to grab attention in the same way that 2 Mbps did for 3G ten years earlier. Like its 3G predecessor, the 1-Gbps peak figure is not without qualification since it applies only for low mobility in ideal radio conditions and requires up to 100 MHz of spectrum. Nevertheless, these caveats may be overlooked, and, as with 3G, expectations of 4G may outstrip reality for what could be a long time.

Key features of IMT-Advanced

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- A high degree of commonality of functionality world wide while retaining the flexibility to support a wide range of services and applications in a cost-efficient manner
- Compatibility of services within IMT and with fixed networks
- Capability of interworking with other radio access systems
- High-quality mobile services
- User equipment suitable for worldwide use
- User-friendly applications, services and equipment
- Worldwide roaming capability
- Enhanced peak data rates to support advanced services and applications (100 Mbps for high and 1 Gbps for low mobility were established as targets for research)

* W-CDMA FDD, W-CDMA TDD, TD-SCDMA, cdma2000, UWC-136 and Mobile WiMAX

Reviewing detailed 4G performance requirements

Besides the headline peak data rates, 4G — unlike 3G — is setting targets for average spectral efficiency and cell-edge performance. This is a welcome development and these figures can be seen in Table 1.

The first point of note is that the peak efficiency targets for LTE-Advanced are substantially higher than the targets for 4G — thus the focus on peak performance is maintained despite the averages being very similar. That said, 3GPP have emphasized that the average and cell-edge targets are more important than the peaks. The LTE targets are based on 2x to 4x improvements to Release 6 HSPA (single-stream downlink with diversity UE receiver), which produces a microcell average efficiency of around 0.53 b/s/Hz/cell.[4] At 2.6 b/s/Hz/cell the targets for 4G and LTE-Advanced are around five times higher and, should they be met, would truly be worth the investment. However, we are still some way from demonstrating cost-effective technology that can deliver on the lower 1.69 b/s/Hz/cell LTE target. The industry knows how to increase the peak figures by adding more bandwidth or higher-level modulation and less coding (with consequential negative impact on coverage), but with targets for average performance there is nowhere to hide.

Consider this automotive example: Let's say the average speed of metropolitan rush-hour traffic is 20 mph. Compare the difficulty of designing a car that can travel at ten times the average speed with no environmental restrictions (e.g., assume perfect roads and no traffic) versus designing an entire traffic system — not just a car — that can double the average speed during rush hour. This offers a qualitative feel for the enormity of the challenge 4G is setting in improving on today's average wireless performance by a factor of five.

Aggregating bandwidth

Those familiar with today's spectrum allocations might well be wondering where space for the 100-MHz channels needed for 1 Gbps will be found. Some new IMT spectrum was identified at the World Radio Conference in 2007 (WRC-07) but there are still only a few places where continuous blocks of 100 MHz might be found (e.g., at 2.6 GHz or 3.5 GHz). One possibility would be to encourage network sharing, which reduces fragmentation caused by splitting one band between several operators; however, sharing the spectrum, as opposed to just the sites and towers, is a considerable step up in difficulty. The ITU recognizes the challenge that wide-bandwidth channels present and so it is an expectation that the required 100 MHz can be created by the aggregation of non-contiguous channels from different bands in a multi-transceiver mobile device.

Table 1. LTE, LTE-Advanced and IMT-Advanced performance requirements

Item	Sub-category	LTE (3.9G) target[4]	LTE-Advanced (4G) target[2]	IMT-Advanced (4G) requirement[5]
Peak spectral efficiency (b/s/Hz)	Downlink	16.3 (4x4 MIMO)	30 (up to 8x8 MIMO)	15 (4x4 MIMO)
	Uplink	4.32 (64QAM SISO)	15 (up to 4x4 MIMO)	6.75 (2x4 MIMO)
Downlink cell spectral efficiency (b/s/Hz/cell) Microcellular 3 km/h	(2x2 MIMO)	1.69	2.4	
	(4x2 MIMO)	1.87	2.6	2.6
	(4x4 MIMO)	2.67	3.7	
Downlink cell-edge spectral efficiency (b/s/Hz/user)*	(2x2 MIMO)	0.05	0.07	
	(4x2 MIMO)	0.06	0.09	0.075
	(4x4 MIMO)	0.08	0.12	

*5 percentile, 10 users

The beginnings of such aggregation techniques are already showing up in established technologies, first with EDGE Evolution, for which standards are being written to aggregate two non-adjacent 200-kHz channels to potentially double the single-user data rates possible with standard EDGE. Along similar lines, there are 3GPP proposals for "dual-carrier" High Speed Downlink Packet Access (HSDPA) to try to close the "bandwidth" gap between 5-MHz UMTS and 20-MHz LTE. Multi-carrier cdma2000 has also been considered, although its use of adjacent channels avoids the need for multiple transceivers.

There is clearly precedence for the ITU's bandwidth aggregation proposals but there are unanswered questions about the viability of such solutions at 100 MHz due to the implications for user equipment (UE) cost and complexity. This is compounded by the fact that commercially-viable applications for 1-Gbps data rates to a single mobile device have yet to be articulated. It should also be noted that bandwidth-aggregation does not increase network capacity. Taking all these factors into account suggests a very uncertain future for 100-MHz multi-transceiver bandwidth aggregation as a means of delivering extreme single-user peak data rates.

Summarizing 4G solution proposals

During the 4G workshop there were numerous proposals from the industry as to how LTE-Advanced might deliver and even exceed 4G requirements. Space does not permit detailed analysis but the proposals included the following:

- Higher-order multiple-input/multiple-output (MIMO) and beamforming (up to 8x8)
- Co-operative MIMO
- Cell-edge interference coordination and cancellation
- Advanced coding and scheduling
- In-channel relay for backhaul
- Femtocell / Home Node B using self-configuring/ self-optimizing networks

Further details can be found in the workshop report and documents.[6]

Evaluating 4G

So how should 4G be evaluated given the history of previous generations? We could analyze many factors — but one undeniable truth supporting the phenomenal growth in the wireless market has been the parallel growth in system capacity. This should be no surprise since capacity is the raw material required to deliver value-added services. If capacity is not growing then neither is the industry. Most of the capacity in today's infrastructure is consumed with telephony and messaging, with demand being fueled by growth in subscriptions of typical voice usage, which averages globally at around three hours per user per month. However, the advent of higher-rate data services changes this model and it is now possible for one user to demand far more capacity from the system than was possible with voice. If higher-rate 3G and 4G services are to be viable there has to be a corresponding growth in system capacity.

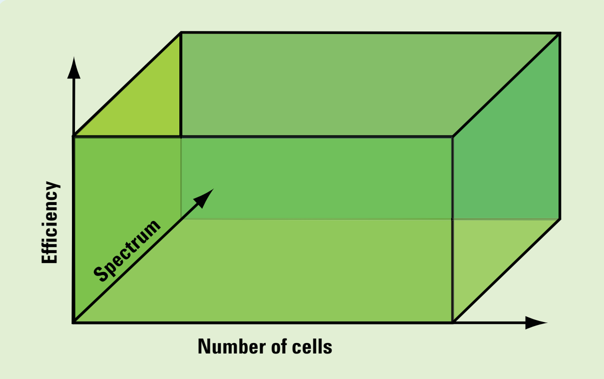

Figure 2. Volume model for wireless system capacity

Figure 2 presents a simple model for evaluating system capacity with three axes: spectrum, spectral efficiency and number of cells (which is a form of frequency reuse). The product of these three axes represents the volume or capacity of the system. Over the last 50 years there has been phenomenal capacity growth of around one million. Further analysis shows that efficiency has improved 20x and spectrum by around 25x, but the number of cells has grown by a staggering 2000x, making this axis 80 to 100x more significant.

Figure 3 shows a more detailed view of how peak data rates and system capacity have grown, spanning 1992 (2G) to 2015 (4G projections). The trends shown are based on a European model and are valid in general, though not necessarily in the fine detail. The Y scale is the peak data rate in kbps and the other traces (normalized to single-band GSM in 1992) are: average efficiency (b/s/Hz/cell); spectrum; and their product, which is cell capacity (b/s/cell).

The efficiency figures are taken from various sources with the value in 2015 being projected at 1.3 b/s/Hz/cell, which is a safer figure to use than the 2.6 b/s/Hz/cell 4G target based on 4x2 MIMO. The spectrum growth follows the GSM900, DCS1800, E-GSM, UMTS2100 historical progression with projections for 700 MHz, 2.6 GHz and 3.5 GHz leading to a total of 680 MHz by 2015.

In the early days, 2G systems were deployed to operate at a peak rate of around 10 kbps at the cell edge, enabling uniform, if somewhat inefficient, service. In later generations, many techniques have been used to increase average efficiency by exploiting better radio conditions further into the cell. The result is better efficiency — but service coverage is no longer uniform.

Until about 2002, the peak data rates tracked the growth in cell capacity, meaning that, on average, a loaded cell could deliver the higher rates to its users. The number of users will obviously vary depending on the service, but if we take as a reference the number of users in the original GSM cell at its capacity, then these same users would experience a nearly 50x growth in data rates in ten years — quite impressive! However, after 2002 we see a growing gap between cell capacity and the peak rates possible for single users. This is significant because our same set of users will, on average, see only one-tenth of the possible peak data rates today's unloaded systems can deliver.

Using the projections for LTE and 4G, we can see the gap widening such that by 2015 the peak rates of the system will have outpaced system capacity by 100x. This means that, on average, the cell's set of users will experience only one percent of the headline data rates. Even these figures are optimistic since Figure 3 is simplified by assuming constant load, ideal scheduling and the absence of deployed legacy terminals.

There are many ways 4G systems could be analyzed, but the fundamentals of capacity and coverage are essential. In addition to the predicted capacity limitations, the delivery of very high data rates in a macrocell radio environment is restricted to a small area near the center of the cell (as discussed in Issue Three of Agilent Measurement Journal). If mobile broadband is to become a reality, both the capacity and coverage limitations of current macrocell systems need to be addressed, otherwise the result will be a continuation of the trend towards inconsistent service provision known to have held back the adoption of 3G.

Although projected capacity growth through additional spectrum and improvements in efficiency are real, neither can deliver the substantial growth that is required for the mobile broadband revolution. To meet this challenge we must turn to the third axis in Figure 2, that being growth in cell numbers.

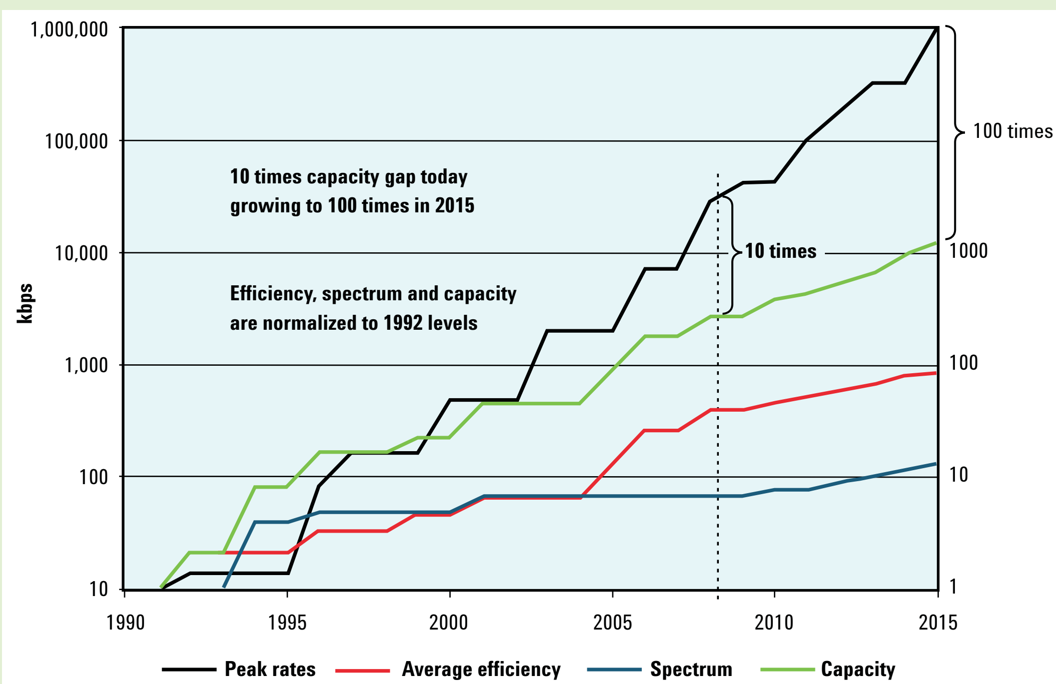

Figure 3. Growth in peak data rates and system capacity

Growing capacity by increasing cell numbers

Today there are approximately 1,000 subscribers per macro base station. Reducing this ratio has historically been the way system capacity has grown to meet demand. However, it seems evident from operators that making more than a token increase in macrocell density is not economically viable and thus the primary growth mechanism that has served us since wireless began seems to be nearing its end. There are ongoing efforts to deploy picocells and in-building systems but these too have practical limits. Breaking through to the next 10x or 100x of capacity growth means a dramatic increase in cell numbers is required — but the current centrally-managed deployment model will not scale due to costs and environmental factors such as planning and site availability.

The time now seems right for the home base station or femtocell. With a femtocell in every second home it is possible to imagine a 100x growth in cell numbers compared to the current macrocellular model. With this femtocell assumption, a comparison of the capacity potential of the three axes in the capacity model from today through 2015 is shown in Figure 4. It is interesting to note that the outlook for capacity growth is much like the previous 50 years, with cell number upside being 100x more significant than growth in either spectrum or efficiency.

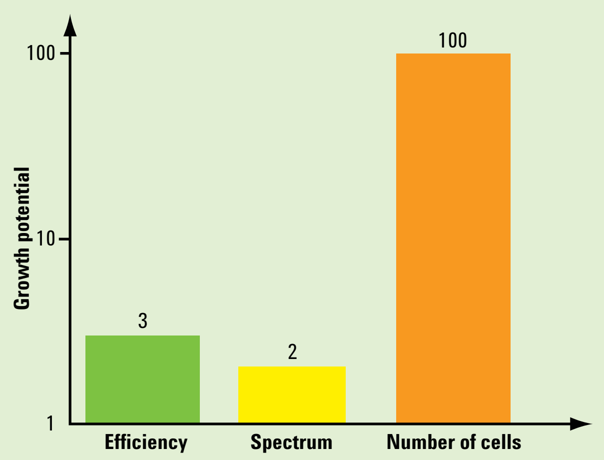

Figure 4. Capacity growth potential 2008 through 2015

How well are the 4G requirements addressing the need for capacity growth to match the demand from higher peak-data rates? Taking spectrum first, this will always be mired in the slow-moving politics of international regulation. There are no expectations that the existence (or absence) of 4G will make much change in the projected 2x spectrum growth through 2015, which will be available for 3G as well. Next we have efficiency, which is the focus of most of the study into 4G, but as we have seen the targets are very challenging and the upside remains low. Finally, regarding the number of cells, there were some encouraging discussions at the Shenzhen workshop on femtocells, although this is not currently seen as a major 4G initiative. For this reason it is perhaps fortuitous that 3GPP is already standardizing femtocell technology for both UMTS and LTE. The significance of this cannot be underestimated since the potential upside from a femtocell deployment will address both the capacity and coverage limitations of current systems, plus the better radio conditions experienced in hotspot femtocell environments go hand in hand with delivering higher data rates.

Femtocells: Enabling mobile broadband?

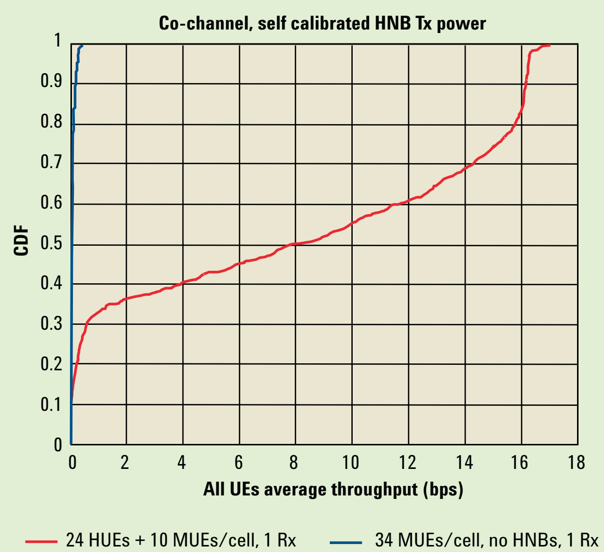

Figure 5. Average throughput per user with and without femtocells

The potential of femtocells is illustrated in Figure 5. This data was presented in June 2008 at 3GPP RAN WG4 as part of a femtocell study that included a simulation of user data rates with and without femtocells.[7] The air interface is 5-MHz HSDPA using a single receiver with equalizer, 64QAM and 15 codes. For the macrocell case (blue trace), 34 UEs are evenly distributed across the cell and the median throughput is 40 kbps with the peak at 400 kbps. When the 96 femtocells are enabled, 24 UE choose to switch to the femtocells, leaving only 10 UE on the macrocell.

The new median data rate (red trace) is 8 Mbps with the peak around 17 Mbps. In addition, by offloading users to the femtocells, the remaining macrocell users see their median data rate move from 50 kbps to around 170 kbps.

This simulation clearly shows the difference between trying to improve capacity and median data rates by enhancing a single macro cell versus adding femtocells. This macrocell with 34 distributed users has a capacity of around 1.3 Mbps (0.26 b/s/Hz/cell), resulting in the median of 40 kbps. Note that the macrocell is capable of supporting 17 Mbps, but only for one user near the cell center. If efficiency gains of 3x were realized, the median would rise to around 120 kbps, but this is a difficult and expensive task with no guarantee of success. In contrast, by deploying low-cost femtocells using existing less-sophisticated technology, median data rates, due to better radio conditions and lower cell loading, are seen to rise a massive 200x to 8 Mbps.

Looking briefly at femtocells

A femtocell differentiates itself from the traditional centrally-deployed model according to the attributes in Table 2.

Table 2. Comparison of traditional cellular and femtocellular

Attribute	Traditional cellular	Femtocellular
Infrastructure cost	$10,000 - $100,000	$100 - $200
Infrastructure finance	Operator	End user
Backhaul	Expensive leased E1/T1 lines	Existing end-user DSL or cable broadband
Planning	Operator	End-user (no central planning)
Deployment	Operator truck roll	End-user one-touch provisioning
Quality of Service (QoS)	Operator controlled	Best effort
Control	Operator via O&M	Operator via Internet
Mobility	Good/excellent	Nomadic/best effort
Performance	Limited	Excellent

It is easy to assume that femtocells are just a further progression down the macro/micro/picocellular model of decreasing cell radius. This is true in terms of the coverage area, which for picocells and femtocells is in the range of 10 m, but it should be evident from Table 2 that the femtocell approach is fundamentally different from today's cellular. A closer model would be that of a cellular version of Wi-Fi hotspots but with much better control over QoS through use of cognitive radio techniques inherent to cellular's awareness of its environment, and the ability of the operator to remotely control the femtocell via the Internet-based backhaul. Note that the 200x femtocell improvement is delivered with a peak rate of 17 Mbps, well within range of evolving end-user backhaul.

To be fair, femtocells have been tried — unsuccessfully — several times in the past, with the focus having been on telephony. Understanding those failures, and embracing the new potential for data services, will determine if femtocells have now come of age. To this end, one crucial factor now making a big difference is the Femtoforum, which is addressing many of the issues necessary to ensure commercial femtocell success.[8] The challenges remain significant and include aspects of end-to-end service — such as backhaul network neutrality and commercial roaming agreements — that are outside the scope of traditional standards bodies.

The prize, however, if these obstacles can be overcome, is that femtocells have the potential to deliver massive capacity gains and corresponding increases in average data rates for the nomadic data-using community — gains that could never be achieved with macrocell improvements alone. It will be some time before femtocells are as prevalent as Wi-Fi is today, but the outlook is good and the next two years will be key for this fledgling technology.

Offering a 4G prognosis

Let's repeat two key points. First, the provision of higher data rates drives up expectations but does not significantly increase system capacity or median data rates. Second, with the projected efficiency and spectrum gains, median data rates in a loaded network may reach only one percent of the designed peak. If we accept these hypotheses, then it seems evident that 4G's spectrum and efficiency gains are insignificant compared to what could be achieved by enabling a femtocell deployment.

4G is aiming to be a low-cost solution for mobile broadband, but high efficiency and high data rates mitigate against this. Ever-higher peak rates drive up the cost of infrastructure and terminals, and high-efficiency systems are inherently complex and therefore also drive up costs. If there is neither the demand for extreme high-rate services, nor the ability to deliver them uniformly, 4G could be in danger of becoming an expensive white elephant. In reality, subscribers pay for peak performance but experience the average. With current plans, the top end of 4G at 100:1 will have the highest peak-to-average performance ratio of any wireless system to date. The contrast with today's most successful and ubiquitous wireless services — voice telephony with a 1:1 ratio and highly inefficient text messaging — could not be starker.

The pursuit of capacity gains through efficiency will have a positive effect — and the engineering challenge this presents is both fascinating and formidable. However, the question the industry must ask itself is whether efficiency should be a primary goal. The 100x capacity gains that might be realized using a high-mobility macro network complemented by a femtocell network for nomadic use in the locations of highest demand cannot be ignored.

Conclusion

The door is not yet shut on the definition of 4G, but it is closing fast. The extent to which 4G can address the capacity and coverage issues in a cost-effective manner will determine if it will be the enabler of the mobile broadband revolution — or if it will compound the issues that have hindered 3G. One thing is certain: The market will select, in Darwinian fashion, the lowest-cost way to realize the mobile broadband opportunity. If 4G does not address the bottlenecks in today's systems then several alternative technologies — all based on existing and evolving 2G and 3G standards — are ready to step up and clear the way. In particular, femtocells (based on simpler, existing air-interface technology) and even evolving Wi-Fi technologies have the potential to deliver high-performance, cost-effective alternatives to enable the mobile broadband revolution.

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