

Lecture 16- Pre-lecture reading

The world of digital cellular systems- 2G, 3G, 4G and 5G

The world of 2G: explosive growth of voice services and text-messaging

A good way to see what was happening in cellular is to review the CTIA data. If we review our CTIA data for 2G period (roughly 1998-2008), we notice that the results are a huge surprise. Instead of three times as many users per cell, which seemed like a big advantage for the providers, there were about the same 1000 users per cell, and they were talking 6 times as much! This is a good example of the power of competition. We have discussed AT&T's role in this process, where they bought McCaw cellular and used the 2G capacity to offer "nationwide calling packages" that offered many minutes for a fixed and attractive price. People flocked from other providers to AT&T, so the other providers started to offer bigger and cheaper packages. It appears that in 2008, users finally reached the point where (even with "unlimited" calling packages) they were talking as much as they wanted to (about 8000 minutes/year). Voice traffic per user hasn't increased since then.

But if usage increased 6x and only 3x was provided by 2G technology, where did the rest of that 6x come from? It wasn't with more cells. The data shows that the number of cells increased only as much as the number of users, and not significantly more (thus preserving the 1000 users/cell). It could have been more spectrum in the base stations (we don't have good information on this, except for Verizon's expensive spectrum purchase for New York City) but it is likely that most of the increase was sort of a free gift to both the users and the providers. Before portable phones, minutes were limited to when people were in their cars, but the introduction of pocket phones made cell phones available all the time. Systems are designed to meet demand during the busy hour, so calls in other hours are essentially free (they simply use capacity that is already paid for). For car phones the busy hours are the morning and evening commuting hours and most people don't spend a lot of hours in their cars beyond that. The pocket phone made calling possible any time, so that same system could carry many more off-peak minutes in a pocket-phone world.

Remarkably, not only were users in 2008 talking 6x as much—the "low-cost packages" had caused revenues per user to fall 20%, to \$40/user/month, but amazingly, 2G was the probably a golden age of growth and profit for the service providers. First, all those low cost offers got a lot more people to become cellular users. The number of users almost quadrupled in what we are calling the 2G decade, from 69M users in 1998 to 270M in 2008, but the dramatic growth started a bit earlier. From 1995 to 2008, the number of user increased almost 8x. Cellular service was almost universal by the end of the 2G era. As we have discussed, as businesses grow they generally get more efficient (they require fewer employees per customer, so their SG&A expenses per user are reduced). Due to the dramatic growth during that period, reductions in SG&A alone more than made up for the lost revenue, and then text-messaging (made possible by 2G digital radios) became the icing on the cake.

There were 90 billion text messages sent in 2005, bringing in revenues of about \$9B (or about 10 cents per message). Three years later, in 2008, the number of text messages had increased 11x (there were a trillion text-messages bringing in \$28B). Once again, competitive "packages" increased the volume of messages dramatically and reduced the cost. The revenue per message fell to 5 cents, but the messages were essentially "free" for the providers. Total revenue from text-messaging was increasing sharply,

bringing in another \$8 per month per user and making up for most of the \$10 drop in voice revenue/user/month. One character of text is a Byte, or 8 bits, and messages are pretty short, so an entire message will generally require less than one hundred Bytes— a tiny fraction of the system's capacity. A minute of voice, which was bringing in the same 5 cents, needs about 100,000 Bytes (a thousand times more Bytes for the same price). In 2008, 20% of cellular revenues came from text messaging, but this consumed about 0.1% of the system capacity, so no new cells or spectrum were required for this service. It's easy to see why the cellular providers might have thought that digital services were wonderfully profitable, and that providing 3G access to the Internet would be a great business.

The world of 3G and 4G: Cellular meets the Internet (and spends a lot of money)

The 3G dream began much earlier than we might imagine. There was the realization that “communication, information and entertainment” were all just bits, and the magical fiber capacity of the internet could provide them all rather well. This idea was called the “convergence” of data, communications and entertainment (in the same system). As early as the mid-1990s (at the beginning of the 2G era) the cellular providers were already looking forward to a new “third generation” technology that would bring the dream of “convergence” to cellular users. Just as WiFi seemed to offer “unlimited and free” access to the Internet where it was available, cellular systems would do the same thing “everywhere”. We have noticed that WiFi was able to offer that seemingly unlimited and free access because of its wide channels and short range. Cellular radio channels didn't offer the “unlimited and free” capability of WiFi, but there was a new technology associated with 3G that seemed promising.

3G and 4G used improved information coding and (in particular) smart antenna arrays (called *multiple input multiple output (MIMO)*) and the technique of antenna steering (called *beamforming* that allows for directional signal transmission and reception) to increase the capacity of a cellular radio channel beyond the 1.5 bits/sec/Hz that was achieved in 2G. As usual, claims and demos suggested more dramatic increases than were actually achieved. Industry groups began to argue about 3G standards, and demonstrations of 3G began to appear in the popular press.

The focus of those 3G (and later 4G) demos” and press releases was always on impressive download speeds that could handle video rather than the download capacity that would allow a lot of users to do that at the same time. Experimental bit-rates like 384 Kbps (and even 2 Mbps where the signal was stronger) were demonstrated and reported in the news, but there was never any mention of the resulting capacity of a cell. This was an important oversight. Even with 2G a typical cellular base station had on the order of 1-2 MHz of spectrum in each direction, so it could download a movie or two at a time. The problem is that there are 1000 users in the typical cell and about 30 of them tend to be using their cell phones at any given moment. What if more than one or two of them at a time wanted some video entertainment? Download speed mattered, but what mattered even more was the total capacity that the occupants of a cell might demand. An example of the press coverage of a later 4G/LTE demonstration is a good example. It didn't mention that the demo used about 20 MHz of spectrum, so it achieved 150Mbps with 20 MHz of spectrum, or about 7.5 bits/second/Hz (a 5x improvement over 2G). That wasn't going to handle the internet.

LTE: Dreaming of wireless Broadband

Stacey Higginbotham (tech reporter)

"After a quick demonstration of Ericsson's LTE base station, which boasted a throughput of 150 Mbps on download and 30 Mbps for uploads, I experienced one of those moments of technology utopia. I could see a world without wires, a life with fewer cables running into the house and no phone jacks on the wall.

... "With speeds like that, ... the landline might finally be ready to give up the ghost. ... Streaming HD movies while someone else talks on the phone or transfers files requires a lot of bandwidth. It looks like LTE could do that.

Things that seem too good to be true are often too good to be true

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It was certainly true that video takes a higher bit-rate than voice, but what was overlooked was the nature of the Internet—the seemingly infinite fiber-based capacity that let users believe they could have all the information and entertainment they wanted for a very low price. For access to that "Infinite and free" Internet, the cellular system (even with 3G and 4G), would be an expensive bottleneck. Another characteristic of the Internet was that demand for capacity kept increasing. It was much greater in 2008, when 3G really got going, than it was in the 1990s, and is much greater today than it was in 2008. This never-ending demand for "more" bothered the Internet providers "a bit", but not too much, because the capacity of fiber kept increasing. For the cellular providers those never-ending increases in demand have been a much more serious problem.

Optimism about 3G remained high at the turn of the millennium, as auctions were held in the US and in Europe for what was generally considered to be "3G spectrum". As we see below, very high prices were paid for that spectrum, and optimism about 3G among providers was reduced somewhat.

3G Euphoria: Providers began to buy spectrum at very high prices

Germany's 3G auction fetches EU50bn

"Six bidders have won 3G mobile phone licenses in Germany.

18 August 2000

After 14 days of bidding, the German auction for third-generation (3G) mobile phone licenses came to an end on August 18 2000, with the six winners paying around EU50.5bn between them."

UK wireless license auctions close at 22.48 billion pounds

April 28, 2000

"Damned if you do. Damned if you don't.

That was the resounding message following the close of the UK government's auctions for third-generation (3G) mobile phone spectrum licenses. After one hundred fifty rounds and nearly eight weeks, the five winners -- Vodafone, British Telecommunications, One2One, Orange, and Telesystem International Wireless UTMS -- have coughed up a shocking \$35.4 billion dollars."

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Optimism was further dampened by delays in the technology and in the somewhat disappointing performance of the first smart phones. Moreover, as is common with new services, it turned out that people didn't really know what they wanted smart phones for.

And the morning after, and the mourning after

Operators and investors concerned over just how 3G investment will ever be recouped. (they had a right to be concerned)

Worldwide roll-out of 3G networks delayed by the enormous costs of upgrading the equipment and spectrum licensing fees.

3G handsets unfit for consumers, operators say

"Third-generation (3G) mobile phones offering fast Internet access should be kept from European stores as they are unreliable, expensive, bulky and offer too limited services, mobile operators said on Thursday. Others said no handset could yet deliver all the promises of 3G telephony such as high-speed Internet access, crystal clear voice, video telephony and smooth handovers between radio base stations." (at least that problem got solved)

3G's killer application?

"Remember those distant days when we imagined a golden age of 3G phones would mean person to person video calls to Australia, downloading the new Radiohead album on the bus, and e-mail on tap everywhere. How naïve we were. Apparently, the killer application for 3G is, err..., Voice calls." (and that did change)

3G service was delayed for several years, but Steve Jobs' announcement of the I-phone in 2007 marked the beginning of the public infatuation with smart phones, and the beginning of the cellular providers' struggles to meet the demand for ever increasing capacity.

From the peak voice capacity of about 8000 minutes/user/year at the end of 2G to more than 4GB/user/month that is now being consumed by almost 300 million smart phones, providers have been forced to increase the total capacity of their systems by an incredible 70x! To achieve this amazing result they added 100,000 new base stations, upgraded all the base stations from 2G to 3G and then 4G, and bought a lot of new spectrum. The cost of about \$450 billion dollars was more than they they had spent in the first 23 years of cellular. They expected 3G/4G to be a premium service costing about \$20/month more than voice, but their revenue per user has remained flat at about \$50/month during the smart phone era. This story of huge investments, dramatic increases in capacity and a lack of financial reward is worth telling.

Achieving the 70x capacity increase: a dramatic success

When 3G services did begin in the early 2000s, it took a few years for growth to take hold, and more years for "apps" to emerge that sparked significant usage. In 2008, about 15% of cellular customers had smartphones, but their usage was less than 1 GB per year (about the same as voice). A decade later, CTIA data shows that the final growth of cellular to "everybody" (about 300M users) had happened. 90% of users had smartphones, and their data usage had increased to more than 4 GB per month! Between the final increase of 25% in the number of users and the huge increase in demand per user, the total demand for capacity has increased 70x since 2008. We need to understand how that incredible increase was achieved.

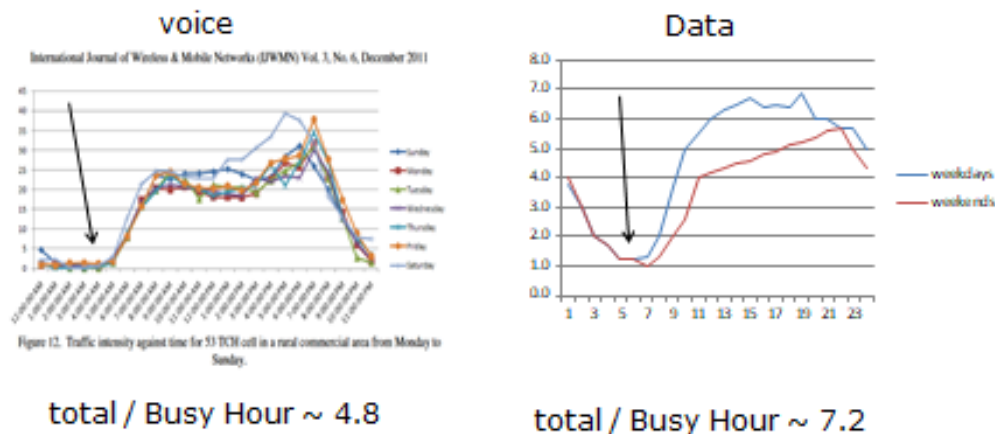
We see from the CTIA data that the number of cells increased by about 50% (a factor of 1.5). Turning to spectrum purchases, it's hard to be precise because published numbers are somewhat confusing, but a good guess is that the providers tripled their spectrum holdings for 3G/4G, which of course would account for a 3x increase in capacity. Thus, the combined effect of new cells and new spectrum (an investment of perhaps \$150B), provided only a 4.5x gain in capacity. We know that 3G/4G technology would have increased the capacity of the existing cells, but early claims of 3G and 4G capacity were often unrealistic and the calculation is actually quite complex.

We have now accounted for increases of 1.5x for new base stations (costing \$100B), 3x for new spectrum (costing perhaps \$150B), and 5x for 3G and 4G technology (costing \$200B, or about \$600K per base station!). Thus we have now accounted for an increase of 23x costing \$350B and we still need to find another 3x to account for the full 70x we are looking for.

One good guess is that data is more efficient than voice in terms of the spectrum needed. Voice requires an uplink and a downlink and only one is in use at any moment, so it wastes half the spectrum. For data, on the other hand, we can use whatever amount of spectrum we need in the two directions on an instantaneous basis (mostly the downlink for smart phones) and we can use both directions simultaneously, so as a first approximation we will assume that this provides a 2x increase in capacity from a given amount of spectrum. Happily, this 2x increase was due to the nature of the information, as was therefore "free".

A final guess involves off-peak usage. As we observed earlier, the transition to portable phones made systems more efficient because people could use them all day, but in a polite world there isn't much voice calling at night. Data usage is more consistent during the entire 24-hour day, so it loads the system more efficiently in the off-peak hours. This is illustrated in the figure below which supports an increase of about 1.5x from the "24/7" usage of smart phones.

Increased night time usage for data



Improved 24/7 usage for data = $7.2/4.8$
= **1.5x** increase in data capacity

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Combining all our results for new cells (1.5x), new spectrum (3x), 3G/4G technology (5x), 1-way transmission (2x), and "24/7" usage (1.5x), we get a total increase of $1.5 * 3 * 5 * 2 * 1.5 \sim 70x$. This is close to the CTIA results, which increases our confidence in our assumptions and calculations.

Unfortunately, that impressive increase in capacity came with a huge price-tag. The investment in 100,000 new base stations (\$100B), upgrading all 300,000 base stations to 3G and 4G (\$200B) and buying more spectrum (perhaps \$150B) adds up to \$450B (about \$1500/user in new investment during the smart phone era).

Paying for it all without increased revenues: a difficult problem

The calculation shown below for all systems calculates that based on a 10% return the incremental investments made by providers during the smart phone era required incremental revenue of \$105B. The growth we are discussing includes an increase of 60M new users in the first few years of the smart-phone era, until "universal" cell phone ownership was achieved in 2012 (at about 300M users). We will assume that those new users paid at least the base rate of about \$600/user/year (a total of \$36B), but the remaining \$69B would have to be shared by about 270M smart phone users nationwide. As calculated below, this means that the investment made in the smart phone era should have resulted in a premium of about \$20/month/smart phone user. This is

consistent with statements made by the providers (they initially described smart phone service as a premium cell phone service that would cost about \$20 extra per month.

Alas, as we have seen in earlier examples, the expected revenues never materialized. Once again, providers competed with package offers of more data—even unlimited data—for prices that were unprofitably low. Users did pay slightly more for a few years, while demand was doubling every year, and then they actually started to pay less. Over the smartphone decade 2008-2018 the revenues were essentially flat at \$50/month.

Calculating incremental revenues required from smart phone users based on the investment made by providers

Balance Sheet		P&L	
		Incremental revenue per smart phone user=\$69B/270M= \$256/user = \$21/month	
		Remaining Incremental Rev of \$105B - \$36B = 69B must be paid by all 270M Smart Phone users	
		Incremental Rev paid by 60M <u>new</u> users @ \$600/year/new user= \$36B	
Provide 100K new cells @ \$1M/cell	\$100B	Reqd incr revenue	\$105B
Upgrade base stations for 3G and 4G	\$200B	Tot incr Expenses	\$38B
Add 150 MHz spectrum At \$1/MHz/POP	\$150B	10% Depreciation	\$30B
		5% Amortization	\$ 8B
TOT increase in assets	\$450B	Req BT Earnings	\$67B
(10% return on equity)		33% Tax	\$22B
		Reqd incremental Profit	\$45 B

It seems logical that spending more than a quarter of a trillion dollars to provide smart phone access without an increase in revenues would show up dramatically in the profits of the providers, but in fact it does not. Their P&L reports seem pretty stable through that time. This is a puzzle we must return to in lecture 21 and later. For now, we will finish this lecture with a brief introduction to “5G”.

The world of “5G”

We have seen that cellular providers have been forced to invest unprofitable amounts in 3G and 4G to give smart phone users an average of about 50GB of data per year. Since revenues have been flat it is not wise to keep investing in that direction but competition is fierce so it's important to “be the leader”, even if we aren't sure where we are going. Reporting on the subject of 5G was impressively grand but somewhat vague and confusing, as illustrated in the article below (from 2020):

<https://www.cnn.com/2020/02/03/perspectives/5g-disruption/index.html>

Below are snapshots of press releases that describe how investors, politicians and service providers felt about 5G.

A hype opportunity for everyone

Investors: The opportunity of the decade

5G Could Be The Single Biggest Investment of 2019

If you aren't up to speed on "5G" yet, then get ready, because it's expected to be one of the biggest stories of 2019.

Politicians: Trump campaign pushes 5G (let's beat China)

The president's reelection team is backing a plan the wireless industry fears would impose a heavy government hand over America's communications future.

Providers: AT&T's "vision"

"Much like 4G introduced the world to the gig economy, we believe mobile 5G will jumpstart the next wave of unforeseen innovation. AT&T is the only U.S. carrier that has a standards-based, mobile 5G network live in parts of a dozen cities."

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We can understand that Wall Street analysts are not likely to understand and debunk those exaggerations and politicians have rather different objectives than system designers, but what about the service providers? Shouldn't they know better? Is this all smoke and mirrors with no real substance, or are we at the verge of great things? Maybe it's just that claims are cheaper than systems, or maybe it all makes sense. What "unforeseen innovations" does AT&T foresee as identified in the press release below? Is it about vast reaches of spectrum at millimeter wave frequencies that can download a movie in 5 seconds, or new services at conventional frequencies?

From the strange economics of 3G and 4G, (where providers can invest hundreds of billions of dollars with no increase in revenues) to the promise of 5G (which is either very important or just "propaganda and politics") we will spend several lectures after the 2nd Midterm Exam trying to make sense of it all.