Mobile Networks

PERFORMANCE OF WIRELESS NETWORKS, CHAPTER 7

As of early 2013, there are now an estimated 6.4 billion worldwide cellular connections. For 2012 alone, IDC market intelligence reports show an estimated 1.1 billion shipments for smart connected devices—smartphones, tablets, laptops, PCs, and so on. However, even more remarkable are the hockey stick growth projections for the years to come: the same IDC reports forecast the new device shipment numbers to climb to over 1.8 billion by 2016, and other cumulative forecasts estimate a total of over 20 billion connected devices by 2020.

With an estimated human population of 7 billion in 2012, rising to 7.5 billion by 2020, these trends illustrate our insatiable appetite for smart connected devices: apparently, most of us are not satisfied with just one.

However, the absolute number of connected devices is only one small part of the overall story. Implicit in this growth is also the insatiable demand for high-speed connectivity, ubiquitous wireless broadband access, and the connected services that must power all of these new devices! This is where, and why, we must turn our conversation to the performance of the various cellular technologies, such as GSM, CDMA, HSPA, and LTE. Chances are, most of your users will be using one of these technologies, some exclusively, to access your site or service. The stakes are high, we have to get this right, and mobile networks definitely pose their own set of performance challenges.

Brief History of the G’s §

Navigating the forest of the various cellular standards, release versions, and the pros and cons of each could occupy not chapters, but entire books. Our goal here is much more humble: we need to develop an intuition for the operating parameters, and their implications, of the major past and future milestones (Table 7-1) of the dominant wireless technologies in the market.

Generation	Peak data rate	Description
1G	no data	Analog systems
2G	Kbit/s	First digital systems as overlays or parallel to analog systems
3G	Mbit/s	Dedicated digital networks deployed in parallel to analog systems
4G	Gbit/s	Digital and packet-only networks

Table 7-1. Generations of mobile networks

expressed in terms of *peak spectral efficiency* (bps/Hz), which is then translated to impressive numbers such as Gbit/s+ peak data rates for 4G networks. However, you should now recognize the key word in the previous sentence: *peak!* Think back to our earlier discussion on Measuring Real-World Wireless Performance—peak data rates are achieved in ideal conditions.

Regardless of the standard, the real performance of every network will vary by provider, their configuration of the network, the number of active users in a given cell, the radio environment in a specific location, the device in use, plus all the other factors that affect wireless performance. With that in mind, while there are no guarantees for data rates in real-world environments, a simple but effective strategy to calibrate your performance expectations (Table 7-2) is to assume much closer to the lower bound for data throughput, and toward the higher bound for packet latency for every generation.

Generation	Data rate	Latency
2G	100–400 Kbit/s	300–1000 ms
3G	0.5–5 Mbit/s	100–500 ms
4G	1–50 Mbit/s	< 100 ms

Table 7-2. Data rates and latency for an active mobile connection

To complicate matters further, the classification of any given network as 3G or 4G is definitely too coarse, and correspondingly so is the expected throughput and latency. To understand why this is the case, and where the industry is heading, we first need to take a quick survey of the history of the different technologies and the key players behind their evolution.

First Data Services with 2G §

The first commercial 1G network was launched in Japan in 1979. It was an analog system and offered no data capabilities. In 1991, the first 2G network was launched in Finland based on the emerging GSM (Global System for Mobile Communications, originally Groupe Spécial Mobile) standard, which introduced digital signaling within the radio network. This enabled first circuit-switched mobile data services, such as text messaging (SMS), and packet delivery at a whopping peak data rate of 9.6 Kbit/s!

It wasn't until the mid 1990s, when general packet radio service (GPRS) was first introduced to the GSM standard that wireless Internet access became a practical, albeit still very slow, possibility: with GPRS, you could now reach 172 Kbit/s, with typical roundtrip latency hovering in high hundreds of milliseconds. The combination of GPRS and earlier 2G voice technologies is often described as 2.5G. A few years later, these networks were enhanced by EDGE (Enhanced Data rates for GSM Evolution), which increased the peak data rates to 384 Kbit/s. The first EDGE networks (2.75G) were launched in the U.S. in 2003.

decades old, but practical, consumer-oriented data services over mobile networks are a recent phenomenon! 2.75G networks are barely a decade old, which is recent history, and are also still widely used around the world. Yet, most of us now simply can't imagine living without high-speed wireless access. The rate of adoption, and the evolution of the wireless technologies, has been nothing short of breathtaking.

3GPP and 3GPP2 Partnerships §

Once the consumer demand for wireless data services began to grow, the question of radio network interoperability became a hot issue for everyone involved. For one, the telecom providers must buy and deploy the hardware for the radio access network (RAN), which requires significant capital investments and ongoing maintenance—standard hardware means lower costs. Similarly, without industry-wide standards, the users would be restricted to their home networks, limiting the use cases and convenience of mobile data access.

In response, the European Telecommunication Standards Institute (ETSI) developed the GSM standard in the early 1990's, which was quickly adopted by many European countries and around the globe. In fact, GSM would go on to become the most widely deployed wireless standard, by some estimates, covering 80%–85% of the market (Figure 7-1). But it wasn't the only one. In parallel, the IS-95 standard developed by Qualcomm also captured 10%–15% of the market, most notably with many network deployments across North America. As a result, a device designed for the IS-95 radio network cannot operate on the GSM network, and vice versa—an unfortunate property that is familiar to many international travelers.

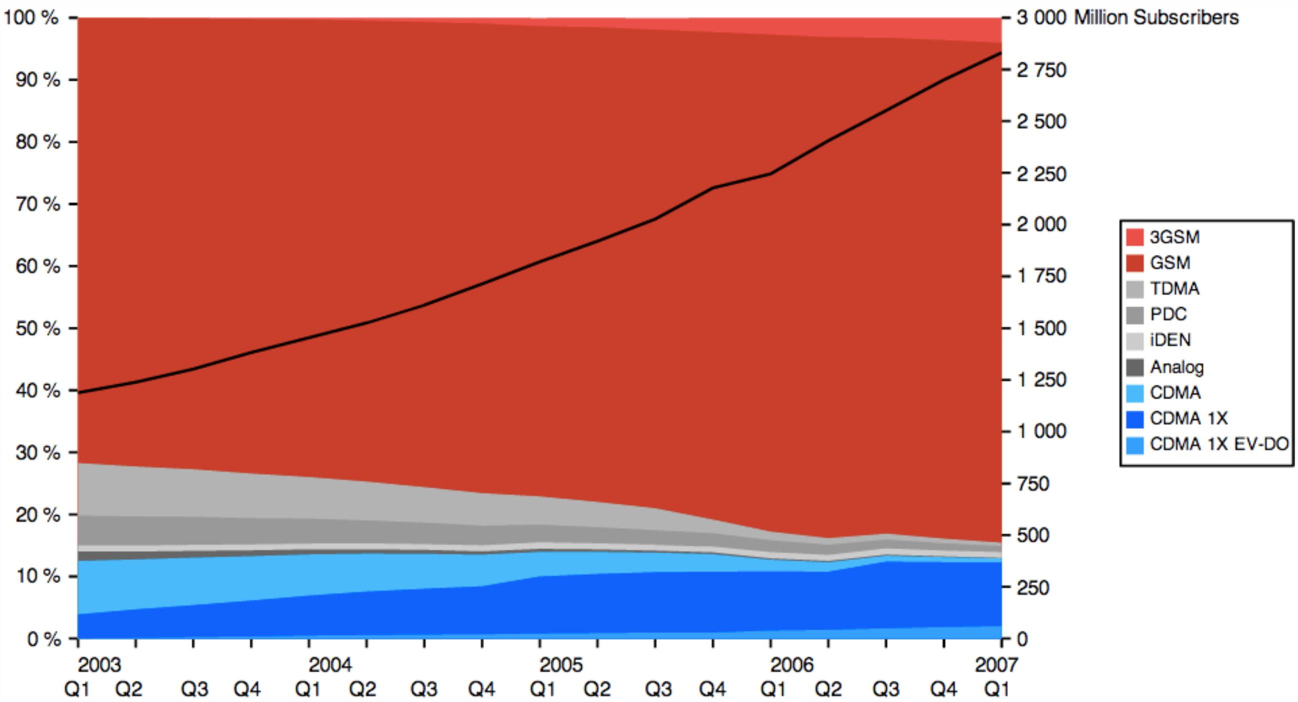


Figure 7-1. Market share of mobile standards for 2003–2007 (Wikipedia)

the requirements for the next generation (3G) networks, the participants in GSM and IS-95 standards organizations formed two global partnership projects:

3rd Generation Partnership Project (3GPP)

Responsible for developing the Universal Mobile Telecommunication System (UMTS), which is the 3G upgrade to GSM networks. Later, it also assumed maintenance of the GSM standard and development of the new LTE standards.

3rd Generation Partnership Project 2 (3GPP2)

Responsible for developing the 3G specifications based on the CDMA2000 technology, which is a successor to the IS-95 standard developed by Qualcomm.

Consequently, the development of both types of standards (Table 7-3) and associated network infrastructure has proceeded in parallel. Perhaps not directly in lockstep, but nonetheless following mostly similar evolution of the underlying technologies.

Generation	Organization	Release
2G	3GPP	GSM
	3GPP2	IS-95 (cdmaOne)
2.5G, 2.75G	3GPP	GPRS, EDGE (EGPRS)
	3GPP2	CDMA2000
3G	3GPP	UMTS
	3GPP2	CDMA 2000 1x EV-DO Release 0
3.5G, 3.75G, 3.9G	3GPP	HSPA, HSPA+, LTE
	3GPP2	EV-DO Revision A, EV-DO Revision B, EV-DO Advanced
4G	3GPP	LTE-Advanced, HSPA+ Revision 11+

Table 7-3. Cellular network standards developed by 3GPP and 3GPP2

Chances are, you should see some familiar labels on the list: EV-DO, HSPA, LTE. Many network operators have invested significant marketing resources, and continue to do so, to promote these technologies as their "latest and fastest mobile data networks." However, our interest and the reason for this historical detour is not for the marketing, but for the macro observations of the evolution of the mobile wireless industry:

- There are two dominant, deployed mobile network types around the world.
- 3GPP and 3GPP2 manage the evolution of each technology.
- 3GPP and 3GPP2 standards are not device interoperable.

international standards and performance characteristics, such as data rates and latency, for each wireless generation, and the 3GPP and 3GPP2 organizations then define the standards to meet and exceed these expectations within the context of their respective technologies.

Note

How do you know which network type your carrier is using? Simple. Does your phone have a SIM card? If so, then it is a 3GPP technology that evolved from GSM. To find out more detailed information about the network, check your carrier's FAQ, or if your phone allows it, check the network information directly on your phone.

For Android users, open your phone dial screen and type in: `*#*#4636#*#*`*. If your phone allows it, it should open a diagnostics screen where you can inspect the status and type of your mobile connection, battery diagnostics, and more.*

Evolution of 3G Technologies

In the context of 3G networks, we have two dominant and competing standards: UMTS and CDMA-based networks, which are developed by 3GPP and 3GPP2, respectively. However as the earlier table of cellular standards (Table 7-3) shows, each is also split into several transitional milestones: 3.5G, 3.75G, and 3.9G technologies.

Why couldn't we simply jump to 4G instead? Well, standards take a long time to develop, but even more importantly, there are big financial costs for deploying new network infrastructure. As we will see, 4G requires an entirely different radio interface and parallel infrastructure to 3G. Because of this, and also for the benefit of the many users who have purchased 3G handsets, both 3GPP and 3GPP2 have continued to evolve the existing 3G standards, which also enables the operators to incrementally upgrade their existing networks to deliver better performance to their existing users.

Not surprisingly, the throughput, latency, and other performance characteristics of the various 3G networks have improved, sometimes dramatically, with every new release. In fact, technically, LTE is considered a 3.9G transitional standard! However, before we get to LTE, let's take a closer look at the various 3GPP and 3GPP2 milestones.

Evolution of 3GPP technologies

Release	Date	Summary
99	1999	First release of the UMTS standard
4	2001	Introduced an all-IP core network

5	2002	Introduced High-Speed Packet Downlink Access (HSDPA)
6	2004	Introduced High-Speed Packet Uplink Access (HSUPA)
7	2007	Introduced High-Speed Packet Access Evolution (HSPA+)
8	2008	Introduced new LTE System Architecture Evolution (SAE)
9	2009	Improvements to SAE and WiMAX interoperability
10	2010	Introduced 4G LTE-Advanced architecture

Table 7-4. 3GPP release history

In the case of networks following the 3GPP standards, the combination of HSDPA and HSUPA releases is often known and marketed as a High-Speed Packet Access (HSPA) network. This combination of the two releases enabled low single-digit Mbit/s throughput in real-world deployments, which was a significant step up from the early 3G speeds. HSPA networks are often labeled as 3.5G.

From there, the next upgrade was HSPA+ (3.75G), which offered significantly lower latencies thanks to a simplified core network architecture and data rates in mid to high single-digit Mbit/s throughput in real-world deployments. However, as we will see, release 7, which introduced HSPA+, was not the end of the line for this technology. In fact, the HSPA+ standards have been continuously refined since then and are now competing head to head with LTE and LTE-Advanced!

Evolution of 3GPP2 technologies

Release	Date	Summary
Rel. 0	1999	First release of the 1x EV-DO standard
Rev. A	2001	Upgrade to peak data-rate, lower latency, and QoS
Rev. B	2004	Introduced multicarrier capabilities to Rev. A
Rev. C	2007	Improved core network efficiency and performance

Table 7-5. 3GPP2 release history of the CDMA2000 1x EV-DO standard

The CDMA2000 EV-DO standard developed by 3GPP2 followed a similar network upgrade path. The first release (Rel. 0) enabled low single digit Mbit/s downlink throughput but very low uplink speeds. The uplink performance was addressed with Rev. A, and both uplink and downlink speeds were further improved in Rev. B. Hence, a Rev. B network was able to deliver mid to high networks—aka, 3.5–3.75G.

The Rev. C release is also frequently referred to as EV-DO Advanced and offers significant operational improvements in capacity and performance. However, the adoption of EV-DO Advanced has not been nearly as strong as that of HSPA+. Why? If you paid close attention to the standards generation table (Table 7-3), you may have noticed that 3GPP2 does not have an official and competing 4G standard!

While 3GPP2 could have continued to evolve its CDMA technologies, at some point both the network operators and the network vendors agreed on 3GPP LTE as a *common 4G successor* to all types of networks. For this reason, many of the CDMA network operators are also some of the first to invest into early LTE infrastructure, in part to be able to compete with ongoing HSPA+ improvements.

In other words, most mobile operators around the world are converging on HSPA+ and LTE as the future mobile wireless standards—that's the good news. Having said that, don't hold your breath. Existing 2G and 3–3.75G technologies are still powering the vast majority of deployed mobile radio networks, and even more importantly, will remain operational for at least another decade.

Note

3G is often described as "mobile broadband." However, broadband is a relative term. Some pin it as a communication bandwidth of at least 256 Kbit/s, others as that exceeding 640 Kbit/s, but the truth is that the value keeps changing based on the experience we are trying to achieve. As the services evolve and demand higher throughput, so does the definition of broadband.

In that light, it might be more useful to think of 3G standards as those targeting and exceeding the Mbit/s bandwidth threshold. How far over the Mbit/s barrier? Well, that depends on the release version of the standard (as we saw earlier), the carrier configuration of the network, and the capabilities of the device in use.

IMT-Advanced 4G Requirements §

Before we dissect the various 4G technologies, it is important to understand what stands behind the "4G" label. Just as with 3G, there is no one 4G technology. Rather, 4G is a set of requirements (IMT-Advanced) that was developed and published by the ITU back in 2008. Any technology that meets these requirements can be labeled as 4G.

Some example requirements of IMT-Advanced include the following:

- Based on an IP packet switched network
- Interoperable with previous wireless standards (3G and 2G)

- Sub 100 ms control-plane latency and sub 10 ms user-plane latency
- Dynamic allocation and sharing of network resources between users
- Use of variable bandwidth allocation, from 5 to 20 MHz

The actual list is much, much longer but the preceding captures the highlights important for our discussion: much higher throughput and significantly lower latencies when compared to earlier generations. Armed with these criteria, we now know how to classify a 4G network—right? Not so fast, that would be too easy! The marketing departments also had to have their say.

LTE-Advanced is a standard that was specifically developed to satisfy all the IMT-Advanced criteria. In fact, it was also the first 3GPP standard to do so. However, if you were paying close attention, you would have noticed that LTE (release 8) and LTE-Advanced (release 10) are, in fact, different standards. Technically, LTE should really be considered a 3.9G transitional standard, even though it lays much of the necessary groundwork to meet the 4G requirements—it is almost there, but not quite!

However, this is where the marketing steps in. The 3G and 4G trademarks are held by the ITU, and hence their use should correspond to defined requirements for each generation. Except the carriers won a marketing coup and were able to redefine the "4G" trademark to include a set of technologies that are *significantly close* to the 4G requirements. For this reason, LTE (release 8) and most HSPA+ networks, which do not meet the actual technical 4G requirements, are nonetheless marketed as "4G."

What about the real (LTE-Advanced) 4G deployments? Those are coming, but it remains to be seen how these networks will be marketed in light of their earlier predecessors. Regardless, the point is, the "4G" label as it is used today by many carriers is ambiguous, and you should read the fine print to understand the technology behind it.

Long Term Evolution (LTE) §

Despite the continuous evolution of the 3G standards, the increased demand for high data transmission speeds and lower latencies exposed a number of inherent design limitations in the earlier UMTS technologies. To address this, 3GPP set out to redesign both the core and the radio networks, which led to the creation of the aptly named Long Term Evolution (LTE) standard:

- All IP core network
- Simplified network architecture to lower costs
- Low latencies in user (<10 ms) and control planes (<100 ms)
- New radio interface and modulation for high throughput (100 Mbps)
- Ability to use larger bandwidth allocations and carrier aggregation
- MIMO as a requirement for all devices

earlier. LTE (release 8) laid the groundwork for the new network architecture, and LTE-Advanced (release 10) delivered the necessary improvements to meet the true 4G requirements set by IMT-Advanced.

At this point it is important to note that due to radio and core network implementation differences, LTE networks are not simple upgrades to existing 3G infrastructure. Instead, LTE networks must be deployed in parallel and on separate spectrum from existing 3G infrastructure. However, since LTE is a common successor to both UMTS and CDMA standards, it does provide a way to interoperate with both: an LTE subscriber can be seamlessly handed off to a 3G network and be migrated back where LTE infrastructure is available.

Finally, as the name implies, LTE is definitely the long-term evolution plan for virtually all future mobile networks. The only question is, how distant is this future? A few carriers have already begun investing into LTE infrastructure, and many others are beginning to look for the spectrum, funds, or both, to do so. However, current industry estimates show that this migration will indeed be a *long-term one*—perhaps over the course of the next decade or so. In the meantime, HSPA+ is set to take the center stage.

Note

Every LTE-capable device must have multiple radios for mandatory MIMO support. However, each device will also need separate radio interfaces for earlier 3G and 2G networks. If you are counting, that translates to three or four radios in every handset! For higher data rates with LTE, you will need 4x MIMO, which brings the total to five or six radios. You were wondering why your battery is drained so quickly?

HSPA+ is Leading Worldwide 4G Adoption §

HSPA+ was first introduced in 3GPP release 7, back in 2007. However, while the popular attention quickly shifted toward LTE, which was first introduced in 3GPP release 8 in 2008, what is often overlooked is that the development of HSPA+ did not cease and continued to coevolve in parallel. In fact, HSPA+ release 10 meets many of the IMT-Advanced criteria. But, you may ask, if we have LTE and everyone is in agreement that it is *the standard* for future mobile networks, why continue to develop and invest into HSPA+? As usual, the answer is a simple one: cost.

3GPP 3G technologies command the lion’s share of the established wireless market around the world, which translates into huge existing infrastructure investments by the carriers around the globe. Migrating to LTE requires development of new radio networks, which once again translates into significant capital expenditures. By contrast, HSPA+ offers a much more capital efficient route: the carriers can deploy incremental upgrades to their existing networks and get comparable performance.

(Figure 7-2) show HSPA+ as responsible for the majority of 4G upgrades around the world for years to come. In the meantime, CDMA technologies developed by 3GPP2 will continue to coexist, although their number of subscriptions is projected to start declining slowly, while new LTE deployments will proceed in parallel with different rates in different regions—in part due to cost constraints, and in part due to different regulation and the availability of required radio spectrum.

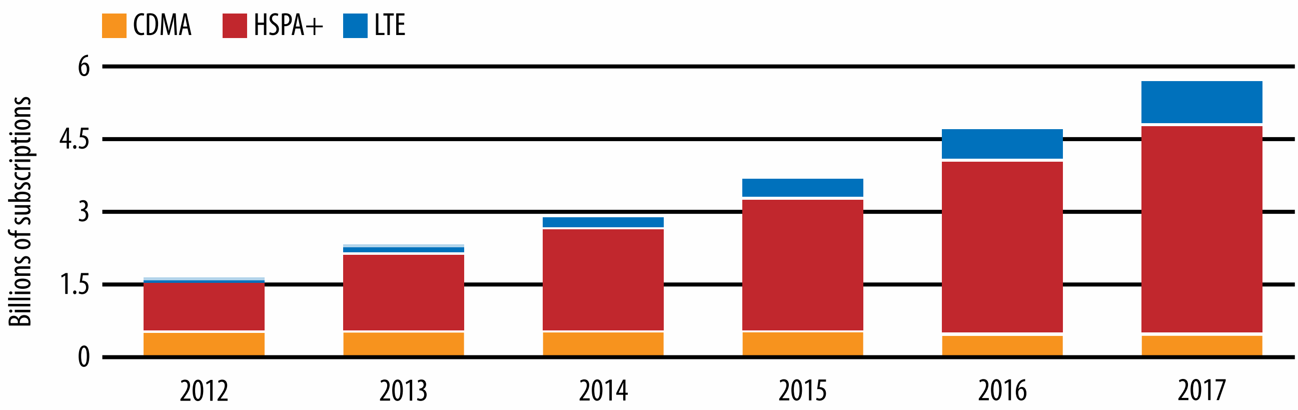


Figure 7-2. 4G Americas: HSPA+ and LTE mobile broadband growth forecast

For a variety of reasons, North America appears to be the leader in LTE adoption: current industry projections show the number of LTE subscribers in U.S. and Canada surpassing that of HSPA by 2016 (Figure 7-3). However, the rate of LTE adoption in North America appears to be significantly more aggressive than in most other countries. Within the global context, HSPA+ is set to be the dominant mobile wireless technology of the current decade.

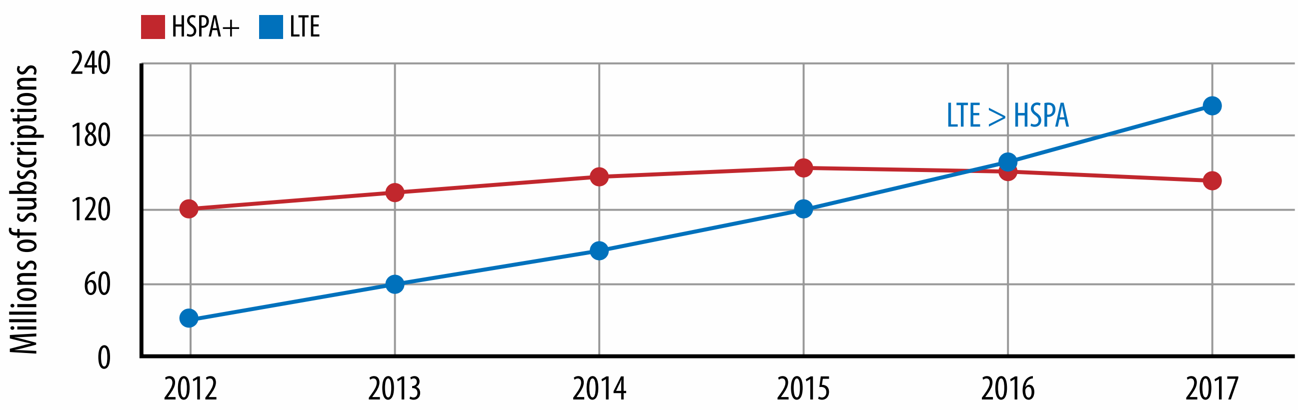


Figure 7-3. 4G Americas: U.S./Canada HSPA+ and LTE growth forecast

Note

While many are first surprised by the trends in the HSPA+ vs. LTE adoption, this is not an unexpected outcome. If nothing else, it serves to illustrate an important point: it takes roughly a decade from the first specification of a new wireless standard to its mainstream availability in real-world wireless networks.

By extension, it is a fairly safe bet that we will be talking about LTE-Advanced in earnest by the early 2020s! Unfortunately, deploying new radio infrastructure is a costly and time-consuming

Building for the Multigeneration Future §

Crystal ball gazing is a dangerous practice in our industry. However, by this point we have covered enough to make some reasonable predictions about what we can and should expect out of the currently deployed mobile networks, as well as where we might be in a few years' time.

First, the wireless standards are evolving quickly, but the physical rollout of these networks is both a costly and a time-consuming exercise. Further, once deployed, the network must be maintained for significant amounts of time to recoup the costs and to keep existing customers online. In other words, while there is a lot of hype and marketing around 4G, older-generation networks will continue to operate for at least another decade. When building for the mobile web, plan accordingly.

Note

Ironically, while 4G networks provide significant improvements for IP data delivery, 3G networks are still much more efficient in handling the old-fashioned voice traffic! Voice over LTE (VoLTE) is currently in active development and aims to enable efficient and reliable voice over 4G, but most current 4G deployments still rely on the older, circuit-switched infrastructure for voice delivery.

Consequently, when building applications for mobile networks, we cannot target a single type or generation of network, or worse, hope for specific throughput or latency performance. As we saw, the actual performance of any network is highly variable, based on deployed release, infrastructure, radio conditions, and a dozen other variables. Our applications should adapt to the continuously changing conditions within the network: throughput, latency, and even the availability of the radio connection. When the user is on the go, it is highly likely that he may transition between multiple generations of networks (LTE, HSPA+, HSPA, EV-DO, and even GPRS Edge) based on the available coverage and signal strength. If the application fails to account for this, then the user experience will suffer.

The good news is HSPA+ and LTE adoption is growing very fast, which enables an entirely new class of high-throughput and latency-sensitive applications previously not possible. Both are effectively on par in throughput and latency (Table 7-6): mid to high digit Mbps throughput in real-world environments, and sub-100-millisecond latency, which makes them comparable to many home and office WiFi networks.

	HSPA+	LTE	LTE-Advanced
Peak downlink speed (Mbit/s)	168	300	3,000

Peak uplink speed (Mbit/s)	22	75	1,500
Maximum MIMO streams	2	4	8
Idle to connected latency (ms)	< 100	< 100	< 50
Dormant to active latency (ms)	< 50	< 50	< 10
User-plane one-way latency (ms)	< 10	< 5	< 5

Table 7-6. HSPA+, LTE, and LTE-Advanced comparison

However, while 4G wireless performance is often compared to that of WiFi, or wired broadband, it would be incorrect to assume that we can get away with treating them as the same environments: that they are definitely not.

For example, most users and developers expect an "always on" experience where the device is permanently connected to the Internet and is ready to instantaneously react to user input or an incoming data packet. This assumption holds true in the tethered world but is definitely incorrect for mobile networks. Practical constraints such as battery life and device capabilities mean that we must design our applications with explicit awareness of the constraints of mobile networks. To understand these differences, let’s dig a little deeper.

User-Plane One-way Latency §

User-plane one-way latency is the target time specified by the LTE standard for the one-way transit between a packet being available in the wireless device and the same packet being available at the radio tower. In other words, it is the one-way latency of the first wireless hop when the device is in the high-power continuous reception state. Every application packet will incur this cost—no shortcuts.

Device Features and Capabilities §

What is often forgotten is that the deployed radio network is only half of the equation. It goes without saying that devices from different manufacturers and release dates will have very different characteristics: CPU speeds and core counts, amount of available memory, storage capacity, GPU, and more. Each of these factors will affect the overall performance of the device and the applications running on it.

However, even with all of these variables accounted for, when it comes to network performance, there is one more section that is often overlooked: radio capabilities. Specifically, the device that the user is holding in her hands must also be able to take advantage of the deployed radio earlier release may simply not be able to take advantage of it, and vice versa.

User Equipment Category

Both the 3GPP and 3GPP2 standards continue to evolve and enhance the radio interface requirements: modulation schemes, number of radios, and so on. To get the best performance out of any network, the device must also meet the specified user equipment (UE) category requirements for each type of network. In fact, for each release, there are often multiple UE categories, each of which will offer very different radio performance.

An obvious and important question is, why? Once again, the answer is a simple one: cost. Availability of multiple categories of devices enables device differentiation, various price points for price-sensitive users, and ability to adapt to deployed network infrastructure on the ground.

The HSPA standard alone specifies over 36 possible UE categories! Hence, just saying that you have an "HSPA capable device" (Table 7-7) is not enough—you need to read the fine print. For example, assuming the radio network is capable, to get the 42.2 Mbps/s throughput, you would also need a category 20 (2x MIMO), or category 24 (dual-cell) device. Finally, to confuse matters further, a category 21 device does not automatically guarantee higher throughput over a category 20 handset.

3GPP Release	Category	MIMO, Multicell	Peak data rate (Mbit/s)
5	8	—	7.2
5	10	—	14.0
7	14	—	21.1
8	20	2x MIMO	42.2
8	21	Dual-cell	23.4
8	24	Dual-cell	42.2
10	32	Quad-cell + MIMO	168.8

Table 7-7. Sample 3GPP HSPA user equipment (UE) categories

Similarly, the LTE standard defines its own set of user equipment categories (Table 7-8): a high-end smartphone is likely to be a category 3–5 device, but it will also likely share the network with a lot of cheaper category 1–2 neighbors. Higher UE categories, which require 4x and even 8x MIMO, are more likely to be found in specialized devices—powering that many radios simultaneously consumes a lot of power, which may not be very practical for something in your pocket!

8	1	1x	10.3	5.2
8	2	2x	51.0	25.5
8	3	2x	102.0	51.0
8	4	2x	150.8	51.0
8	5	4x	299.6	75.4
10	6	2x or 4x	301.5	51.0
10	7	2x or 4x	301.5	102.0
10	8	8x	2998.6	1497.8

Table 7-8. LTE user equipment (UE) categories

Note

In practice, most of the early LTE deployments are targeting category 1–3 devices, with early LTE-Advanced networks focusing on category 3 as their primary UE type.

If you own an LTE or an HSPA+ device, do you know its category classification? And once you figure that out, do you know which 3GPP release your network operator is running? To get the best performance, the two must match. Otherwise, you will be limited either by the capabilities of the radio network or the device in use.

Deciphering the Radio Specification on a Mobile Device §

If you have ever read the technical specification of your mobile device, you would have no doubt noticed a long and confusing list of frequencies and technology types under the connectivity section. Well, now we should know enough to decipher this list! As an example, let's take a look at the specification for Google's Nexus 4:

- GSM/EDGE/GPRS (850, 900, 1800, 1900 MHz)
- 3G (850, 900, 1700, 1900, 2100 MHz)
- HSPA+ 42

The first line tells us that the device can operate on 2G networks and is GPRS (2.5G) and EDGE (2.75G) capable—hundreds of Kbit/s peak data rates. The list of frequencies indicates the bands on which the radio is able to operate, to account for the different regulations and network deployments around the world.

The second line is similar, except that it doesn't indicate much in terms of maximum 3G throughput. But that is exactly what the third line reveals: HSPA+ indicates that the phone can network allows it. In fact, Nexus 4 is a category 24 dual-cell device.

Finally, this phone is not LTE capable; for that it would need another radio interface, in addition to the 2G and 3G radios. Many mobile phones are already miracles of miniaturization, but this fact is only more impressive when you realize that most modern phones don’t just have one radio: most have somewhere between two and four!

Radio Resource Controller (RRC) §

Both 3G and 4G networks have a unique feature that is not present in tethered and even WiFi networks. The Radio Resource Controller (RRC) mediates all connection management between the device in use and the radio base station (Figure 7-4). Understanding why it exists, and how it affects the performance of every device on a mobile network, is critical to building high-performance mobile applications. The RRC has direct impact on latency, throughput, and battery life of the device in use.

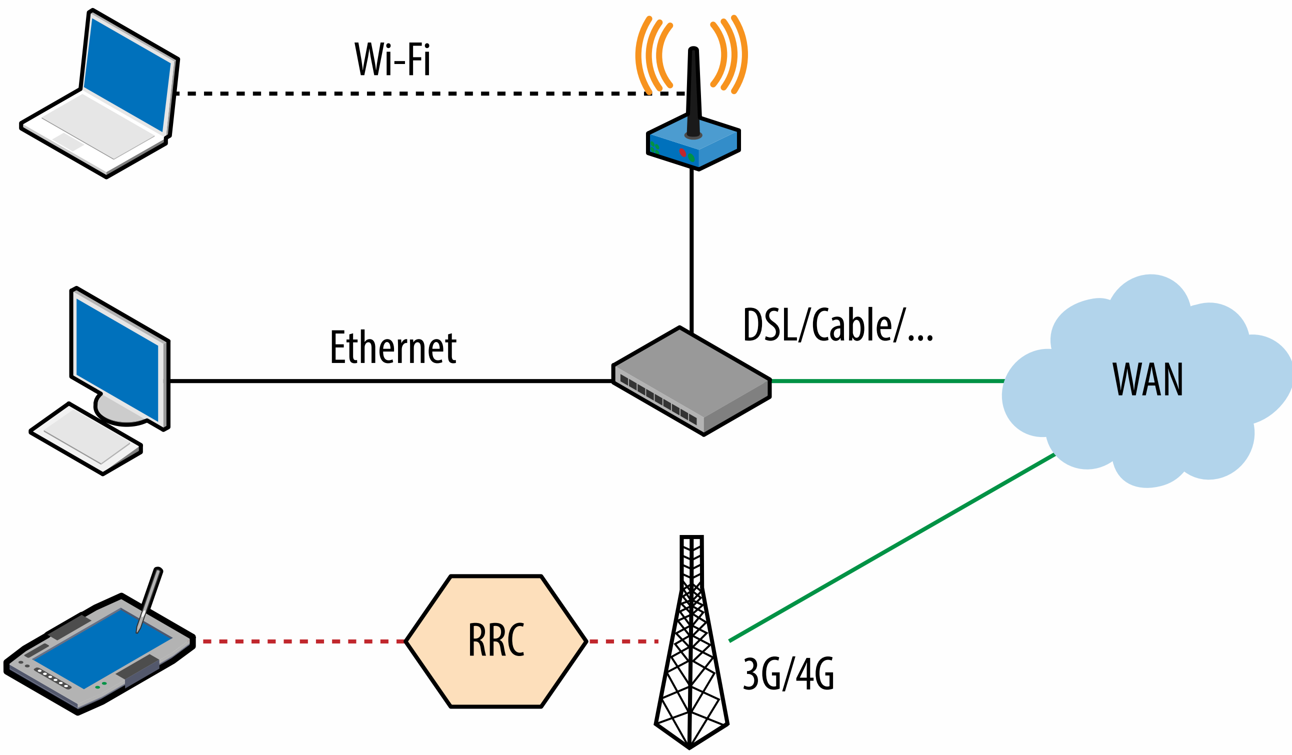


Figure 7-4. Radio Resource Controller

When using a physical connection, such as an Ethernet cable, your computer has a direct and an always-on network link, which allows either side of this connection to send data packets at any time; this is the best possible case for minimizing latency. As we saw in From Ethernet to a Wireless LAN, the WiFi standard follows a similar model, where each device is able to transmit at any point in time. This too provides minimum latency in the best case, but due to the use of the shared radio medium can also lead to high collision rates and unpredictable performance if there others must also be ready to receive. The radio is always on, which consumes a lot of power.

In practice, keeping the WiFi radio active at all times is simply too expensive, as battery capacity is a limited resource on most devices. Hence, WiFi offers a small power optimization where the access point broadcasts a delivery traffic indication message (DTIM) within a periodic beacon frame to indicate that it will be transmitting data for certain clients immediately after. In turn, the clients can listen for these DTIM frames as hints for when the radio should be ready to receive, and otherwise the radio can sleep until the next DTIM transmission. This lowers battery use but adds extra latency.

Note

The upcoming WiFi Multimedia (WMM) standard will further improve the power efficiency of WiFi devices with the help of the new PowerSave mechanisms such as NoAck and APSD (Automatic Power Save Delivery).

Therein lies the problem for 3G and 4G networks: network efficiency and power. Or rather, lack of power, due to the fact that mobile devices are constrained by their battery capacity and a requirement for high network efficiency among a significantly larger number of active users in the cell. This is why the RRC exists.

As the name implies, the Radio Resource Controller assumes full responsibility over scheduling of who talks when, allocated bandwidth, the signal power used, the power state of each device, and a dozen other variables. Simply put, the RRC is the brains of the radio access network. Want to send data over the wireless channel? You must first ask the RRC to allocate some radio resources for you. Have incoming data from the Internet? The RRC will notify you for when to listen to receive the inbound packets.

The good news is all the RRC management is performed by the network. The bad news is, while you can’t necessarily control the RRC via an API, if you do want to optimize your application for 3G and 4G networks, then you need to be aware of and work within the constraints imposed by the RRC.

Note

The RRC lives within the radio network. In 2G and 3G networks, the RRC lived in the core carrier network, and in 4G the RRC logic has been moved directly to the serving radio tower (eNodeB) to improve performance and reduce coordination latency.

3G, 4G, and WiFi Power Requirements §

only component that consumes higher amounts of power when active—emphasis on active. In practice, the screen is off for significant periods of time, whereas the radio must maintain the illusion of an "always-on" experience such that the user is reachable at any point in time.

One way to achieve this goal is to keep the radio active at all times, but even with the latest advances in battery capacity, doing so would drain the battery in a matter of hours. Worse, latest iterations of the 3G and 4G standards require parallel transmissions (MIMO, Multicell, etc.), which is equivalent to powering multiple radios at once. In practice, a balance must be struck between keeping the radio active to service low-latency interactive traffic and cycling into low-power states to enable reasonable battery performance.

How do the different technologies compare, and which is better for battery life? There is no one single answer. With WiFi, each device sets its own transmit power, which is usually in the 30–200 mW range. By comparison, the transmit power of the 3G/4G radio is managed by the network and can consume as low as 15 mW when in an idle state. However, to account for larger range and interference, the same radio can require 1,000–3,500 mW when transmitting in a high-power state!

In practice, when transferring large amounts of data, WiFi is often far more efficient if the signal strength is good. But if the device is mostly idle, then the 3G/4G radio is more effective. For best performance, ideally we would want dynamic switching between the different connection types. However, at least for the moment, no such mechanism exists. This is an active area of research, both in the industry and academia.

So how does the battery and power management affect networking performance? Signal power (explained Signal Power) is one of the primary levers to achieve higher throughput. However, high transmit power consumes significant amounts of energy and hence may be throttled to achieve better battery life. Similarly, powering down the radio may also tear down the radio link to the radio tower altogether, which means that in the event of a new transmission, a series of control messages must be first exchanged to reestablish the radio context, which can add tens and even hundreds of milliseconds of latency.

Both throughput and latency performance are directly impacted by the power management profile of the device in use. In fact, and this is key, in 3G and 4G networks the radio power management is controlled by the RRC: not only does it tell you when to communicate, but it will also tell you the transmit power and when to cycle into different power states.

LTE RRC State Machine §

The radio state of every LTE device is controlled by the radio tower currently servicing the user. In fact, the 3GPP standard defines a well-specified state machine, which describes the possible power states of each device connected to the network (Figure 7-5). The network operator can itself is the same across all LTE deployments.

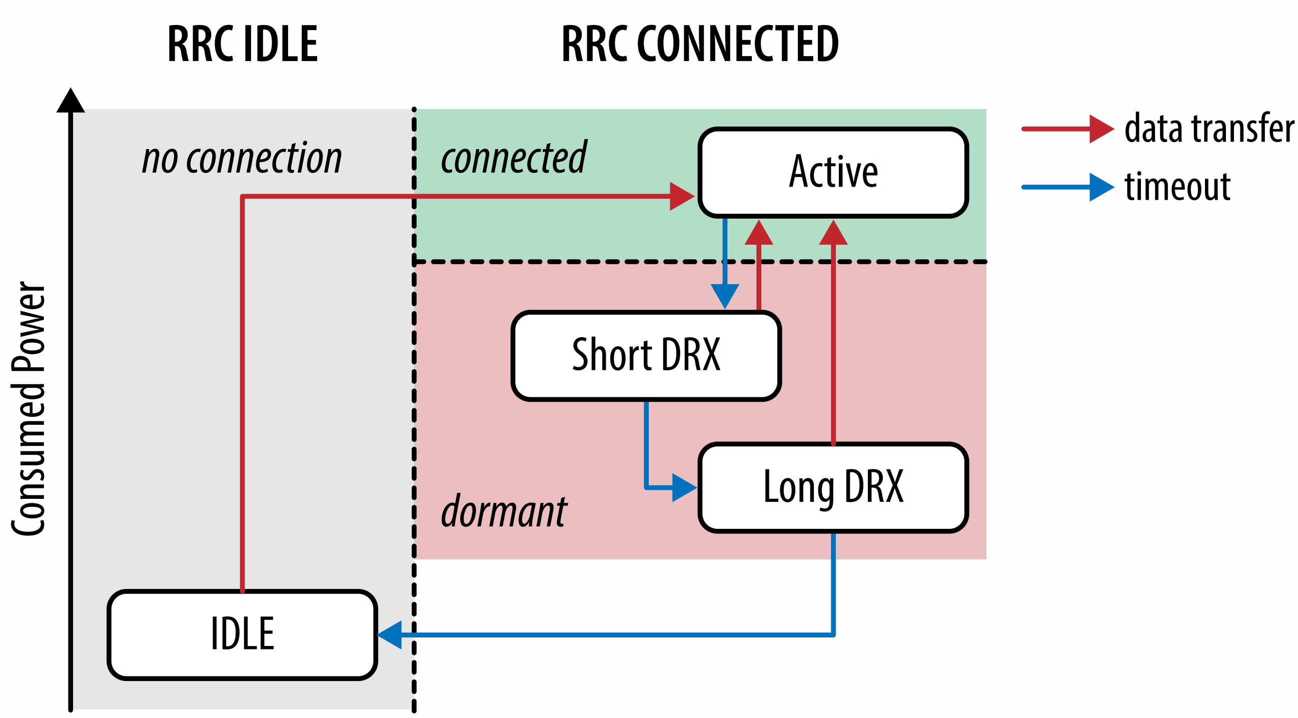


Figure 7-5. LTE RRC state machine

RRC Idle
: Device radio is in a low-power state (<15 mW) and only listening to control traffic. No radio resources are assigned to the client within the carrier network.

RRC Connected
: Device radio is in a high-power state (1000–3500 mW) while it either transmits data or waits for data, and dedicated radio resources are allocated by the radio network.

The device is either idle, in which case it is only listening to control channel broadcasts, such as paging notifications of inbound traffic, or connected, in which case the network has an established context and resource assignment for the client.

When in an idle state, the device cannot send or receive any data. To do so, it must first synchronize itself to the network by listening to the network broadcasts and then issue a request to the RRC to be moved to the "connected" state. This negotiation can take several roundtrips to establish, and the 3GPP LTE specification allocates a target of 100 milliseconds or less for this state transition. In LTE-Advanced, the target time was further reduced to 50 milliseconds.

Once in a connected state, a network context is established between the radio tower and the LTE device, and data can be transferred. However, once either side completes the intended data transfer, how does the RRC know when to transition the device to a lower power state? Trick question—it doesn't!

IP traffic is bursty, optimized TCP connections are long-lived, and UDP traffic provides no "end of transmission" indicator by design. As a result, and not unlike the NAT connection-state timeouts timers to trigger the RRC state transitions.

Finally, because the connected state requires such high amounts of power, multiple sub-states are available (Figure 7-5) to allow for more efficient operation:

Continuous reception
: Highest power state, established network context, allocated network resources.

Short Discontinuous Reception (Short DRX)
: Established network context, no allocated network resources.

Long Discontinuous Reception (Long DRX)
: Established network context, no allocated network resources.

In the high-power state, the RRC creates a reservation for the device to receive and transmit data over the wireless interface and notifies the device for what these time-slots are, the transmit power that must be used, the modulation scheme, and a dozen other variables. Then, if the device has been idle for a configured period of time, it is transitioned to a Short DRX power state, where the network context is still maintained, but no specific radio resources are assigned. When in Short DRX state, the device only listens to periodic broadcasts from the network, which allows it to preserve the battery—not unlike the DTIM interval in WiFi.

What Are "Assigned Radio Resources"? §

In LTE, just as in most other modern wireless standards, there are shared uplink and downlink radio channels, the access to which is controlled by the RRC. When in a connected state, the RRC tells each and every device which timeslots are assigned to whom, which transmit power must be used, modulation, plus a dozen other variables.

If the mobile device does not have an assignment for these resources by the RRC, then it cannot transmit or receive any user data. Consequently, when in a DRX state, the device is synchronized to the RRC, but no uplink or downlink resources are allocated to it: the device is "half awake."

If the radio remains idle long enough, it is then transitioned to the Long DRX state, which is identical to the Short DRX state, except that the device sleeps for longer periods of time between waking up to listen to the broadcasts (Figure 7-6).

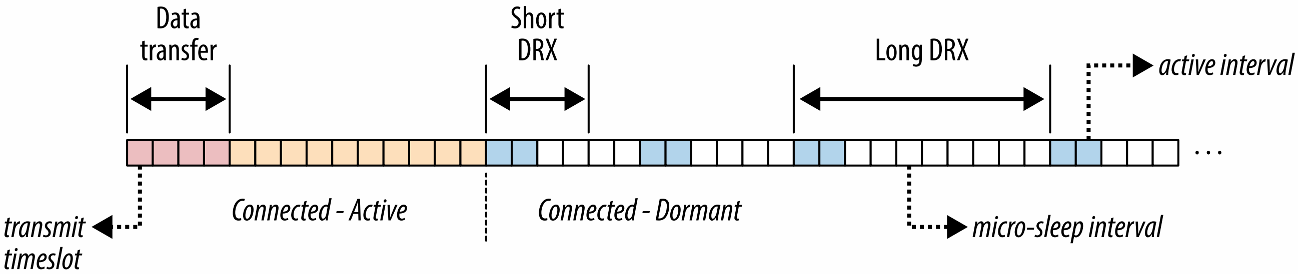


Figure 7-6. Discontinuous reception: Short DRX and Long DRX

Short or Long DRX (dormant) states: The device and the RRC must first exchange control messages to negotiate when to transmit and when to listen to radio broadcasts. For LTE, this negotiation time ("dormant to connected") is specified as less than 50 milliseconds, and further tightened to less than 10 milliseconds for LTE-Advanced.

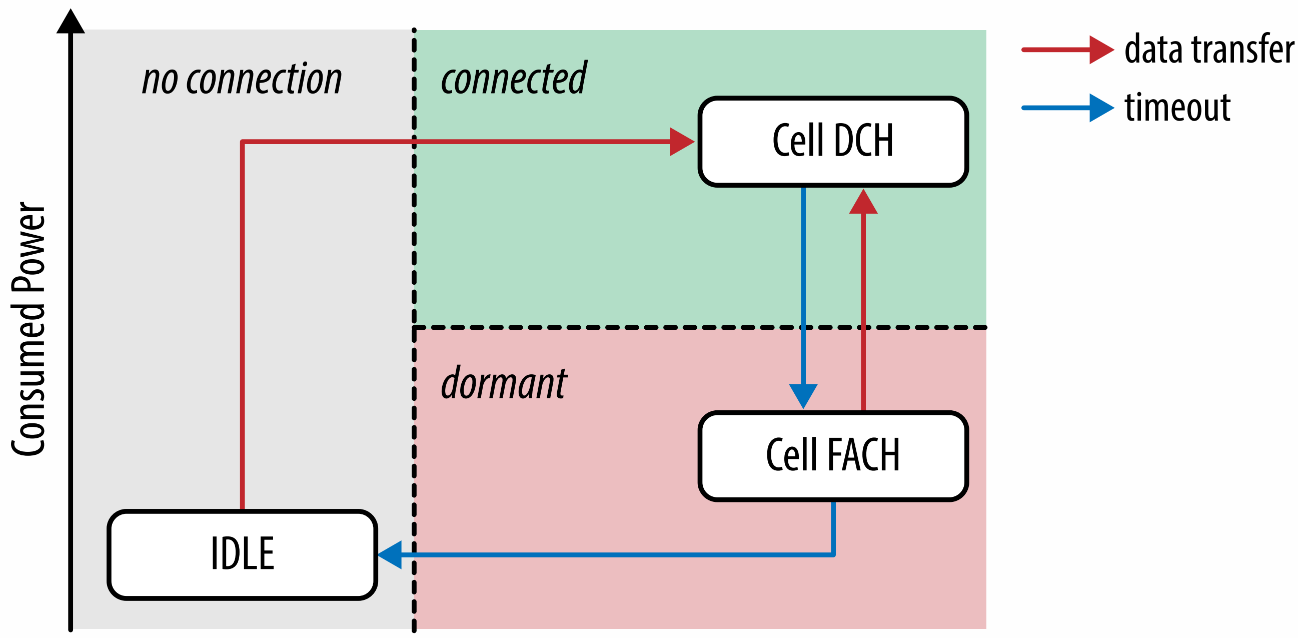
So what does this all mean in practice? Depending on which power state the radio is in, an LTE device may first require anywhere from 10 to 100 milliseconds (Table 7-9) of latency to negotiate the required resources with the RRC. Following that, application data can be transferred over the wireless link, through the carrier's network, and then out to the public Internet. Planning for these delays, especially when designing latency-sensitive applications, can be all the difference between "unpredictable performance" and an optimized mobile application.

	LTE	LTE-Advanced
Idle to connected latency	< 100 ms	< 50 ms
DRX to connected latency	< 50 ms	< 10 ms
User-plane one-way latency	< 5 ms	< 5 ms

Table 7-9. LTE and LTE-Advanced RRC latency

HSPA and HSPA+ (UMTS) RRC State Machine §

Earlier generation 3GPP networks prior to LTE and LTE-Advanced have a very similar RRC state machine that is also maintained by the radio network. That's the good news. The bad news is the state machine for earlier generations is a bit more complicated (Figure 7-7), and the latencies are much, much higher. In fact, one reason why LTE offers better performance is precisely due to the simplified architecture and improved performance of the RRC state transitions.



Idle

Similar to idle in LTE. The device radio is in a low-power state and only listening to control traffic from the network. No radio resources are assigned to the client within the carrier network.

Cell DCH

Similar to connected LTE mode when in continuous reception. The device is in a high-power state, and network resources are assigned both for upstream and downstream data transfer.

Cell FACH

An intermediate power state, which consumes significantly less power than DCH. The device does not have dedicated network resources but is nonetheless able to transmit small amounts of user data through a shared low-speed channel (with speeds of typically less than 20 Kbps).

Idle and DCH states are nearly identical to that of idle and connected in LTE. However, the intermediate FACH state is unique to UMTS networks (HSPA, HSPA+) and allows the use of a common channel for small data transfers: slow, steady, and consuming roughly half the power of the DCH state. In practice, this state was designed to handle non-interactive traffic, such as periodic polling and status checks done by many background applications.

Not surprisingly, the transition from DCH to FACH is triggered by a timer. However, once in FACH, what triggers a promotion back to DCH? Each device maintains a buffer of data to be sent, and as long as the buffer does not exceed a network-configured threshold, typically anywhere from 100 to 1,000 bytes, then the device can remain in the intermediate state. Finally, if no data is transferred while in FACH for some period of time, another timer transitions the device down to the idle state.

Note

Unlike LTE, which offers two intermediate states (Short DRX and Long DRX), UMTS devices have just a single intermediate state: FACH. However, even though LTE offers a theoretically higher degree of power control, the radios themselves tend to consume more power in LTE devices; higher throughput comes at a cost of increased battery consumption. Hence, LTE devices still have a much higher power profile than their 3G predecessors.

Individual power states aside, perhaps the biggest difference between the earlier-generation 3G networks and LTE is the latency of the state transitions. Where LTE targets sub-hundred milliseconds for idle to connected states, the same transition from idle to DCH can take up to two seconds and require tens of control messages between the 3G device and the RRC! FACH to DCH is not much better either, requiring up to one and a half seconds for the state transition.

department and are now competitive with LTE (Table 7-6). However, we can't count on ubiquitous access to 4G or HSPA+ networks; older generation 3G networks will continue to exist for at least another decade. Hence, all mobile applications should plan for multisecond RRC latency delays when accessing the network over a 3G interface.

EV-DO (CDMA) RRC State Machine §

While 3GPP standards such as HSPA, HSPA+, and LTE are the dominant network standards around the globe, it is important that we don't forget the 3GPP2 CDMA based networks. The growth curve for EV-DO networks may look comparatively flat, but even so, current industry projections show nearly half a billion CDMA powered wireless subscriptions by 2017.

Not surprisingly, regardless of the differences in the standards, the fundamental limitations are the same in UMTS- and CDMA-based networks: battery power is a constraining resource, radios are expensive to operate, and network efficiency is an important goal. Consequently, CDMA networks also have an RRC state machine (Figure 7-8), which controls the radio state of each device.

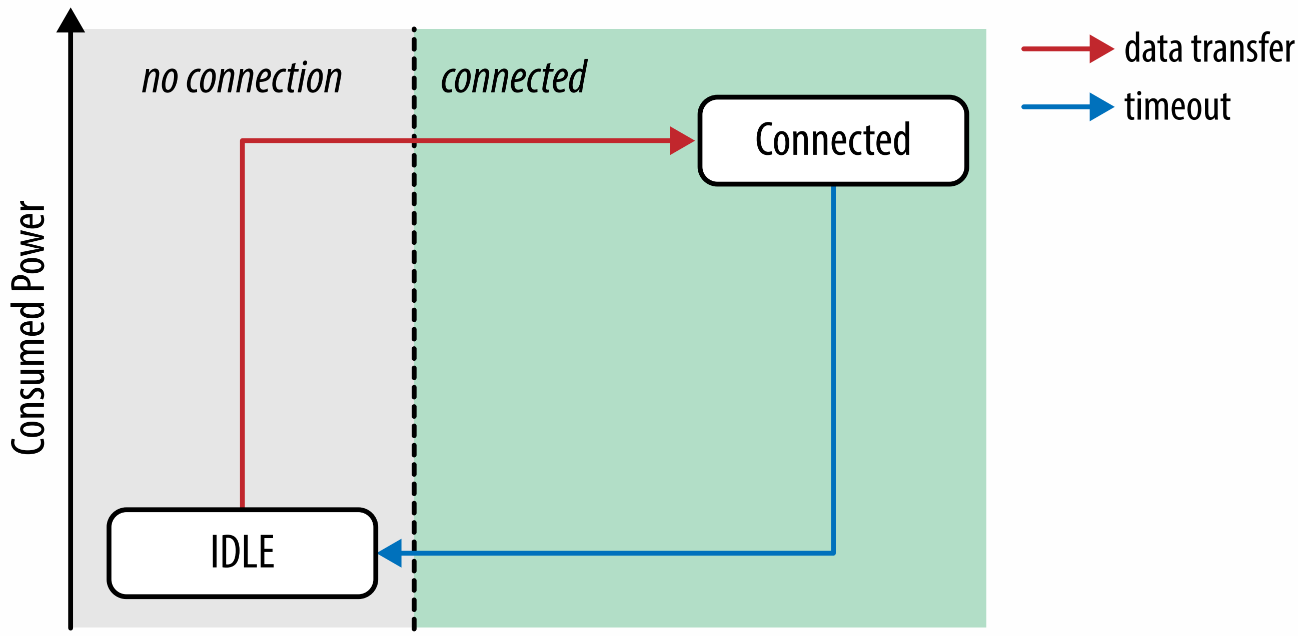


Figure 7-8. CDMA RRC state machine: EV-DO (Rev. 0—DO Advanced)

Idle

Similar to idle in 3GPP standards. The device radio is in a low-power state and only listening to control traffic from the network. No radio resources are assigned to the client within the carrier network.

Connected

Similar to connected LTE mode and DCH in HSPA. The device is in a high-power state and network resources are assigned for both upstream and downstream data transfers.

is either in a high-power state, with allocated network resources, or it is idle. Further, all network transfers require a transition to a connected state, the latency for which is similar to that of HSPA networks: hundreds to thousands of milliseconds depending on the revision of the deployed infrastructure. There are no other intermediate states, and transitions back to idle are also controlled via carrier configured timeouts.

Inefficiency of Periodic Transfers §

An important consequence of the timeout-driven radio state transitions, regardless of the generation or the underlying standard, is that it is very easy to construct network access patterns that can yield both poor user experience for interactive traffic and poor battery performance. In fact, all you have to do is wait long enough for the radio to transition to a lower-power state, and then trigger a network access to force an RRC transition!

To illustrate the problem, let's assume that the device is on an HSPA+ network, which is configured to move from DCH to FACH state after 10 seconds of radio inactivity. Next, we load an application that schedules an intermittent transfer, such as a real-time analytics beacon, on an 11-second interval. What's the net result? The device may end up spending hundreds of milliseconds in data transfer and otherwise idle while in a high-power state. Worse, it would transition into the low-power state only to be woken up again a few hundred milliseconds later—worst-case scenario for latency and battery performance.

Every radio transmission, no matter how small, forces a transition to a high-power state. Then, once the transmission is done, the radio will remain in this high-power state until the inactivity timer has expired (Figure 7-9). The size of the actual data transfer does not influence the timer. Further, the device may then also have to cycle through several more intermediate states before it can return back to idle.

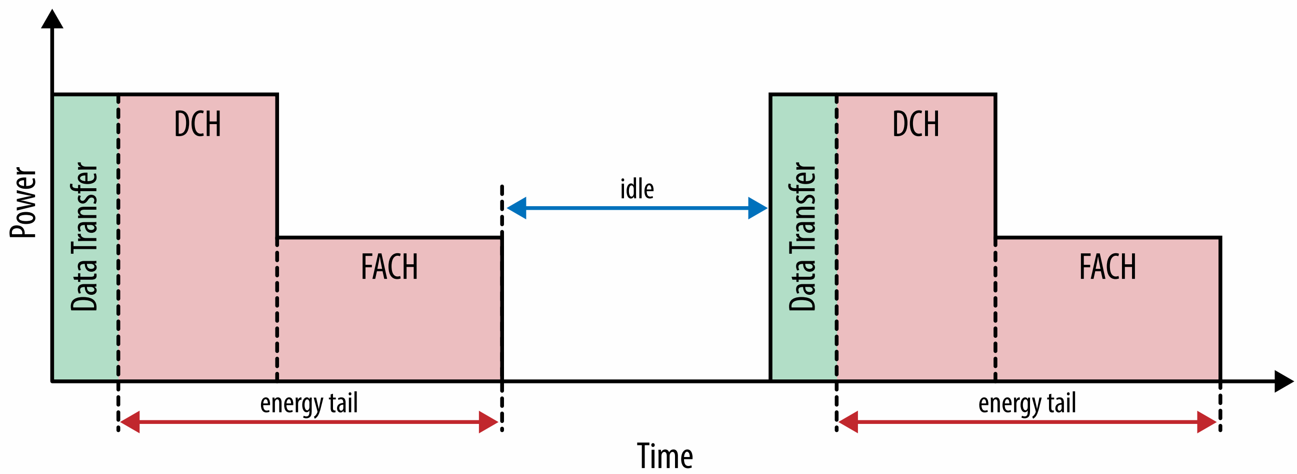


Figure 7-9. HSPA+ energy tail due to DCH > FACH > IDLE transitions

The "energy tails" generated by the timer-driven state transitions make periodic transfers a very inefficient network access pattern on mobile networks. First, you have to pay the latency cost of the timers fire and the device can return to the low-power state.

46% of Battery Consumption to Transfer 0.2% of Total Bytes §

AT&T Labs Research published a great research paper ("Profiling Resource Usage for Mobile Applications") in which it analyzed a number of popular mobile applications for network and battery efficiency. Among these applications, Pandora serves as a great case study for the inefficiency of intermittent network transfers on mobile networks.

Whenever a Pandora user plays a song, the entire music file is streamed by the application from the network in one shot, which is the correct behavior: burst as much data as you can, then turn off the radio for as long as possible. However, following the music transfer, the application would conduct periodic audience measurements by sending intermittent analytics pings every 60 seconds. The net effect? The analytics beacons accounted for 0.2% of the total transferred bytes and 46% of the total power consumption of the application!

The beacon transfers are small, but the energy tails induced by the RRC state transitions were keeping the radio active for significantly longer, unnecessarily wasting 46% of the battery. By coalescing the analytics data into fewer requests, or by sending the audience data when the radio is already active, we can eliminate the unnecessary energy tails and almost double the power efficiency of the application!

End-to-End Carrier Architecture §

Now that we have familiarized ourselves with the RRC and device capabilities, it is useful to zoom out and consider the overall end-to-end architecture of a carrier network. Our goal here is not to become experts in the nomenclature and function of every component, of which there are dozens, but rather to highlight the components that have a direct impact on how the data flows through the carrier network and reasons why it may affect the performance of our applications.

The specific infrastructure and names of various logical and physical components within a carrier network depend on the generation and type of deployed network: EV-DO vs. HSPA vs. LTE, and so on. However, there are also many similarities among all of them, and in this chapter we'll examine the high-level architecture of an LTE network.

Why LTE? First, it is the most likely architecture for new carrier deployments. Second, and even more importantly, one of the key features of LTE is its simplified architecture: fewer components and fewer dependencies also enable improved performance.

Radio Access Network (RAN) §

(Figure 7-10), whose primary responsibility is to mediate access to the provisioned radio channel and shuttle the data packets to and from the user's device. In fact, this is the component controlled and mediated by the Radio Resource Controller. In LTE, each radio base station (eNodeB) hosts the RRC, which maintains the RRC state machine and performs all resource assignment for each active user in its cell.

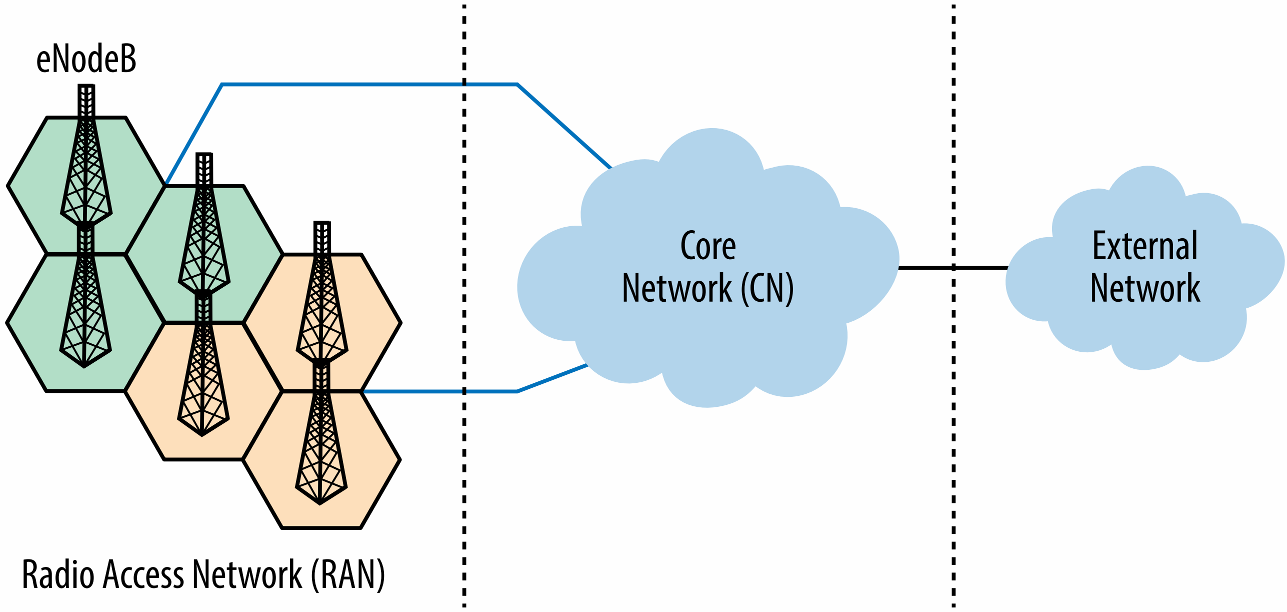


Figure 7-10. LTE radio access network: tracking cells and eNodeBs

Whenever a user has a stronger signal from a nearby cell, or if his current cell is overloaded, he may be handed off to a neighboring tower. However, while this sounds simple on paper, the hand-off procedure is also the reason for much of the additional complexity within every carrier network. If all users always remained in the same fixed position, and stayed within reach of a single tower, then a static routing topology would suffice. However, as we all know, that is simply not the case: users are mobile and must be migrated from tower to tower, and the migration process should not interrupt any voice or data traffic. Needless to say, this is a nontrivial problem.

First of all, if the user's device can be associated with any radio tower, how do we know where to route the incoming packets? Of course, there is no magic: the radio access network must communicate with the core network to keep track of the location of every user. Further, to handle the transparent handoff, it must also be able to dynamically update its existing tunnels and routes without interrupting any existing, user-initiated voice and data sessions.

Note

In LTE, a tower-to-tower handoff can be performed within hundreds of milliseconds, which will yield a slight pause in data delivery at the physical layer, but otherwise this procedure is completely transparent to the user and to all applications running on her device. In earlier-generation networks, this same process can take up to several seconds.

density urban and office environments, and requiring the user's device to continuously perform the cell handoff negotiations, even when the device is idle, would consume a lot of energy on the device. Hence, an additional layer of indirection was added: one or more radio towers are said to form a "tracking area," which is a logical grouping of towers defined by the carrier network.

The core network must know the location of the user, but frequently it knows only the tracking area and not the specific tower currently servicing the user—as we will see, this has important implications on the latency of inbound data packets. In turn, the device is allowed to migrate between towers within the same tracking area with no overhead: if the device is in idle RRC state, no notifications are emitted by the device or the radio network, which saves energy on the mobile handset.

Core Network (CN)

The core network (Figure 7-11), which is also known as the Evolved Packet Core (EPC) in LTE is responsible for the data routing, accounting, and policy management. Put simply, it is the piece that connects the radio network to the public Internet.

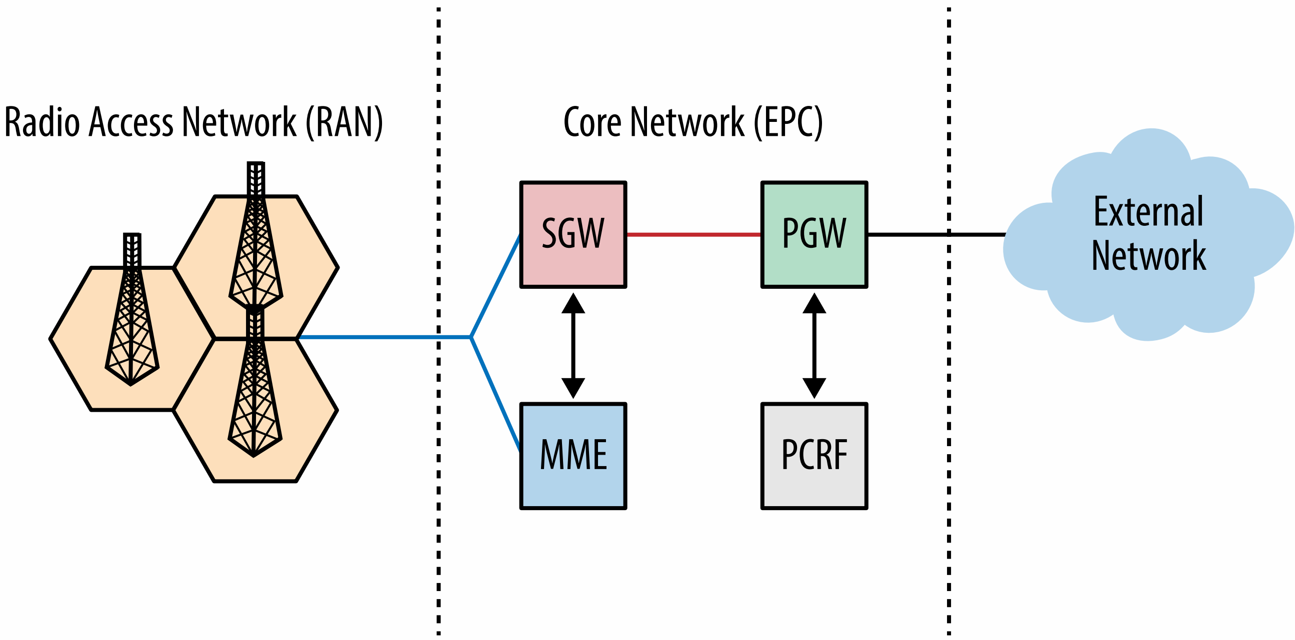


Figure 7-11. LTE core network (EPC): PGW, PCRF, SGW, and MME

First, we have the packet gateway (PGW), which is the public gateway that connects the mobile carrier to the public Internet. The PGW is the termination point for all external connections, regardless of the protocol. When a mobile device is connected to the carrier network, the IP address of the device is allocated and maintained by the PGW.

Each device within the carrier network has an internal identifier, which is independent of the assigned IP address. In turn, once a packet is received by the PGW, it is encapsulated and tunneled through the EPC to the radio access network. LTE uses Stream Control Transmission and UDP for all other data.

Physical Layer vs. Application Layer Connectivity

The fact that the device IP address is allocated and maintained by the PGW has a number of important implications. First, it means that a wireless device can be easily associated with multiple IP addresses. Conversely, if the IP addresses are at a premium, then multiple devices can share the same IP address but be allocated different ports for outgoing and incoming traffic: the PGW acts as a NAT. In fact, the latter case is quite common. The same carrier IP address can be assigned to dozens, if not hundreds, of devices within its network.

Consequently, traffic from the same device may originate from multiple public carrier IP addresses. Don’t be surprised to see the same client request resources from different IPs! With IPv6, this behavior may change, and each device may finally get a unique IP address. Having said that, few carriers support IPv6 today, and the rollout and adoption of IPv6 remains very slow.

However, IP assignment aside, it is arguably even more important to recognize that because it is the PGW that terminates all connections, the device radio state is not tied to application layer connectivity: tearing down the radio context within the radio network terminates the physical radio link between the device and the radio tower, but this does not affect the state of any TCP or UDP sessions. The device radio can be idle, with no link to the local radio tower, while the established connections are maintained by the PGW.

Once application data must be delivered, the physical radio link is reestablished, and communication resumes with no side effects other than the incurred RRC negotiation delays required to reestablish the radio context.

The PGW also performs all the common policy enforcement, such as packet filtering and inspection, QoS assignment, DoS protection, and more. The Policy and Charging Rules Function (PCRF) component is responsible for maintaining and evaluating these rules for the packet gateway. PCRF is a logical component, meaning it can be part of the PGW, or it can stand on its own.

Now, let’s say the PGW has received a packet from the public Internet for one of the mobile devices on its network; where does it route the data? The PGW has no knowledge of the actual location of the user, nor the different tracking areas within the radio access network. This next step is the responsibility of the Serving Gateway (SGW) and the Mobility Management Entity (MME).

The PGW routes all of its packets to the SGW. However, to make matters even more complicated, the SGW may not know the exact location of the user either. This function is, in fact, one of the core responsibilities of the MME. The Mobility Management Entity component is effectively a user database, which manages all the state for every user on the network: their location on the network, type of account, billing status, enabled services, plus all other user metadata. Whenever user turns on their phone, the authentication is performed by the MME, and so on.

Hence, when a packet arrives at the SGW, a query to the MME is sent for the location of the user. Then, once the MME returns the answer, which contains the tracking area and the ID of the specific tower serving the target device, the SGW can establish a connection to the tower if none exists and route the user data to the radio access network.

In a nutshell, that is all there is to it. This high-level architecture is effectively the same in all the different generations of mobile data networks. The names of the logical components may differ, but fundamentally all mobile networks are subject to the following workflow:

- Data arrives at the external packet gateway, which connects the core network to the public Internet.
- A set of routing and packet policies is applied at the packet gateway.
- Data is routed from the public gateway to one or more serving gateways, which act as mobility anchors for the devices within the radio network.
- A user database service performs the authentication, billing, provisioning of services, and location tracking of each user on the network.
- Once the location of the user within the radio network is determined, the data is routed from the serving gateway to the appropriate radio tower.
- The radio tower performs the necessary resource assignment and negotiation with the target device and then delivers the data over the radio interface.

Simplified and Unified Architecture of the LTE Core Network §

One of the main features of LTE is its new Evolved Packet Core (EPC) network, which is based on an IP-only architecture designed to carry both voice and data over the same, unified network. This design allows more cost-effective operation for the carrier but also places much stronger performance requirements on the network: voice requires low latency, and 4G speeds require much higher throughput.

How does the EPC achieve these goals? There are a large number of architectural improvements, but one of the primary differences to previous-generation networks is the simplified architecture of the LTE core network: some components were removed, others were collapsed into fewer logical components, and a lot of the decision making has been moved to the edges of the network.

For example, in LTE the RRC is maintained by the radio tower (eNodeB), whereas in earlier generations the RRC was managed higher up in the network (at the serving gateway), which imposed additional latency and performance bottlenecks on all control traffic within the network.

Backhaul Capacity and Latency §

and capacity between all the logical and physical components. The LTE radio interface may be capable of reaching up to 100 Mbps between the user and the radio tower, but once the signal is received by the radio tower, sufficient capacity must be available to transport all this data through the carrier network and toward its actual destination. Plus, let's not forget that a single tower should be able to service many active users simultaneously!

Delivering a true 4G experience is not a simple matter of deploying the new radio network. The core network must also be upgraded, sufficient capacity links must be present between the EPC and the radio network, and all the EPC components must be able to process much higher data rates with much lower latencies than in any previous generation network.

Note

In practice, a single radio tower may serve up to three nearby radio cells, which can easily add up to hundreds of active users. With 10+ Mbps data rate requirements per user, each tower needs a dedicated fiber link!

Needless to say, all of these requirements make 4G networks a costly proposition to the carrier: running fiber to all the radio stations, high-performance routers, and so on. In practice, it is now not unusual to find the overall performance of the network being limited not by the radio interface, but by the available backhaul capacity of the carrier network.

These performance bottlenecks are not something we can control as developers of mobile applications, but they do, once again, illustrate an important fact: the architecture of our IP networks is based on a best effort delivery model, which makes no guarantees about end-to-end performance. Once we remove the bottleneck from the first hop, which is the wireless interface, we move the bottleneck to the next slowest link in the network, either within the carrier network or somewhere else on the path toward our destination. In fact, this is nothing new; recall our earlier discussion on Last-Mile Latency in wired networks.

Just because you are connected over a 4G interface doesn't mean you are guaranteed the maximum throughput offered by the radio interface. Instead, our applications must adapt to the continuously changing network weather over the wireless channel, within the carrier network, and on the public Internet.

Packet Flow in a Mobile Network §

One of the primary complaints about designing applications for the mobile web is the high variability in latency. Well, now that we have covered the RRC and the high-level architecture of a mobile network, we can finally connect the dots and see the end-to-end flow of the data packets, variability is actually very much predictable!

Initiating a Request

§

To start, let's assume that the user has already authenticated with a 4G network and the mobile device is idle. Next, the user types in a URL and hits "Go." What happens next?

First, because the phone is in idle RRC state, the radio must synchronize with the nearby radio tower and send a request for a new radio context to be established (Figure 7-12, step 1)—this negotiation requires several roundtrips between the handset and the radio tower, which may take up to 100 milliseconds. For earlier-generation networks, where the RRC is managed by the serving gateway, this negotiation latency is much higher—up to several seconds.

Once the radio context is established, the device has a resource assignment from the radio tower and is able to transmit data (step 2) at a specified rate and signal power. The time to transmit a packet of data from the user's radio to the tower is known as the "user-plane one-way latency" and takes up to five milliseconds for 4G networks. Hence, the first packet incurs a much higher delay due to the need to perform the RRC transition, but packets immediately after incur only the constant first-hop latency cost, as long as the radio stays in the high-power state.

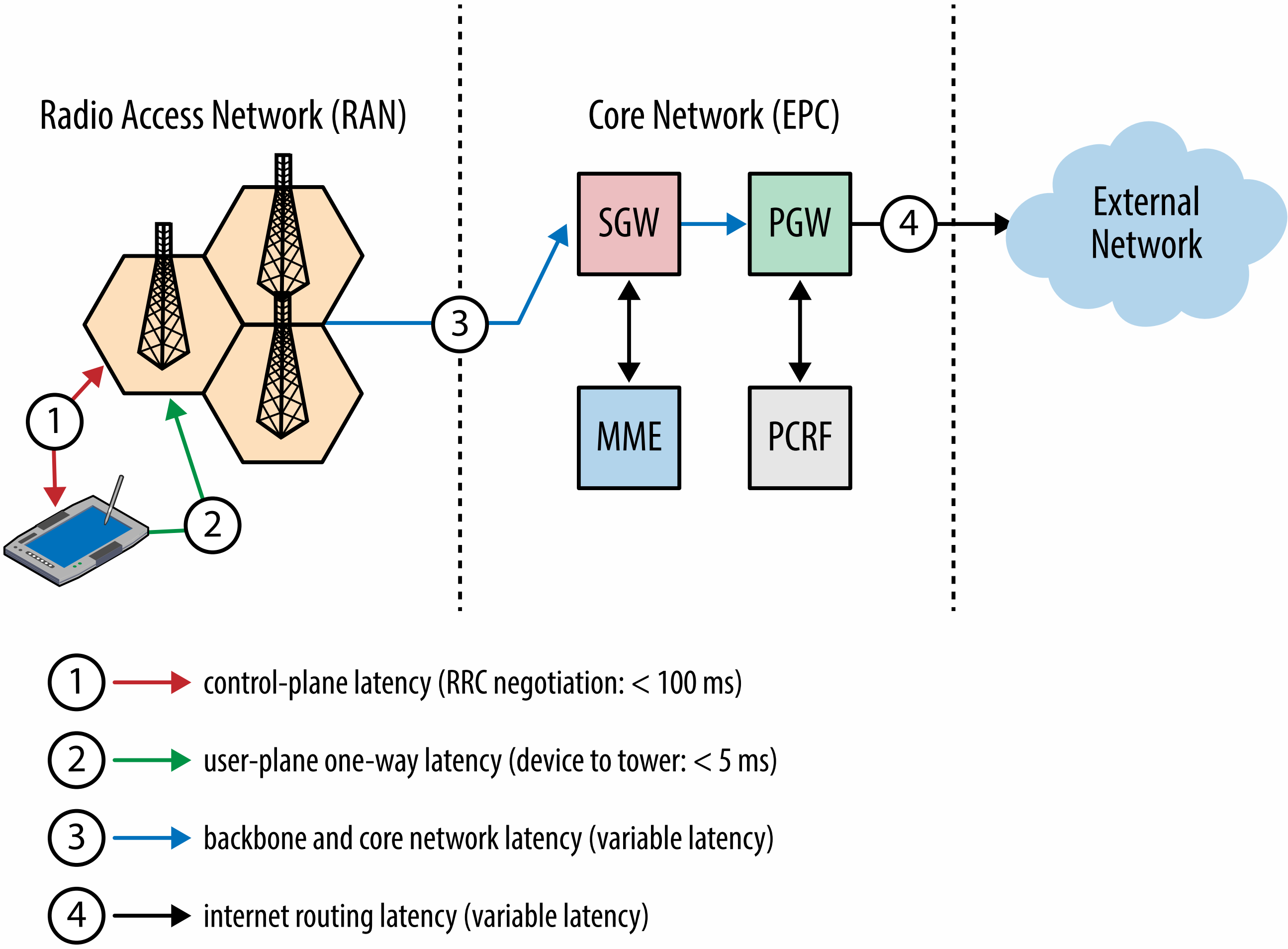


Figure 7-12. LTE request flow latencies

radio tower. From here, the packets have to travel through the core network—through the SGW to the PGW (step 3)—and out to the public Internet (step 4). Unfortunately, the 4G standards make no guarantees on latency of this path, and hence this latency will vary from carrier to carrier.

Note

In practice, the end-to-end latency of many deployed 4G networks tends to be in the 30–100 ms range once the device is in a connected state—that is to say, without the control plane latency incurred by the initial packet. Hence, if up to 5 ms of the total time is accounted for on the first wireless hop, then the rest (25–95 ms) is the routing and transit overhead within the core network of the carrier.

Next, let's say the browser has fetched the requested page and the user is engaging with the content. The radio has been idle for a few dozen seconds, which means that the RRC has likely moved the user into a DRX state (LTE RRC State Machine) to conserve battery power and to free up network resources for other users. At this point, the user decides to navigate to a different destination in the browser and hence triggers a new request. What happens now?

Nearly the same workflow is repeated as we just saw, except that because the device was in a dormant (DRX) state, a slightly quicker negotiation (Figure 7-12, step 1) can take place between the device and the radio tower—up to 50 milliseconds (Table 7-9) for dormant to connected.

In summary, a user initiating a new request incurs several different latencies:

Control-plane latency

Fixed, one-time latency cost incurred for RRC negotiation and state transitions: <100 ms for idle to active, and <50 ms for dormant to active.

User-plane latency

Fixed cost for every application packet transferred between the device and the radio tower: <5 ms.

Core network latency

Carrier dependent cost for transporting the packet from the radio tower to the packet gateway: in practice, 30–100 ms.

Internet routing latency

Variable latency cost between the carrier's packet gateway and the destination address on the public Internet.

The first two latencies are bounded by the 4G requirements, the core network latency is carrier specific, and the final piece is something you can influence by strategically positioning your servers closer to the user; see the earlier discussion on Speed of Light and Propagation Latency.

One frequently shared complaint about mobile networks is the variability, or jitter, in packet latency. And it is certainly true that there are many contributing components that can impact latency. However, once you factor in the control plane cost for RRC state transitions incurred by the first packet, you will likely find that the performance is, in fact, much more predictable than you would otherwise expect.

In LTE, the control plane overhead is up to 100 milliseconds. With LTE-Advanced, this number is further lowered to 50 milliseconds. However, in earlier-generation networks, this same negotiation can take seconds!

Core network routing latency is the second, and often very large, contributing factor to the overall packet latency in mobile networks. The specific delays incurred within the core network vary by generation of the network, as well as the specific infrastructure deployed by the carrier. However, while few carriers openly advertise their latency performance—perhaps because it is nothing to be proud of—it usually can be found in their technical FAQs.

For example, AT&T, which is the largest mobile provider in the U.S., sets the following expectations, which are typical for the industry at large, for core network latency for the various generations within its network:

	LTE	HSPA+	HSPA	EDGE	GPRS
Latency	40–50 ms	100–200 ms	150–400 ms	600–750 ms	600–750 ms

Table 7-10. AT&T latencies for deployed 2G–4G networks

By comparison, the circumference of Earth at the equator is 24,901 miles, which takes 133.7 ms for light to travel. In other words, it may not be entirely unreasonable to think of most mobile requests as requiring, on average, at least one trip around the globe!

Inbound Data Flow §

Now let’s examine the opposite scenario: the user’s device is idle, but a data packet must be routed from the PGW to the user (Figure 7-13). Once again, recall that all connections are terminated at the PGW, which means that the device can be idle, with its radio off, but the connection the device may have established earlier, such as a long-lived TCP session, can still be active at the PGW.

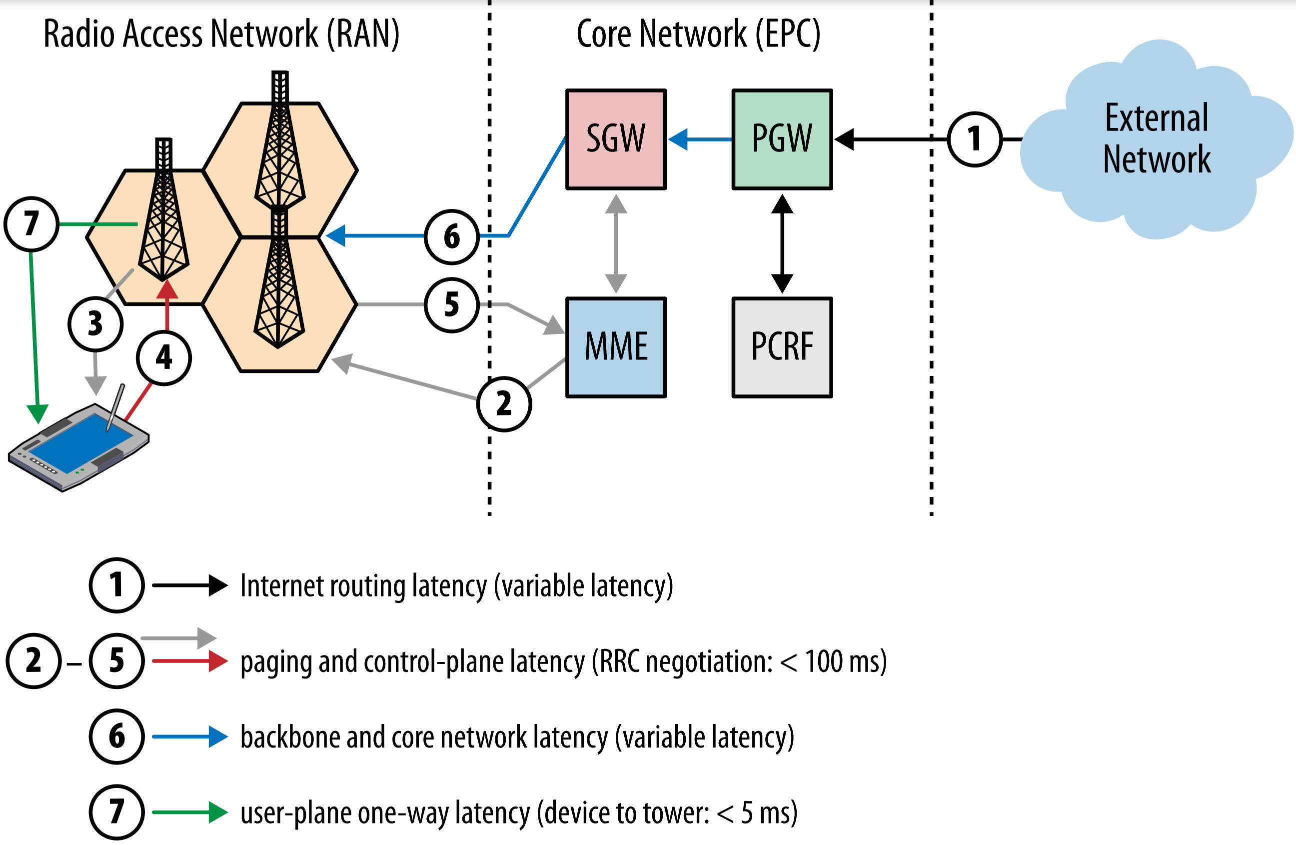


Figure 7-13. LTE inbound data flow latencies

As we saw earlier, the PGW routes the inbound packet to the SGW (step 1), which in turn queries the MME. However, the MME may not know the exact tower currently servicing the user; recall that a collection of radio towers form a "tracking area." Whenever a user enters a different tracking area, its location is updated in the MME, but tower handoffs within the same tracking area do not trigger an update to the MME.

Instead, if the device is idle, the MME sends a paging message (step 2) to all the towers in the tracking area, which in turn all broadcast a notification (step 3) on a shared radio channel, indicating that the device should reestablish its radio context to receive the inbound data. The device periodically wakes to listen to the paging messages, and if it finds itself on the paging list, then it initiates the negotiation (step 4) with the radio tower to reestablish the radio context.

Once the radio context is established, the tower that performed the negotiation sends a message back (step 5) to the MME indicating where the user is, the MME returns the answer to the serving gateway, and the gateway finally routes the message (step 6) to the tower, which then delivers (step 7) the message to the device! Phew.

Once the device is in a connected state, a direct tunnel is established between the radio tower and the serving gateway, which means that further incoming packets are routed directly to the tower without the paging overhead, skipping steps 2–5. Once again, the first packet incurs a much higher latency cost on mobile networks! Plan for it.

Note

applications: the packets are buffered by the PGW, SGW, and the eNodeB at each stage until they can be routed to the device. In practice, this translates to observable latency jitter in packet arrival times, with the first packet incurring the highest delays due to control-plane negotiation.

Heterogeneous Networks (HetNets)

Existing 4G radio and modulation technologies are already within reach of the theoretical limits of the wireless channel. Hence, the next order of magnitude in wireless performance will not come from improvements in the radio interfaces, but rather from smarter topologies of the wireless networks—specifically, through wide deployment of multilayer heterogeneous networks (HetNets), which will also require many improvements in the intra-cell coordination, handoff, and interference management.

The core idea behind HetNets is a simple one: instead of relying on just the macro coverage of a large geographic area, which creates a lot of competition for all users, we can also cover the area with many small cells (Figure 7-14), each of which can minimize path loss, require lower transmit power, and enable better performance for all users.

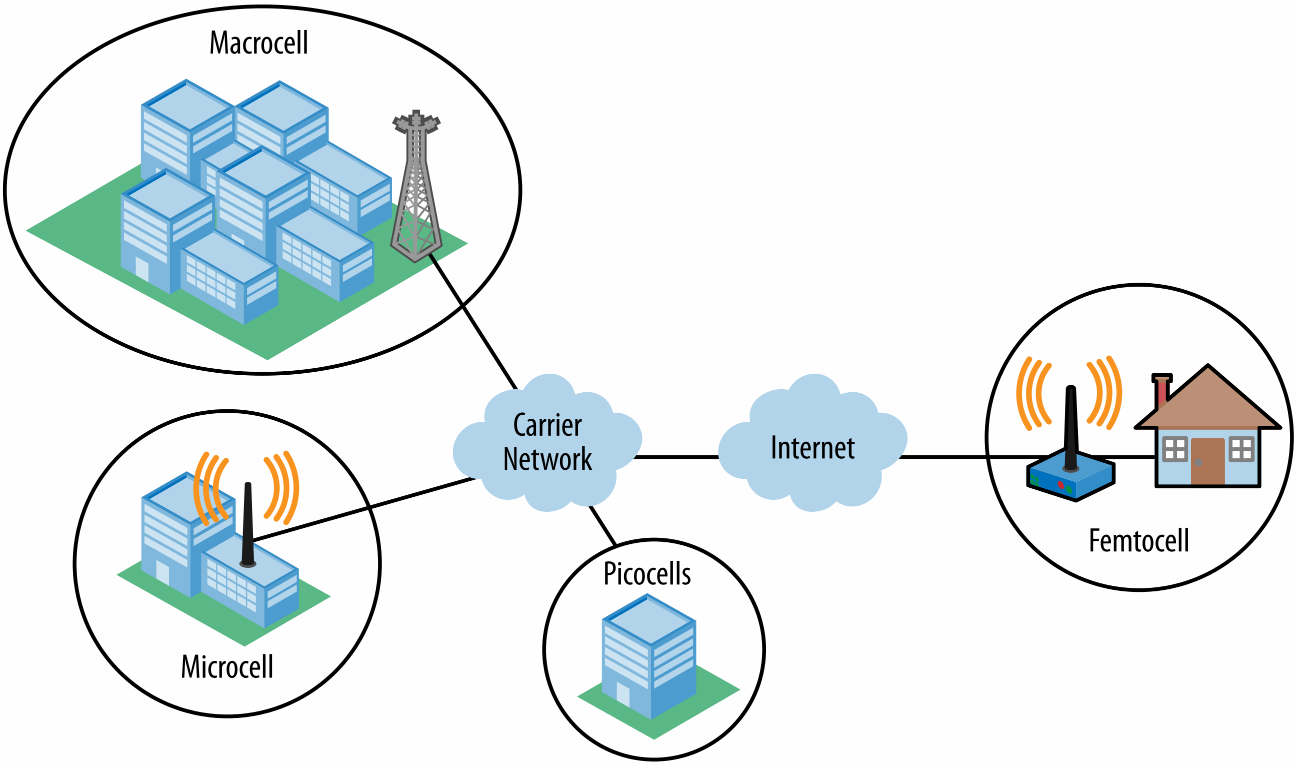


Figure 7-14. Heterogeneous network infographic (Ericsson)

A single macrocell can cover up to tens of square miles in low-density wireless environments, but in practice, in high-density urban and office settings, can be limited to anywhere from just 50 to 300 meters! In other words, it can cover a small block, or a few buildings. By comparison, as the wireless backhaul.

However, note that HetNets are not simply replacing the macrocells with many small cells. Instead, HetNets are layering multiple cells on top of one another! By deploying overlapping layers of wireless networks, HetNets can provide much better network capacity and improved coverage for all users. However, the outstanding challenges are in minimizing interference, providing sufficient uplink capacity, and creating and improving protocols for seamless handoff between the various layers of networks.

What does this mean for the developers building mobile applications? Expect the number of handoffs between different cells to increase significantly and adapt accordingly: the latency and throughput performance may vary significantly.

Modeling and Managing Wireless Network Capacity

Picocells are often used by mobile carriers to extend coverage to indoor and outdoor areas where signal quality may be poor, or to add network capacity in areas with very dense phone usage—e.g., a large public area, a conference hall, stadium, train station, and so on. Some picocells may be deployed permanently, while others may be put up for a specific occasion: wireless capacity planning and modeling (Figure 7-15) is both an art and a science!

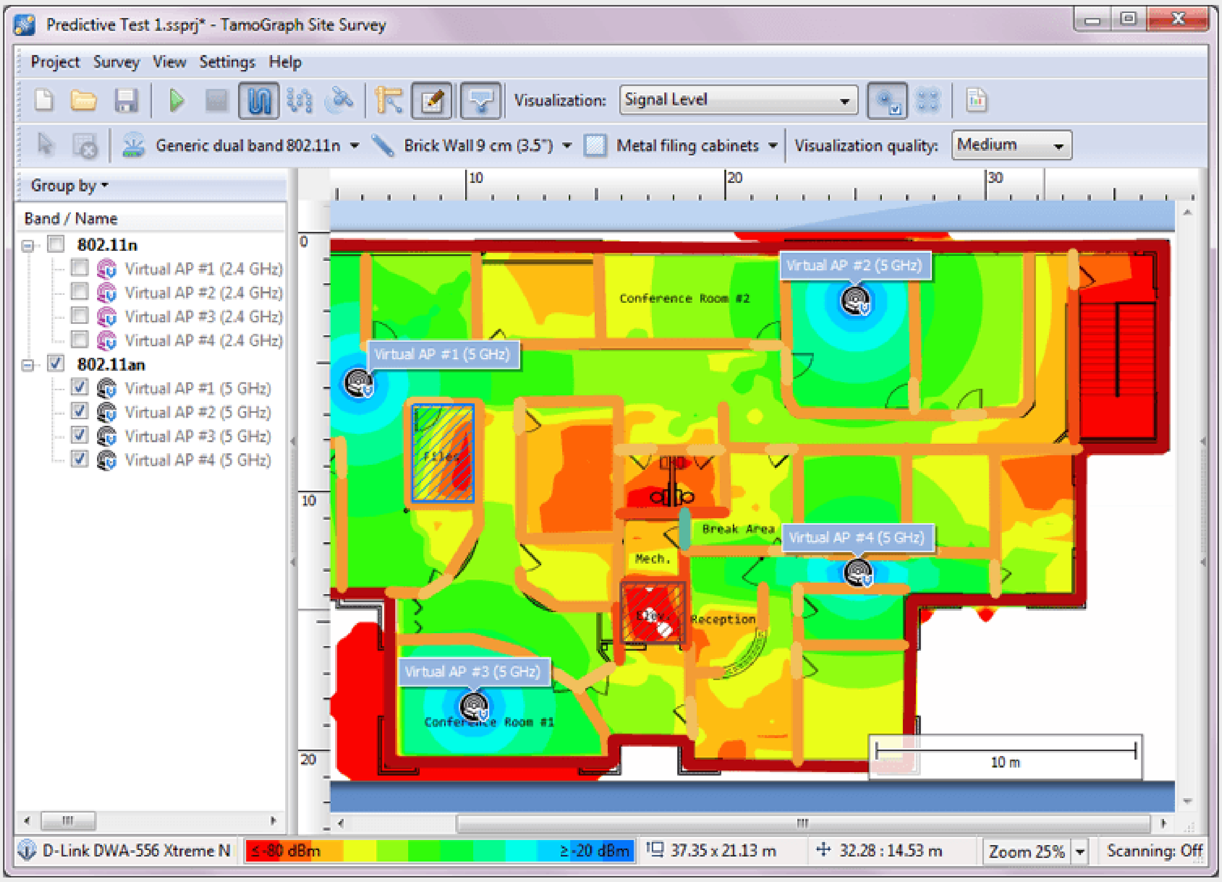


Figure 7-15. Wireless capacity planning with TamoGraph

previous example) to help determine the required number, placement, and configuration of networks.

Real-World 3G, 4G, and WiFi Performance §

By this point, one has to wonder whether all the extra protocols, gateways, and negotiation mechanisms within a 3G or 4G network are worth the additional complexity. By comparison, WiFi implementation is much simpler and seems to work well enough, doesn't it? Answering this question requires a lot of caveats, since as we saw, measuring wireless performance is subject to dozens of environmental and technology considerations. Further, the answer also depends on chosen evaluation criteria:

- Importance of battery performance vs. network performance.
- Per user and network-wide throughput performance.
- Latency and packet jitter performance.
- Cost and feasibility of deployment.
- Ability to meet government and policy requirements.
- And dozens of other and similar criteria…

However, while there are dozens of different stakeholders (users, carriers, and handset manufacturers, just to name a few), each with their own priority lists, early tests of the new 4G networks are showing very promising results. In fact, key metrics such as network latency, throughput, and network capacity are often outperforming WiFi!

As a concrete example, a joint research project between the University of Michigan and AT&T Labs ran a country-wide test (Figure 7-16) within the U.S., comparing 4G, 3G, and WiFi (802.11g, 2.4GHz) performance:

- Performance measurements were done against 46 distinct Measurement Lab nodes, which is an open platform for Internet measurement tools, and via the MobiPerf open-source measurement client.
- Measurements were done over a period of two months in late 2011 by 3,300 users.

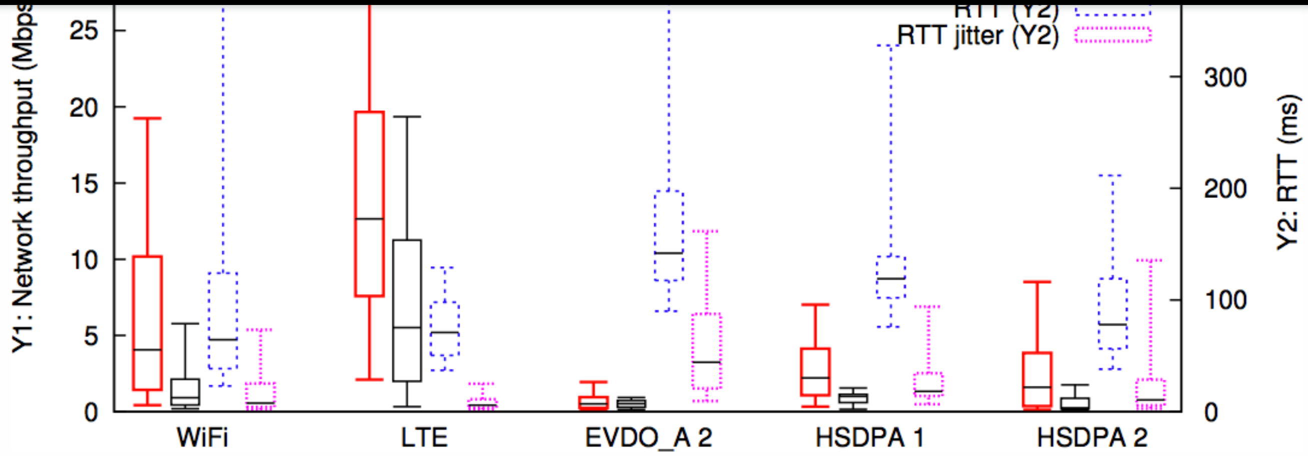


Figure 7-16. Test result analysis of WiFi, LTE, and 3G performance

> **Note**
>
> *The box-and-whisker plot for each connection type packs a lot of useful information into a small graphic: the whiskers show the range of the entire distribution, the box shows the 25%–75% quantiles of the distribution, and the black horizontal line within the box is the median.*

Of course, a single test does not prove a universal rule, especially when it comes to performance, but the results are nonetheless very promising: early LTE networks are showing great network throughput performance, and even more impressively, much more stable RTT and packet jitter latencies when compared with other wireless standards.

In other words, at least with respect to this test, LTE offers comparable and better performance than WiFi, which also shows that improved performance is possible, and all the extra complexity is paying off! The mobile web doesn't have to be slow. In fact, we have all the reasons to believe that we can and will make it faster.

> **Note**
>
> *For full details of the 4G performance study, analysis, and conclusions, refer to "A Close Examination of Performance and Power Characteristics of 4G LTE Networks" presented at MobiSys 2012.*

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