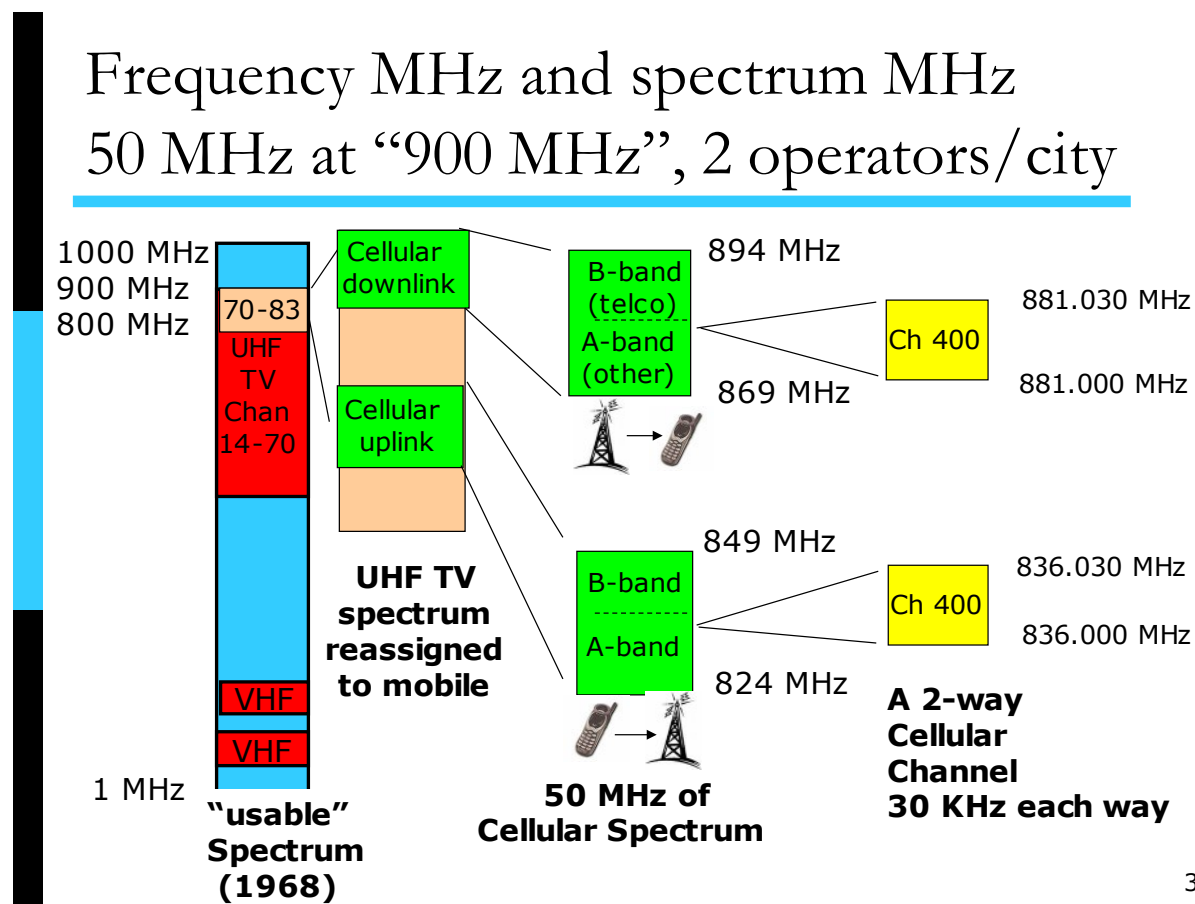


Lecture 8- Pre-lecture reading

Spectrum and its cost: hearings, lotteries and auctions

The spectrum that created the first cellular systems

Before we look at the evolution of spectrum regulation during the 30 years of cellular operations, it may be useful to review once again what the terms “frequency” and “spectrum” refer to, and to identify the specific cellular spectrum we are discussing (frequency and spectrum will be discussed in much greater detail in lectures 12-14, but here we will begin to expand our vocabulary and understanding). In the diagram below [slide 3] the column on the left shows the range of radio frequencies that were considered useful for consumer devices in the 1970s and 1980s. They extend over a range of about 1000 MHz, from AM broadcast at frequencies near 1 MHz at the bottom, to cellular, at frequencies of almost 1000 MHz, which we also call 1 GHz. Today the commonly used frequencies would extend beyond 10 GHz (30 GHz if 5G is successful) so this bar would only be less than 1/10th of the spectrum of common frequencies today.



Moving a bit to the right, we see the UHF-TV channels that were reassigned to mobile communications (TV channels 70-83) including the two 25 MHz (wide) bands (in green) that were assigned to cellular (the remaining spectrum in that band was assigned to

private mobile systems). As shown, there were two separated bands of cellular spectrum. The lower band (from 824 MHz to 849 MHz) was used to transmit from the cell phones to the base stations. The upper block (from 869 MHz to 894 MHz) was used to transmit from the base stations to the cell phones.

This significant separation of the bands in the “uplink” and “downlink” directions is needed for efficient radio design and to minimize a new type of interference (different from the “co-channel interference” we have discussed between cells using the same channel). The relatively powerful transmitted signal that a 2-way radio creates can feed back into its own receiver and overwhelm the desired, but MUCH weaker signal that is being received from a distant radio (the signal being transmitted is on the order of a million times stronger than the received signal). To prevent this form of interference, radio designers use an important filter that passes all the received channels but blocks the powerful transmit signals being transmitted (from inches away) at the same time. Such filters require that there be a significant separation between all the transmitted channels and all the received channels. As shown, the separation used for cellular systems was 20 MHz.

In the decades since 1980, the useful spectrum for consumer products has expanded by a factor of 10, to frequencies as high as 10 GHz. More recently, fifth generation (“5G”) cellular deployments involve frequencies as high as 30 GHz. There is a second issue to be considered in the use of any spectrum for a particular purpose. As we have mentioned and will discuss in more detail in Lectures 12, the best spectrum for cellular is near 1 GHz. Since the 1994 auctions, frequencies near 2GHz have been used for cellular systems as well, but as we will see in Lectures 12, the 2 GHz frequencies have a small but significant disadvantage in terms of coverage range (the largest cell size they allow at startup is reduced by 30%). That doesn’t seem like much, but it means that the largest cells at 2GHz have half the area of cells at 900 MHz, so twice the number of cells are needed at startup, which doubles the cost of a startup system. We are beginning to see (through our financial calculations) that small differences in profitability matter in a competitive situation, particularly if there are other disadvantages (like starting 10 years later than your competitors and paying for the channels they got for free). We will take a closer look at these problems in Lecture 13.

Moving another step to the right on the slide, we further expand the cellular spectrum to show the two bands which were licensed in each location for competitive systems. The B-Band went to the local telephone company and the A-Band went to a competing system.

Moving to the right one last time, we show a single 2-way cellular channel (Channel 400, in this case). It uses 30,000 Hz (30 KHz) in the uplink direction and 30 KHz in the downlink direction (a total of 60 KHz). The exact frequency ranges of the two “half-channels” of channel 400 are shown on the slide). Using simple division, we see that the 50 MHz of “spectrum” assigned to cellular allowed 833 channels. A few channels were used for “data” (to “page” mobiles for incoming calls and to assign talking channels) but almost 800 channels could be used for voice, as we have discussed, so each of the two competing systems got about 400 two-way voice channels.

Since there were seven sets of channels required to achieve co-channel separation for reusing channels in different cells, this would seem to allow about 60 channels per cell, but because of multiple cell sizes and variable traffic demands, the average cell only got

about 30 channels. Those 30 channels in the average cell could serve about 1000 users, (roughly 30 users per channel) creating the economics we have discussed. Recall that that in the mobile telephone systems before cellular, each channel served as many as 60 users, but that led to very poor service (frequently there were no available channels to make a call). With 30 users per channel, there was a 98% probability of having a channel when you wanted one, so the cellular system offered much better service than the old systems. This better quality also assured that cells almost always had some unused channels when a call had to be handed off to a new channel.

Note: We use terms like “megahertz” (MHz) to describe both the frequency of a channel (where it is located on the spectrum bar) and its bandwidth (how much space it occupies on the bar). The spectrum used for cellular was between 800 MHz and 900 MHz and was usually referred to as “900 MHz spectrum.” Thus, cellular was said to have received “50 MHz of spectrum at 900 MHz”.

Comparative Hearings—the first method for assigning spectrum

According to the rules adopted by the FCC in 1981, the existing RCCs were not automatically given the A-Band licenses. They had to compete for these new licenses with any non-telephone company that wanted to operate a cellular business, and this created a problem. The opportunity for free spectrum for a promising new service in many locations attracted many A-Band applications for every possible system. As a result, the traditional “comparative hearings” that the FCC used to decide which applicant was “best qualified” threatened to take many years. Since there was only one Telephone Company in any location, the B-Band applications would be uncontested. The A-Band applicants argued that this created an unfair competitive advantage for the telephone companies (a “head start” of several years) in providing service.

Lotteries—the second method for assigning spectrum

To make the competition fair, the FCC immediately prohibited the telephone companies from building their systems in any market until the A-band licensee had been awarded. It soon became apparent that on this basis, cellular in the US would face additional years of delay, while other countries were already operating many systems. This was finally seen as unacceptable, so the FCC began a new process in which the second license in each market was assigned by lottery (the luck of a drawing) to one of the many applications that met some minimal qualifications. Basically, the applicants had to show they had the money to build a system (generally a promise from some investors or a bank) and a supplier that promised to provide and install the system. The rules didn’t really exclude any of the thousands of applicants, but they did speed the process up dramatically. Cellular systems began to appear in the US in the mid-1980s (almost 20 years after the original Notice of Inquiry).

The lottery process quickly eliminated the logjam in licensing cellular systems, but it had some unforeseen results. People with no experience in radio (and who would have been eliminated in comparative hearings) could now file a cellular plan generated by a consultant, and most applicants simply filed the same computer-generated plan. Those who won would often sell their license to a more appropriate operator. The true value of that spectrum was not fully understood in 1985, so the prices were quite low. Craig

McCaw, a visionary entrepreneur, sold his family's cable TV business and borrowed a lot of additional money to buy such licenses from lottery winners and build a number of systems around the country. In 1994 he sold his systems to (the old) AT&T for \$16B and much of that value was in the spectrum he had bought from lottery winners. So the old AT&T was finally in the cellular business.

Auctions—the third and final method for assigning spectrum

By 1990, the government realized that spectrum was indeed valuable, and that the lottery was transferring this value to people who had no intention of creating systems. From that realization it was a small step to realize that the government could capture those dollars for itself by selling any additional spectrum. Simply setting a price wouldn't work. It would lead to many applicants that were willing to pay and the FCC would still have to choose who got the spectrum. Auctions were the obvious choice since they quickly led to a single highest bidder. The first auction, which was held in 1994, involved new spectrum at 2 GHz. Some went to the old systems who wanted more channels, but the real goal was to create more competing systems (generally two more systems in any location). With the passing of time and after many sales and mergers, the 2 GHz auction of 1994 created T-Mobile and Sprint (more about this in Lecture 13). Those new companies had trouble competing, for many reasons that we will discuss at some length.

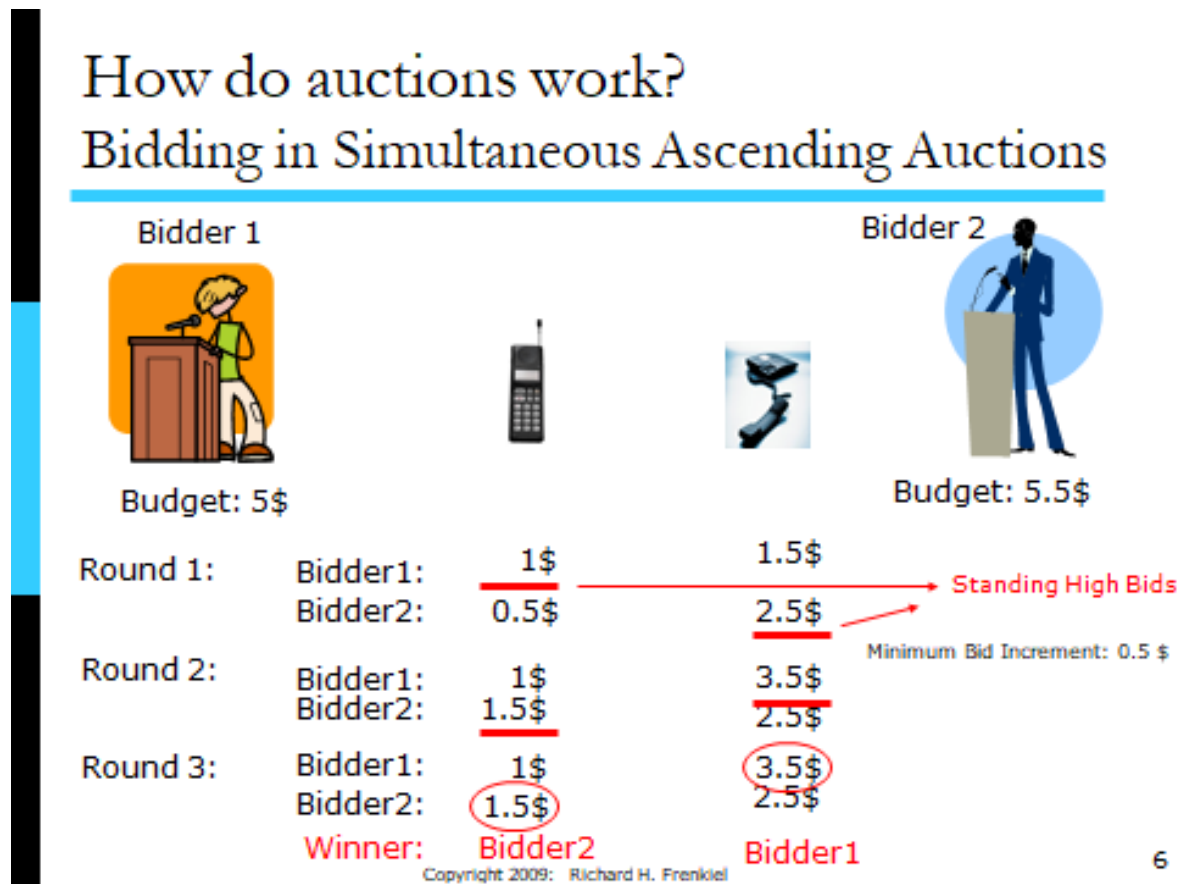
By their nature, auctions are relatively fast, and they have the general property that they discover who is willing to pay the highest price for something. There are several types of auctions, with small differences in the rules they follow. In the English auction, the auctioneer asks for higher and higher bids from an audience, and the auction continues until no one is willing to bid a higher price.

The simultaneous ascending auction [slide 6] was first developed for use in the FCC's 1994 auctions of new cellular frequencies at 2GHz. It is a simple extension of the English auction to the case in which multiple bidders simultaneously compete for multiple items (in this case, multiple licenses in different locations). The bidding occurs in rounds. In each round the bidders make price bids for the items they are interested in (a typical bidder will want certain amounts of spectrum in certain locations). At the end of each round the auctioneer declares the "standing high bid" and the corresponding "high-bidder", for each location, and the minimum new bid for each item for the next round. Note that the enforcement of the minimum bid rule aims at avoiding lengthy bidding periods in which bidders exceed the standing high bids only by negligible amounts each round. The bidding is finalized at the first round in which no bidder can raise his/her bid on any of the items. Each item is then awarded to the bidder who holds the current standing high bid for that item.

In such auction settings, the bidders can often end up with only part of what they desire. A simple example would be a potential new cellular competitor for a system in New York who needs 20-30 MHz to be competitive (recall that competitors are at a significant disadvantage if they have less spectrum than the other competing systems). If there are (say) six licenses being auctioned for the New York area (each for 10 MHz), this new competitor must win at least two or three licenses, and if that bidder wins only one license it is stuck with an expensive but inadequate block of spectrum. In some cases, such bidders are not able to withdraw their bids, and in others they must pay a

significant penalty, so this can be a serious problem. This type of auction mechanism allows buyers to make a more informed valuation of their bids since it offers them the perspective of bidding for packages of items, but it comes with potentially high risks.

Slide 6 provides an illustration of how this problem plays out. For simplicity it shows two bidders competing for two different phones, but we will assume that both bidders need both phones to be successful. Bidder 1 has a budget of 5 dollars while bidder 2 has a budget of 5.5 dollars. The minimum bid increment is assumed to be 0.5 dollars. At the first round, bidder 1 is the high-bidder for the first object and bidder two is the high-bidder for the second object. In the second round, bidder 1 exceeds bidder 2 for the second object and bidder 2 exceeds bidder 1 for the first object. Note that the standing high bids for each object from round 1 are not withdrawn. Since the bidders have reached their budget limit, they cannot make any new offers and the auction is finalized in round 3. If this were two 10 MHz blocks of spectrum in New York, neither bidder would have the 20 MHz needed to compete.



6

It may seem illogical to auction spectrum in blocks that are smaller than is needed for a system, but many bidders are existing operators looking for additional spectrum in increments less than 20-30 MHz, and eager new competitors who want to operate a popular new system like cellular may not understand cellular economics as well as they should.

A relatively new form of auction is the "second price sealed bid" auction (also known as the Vickrey auction). It is similar to the English auction, except that the winner pays the amount of the second highest bid. All bidders simultaneously submit sealed bids and

no participant knows the bids of any other participant. This innovative auction method is designed to force bidders to “truthfully” value their bids (to bid the amount which truly represents the value of the item to them). This also has parallels to the proxy bidding scheme used on eBay, in which the winner pays the second highest bid plus a fixed increment of the price. One could exercise the second price sealed bid mechanism in the context of the simultaneous ascending described above.

It is generally acknowledged that auctions are the best method to distribute spectrum licenses, but when a service like cellular captures the public imagination (as we saw with the dot-com bubble) prices can rise to unrealistic levels, creating businesses that are economically unsustainable. Moreover, the cost of the spectrum must now be shown on the winner’s balance sheet, and profits must be higher to cover the additional investment, so the cost of services increases (or profits decrease). And finally, the FCC must still take the time to decide what spectrum to auction, and how it can be used, so the process is still a combination of slow regulatory deliberations and more rapid auctions. In the 1990s and 2001, the FCC auctioned additional cellular spectrum at 2 GHz, and in the most recent auctions, since 2008, they have auctioned the spectrum from an additional 14 UHF TV channels below 800 MHz, for new 3G and 4G cellular services. There have recently been some auctions of 30GHz spectrum for “5G” cellular

Because systems in more populated areas created higher profits, spectrum in those places was more valuable, so spectrum came to be valued as dollars per MHz per “POP” (where POP was the population of the served area). Note that in this calculation, for no particular reason, population is measured in people but spectrum is measured in millions of Hz. Early estimates were that the new spectrum would have an auction price in the range of \$0.14-\$0.64 per MHz per POP, but enthusiasm created by the popular cellular service drove prices much higher (closer to \$2/MHz/POP).

The economics of buying spectrum

The cost of spectrum, like the cost of base stations, ends up on the Balance Sheet, and adds a new expense called “amortization” to the P&L. Amortization is like depreciation, but of course the spectrum doesn’t wear out. The service providers were “allowed” (and required) to amortize (write off) their spectrum investment over 20 years (5% a year).

More importantly, the investment for spectrum goes on the balance sheet and investors expect a 10% return (not only on the base station investment, but on the spectrum investment as well). For the original service providers, 25 MHz of spectrum was free, so the only investment was for the base stations. For new service providers who bought 25 MHz of spectrum in 1994, the additional cost of that spectrum therefore caused two disadvantages. Amortization added a (relatively small) expense that reduced profit and (more importantly) the desired profit had to cover the investment in spectrum as well as base stations. This was a problem for the new service providers in 1994 because they were competing with the original service providers (who didn’t pay for spectrum) and they couldn’t charge more than those original systems were charging for service. We calculated in Lecture 6 that the original service providers (with 25 MHz of free spectrum) would be charging \$50/user/month for a system with 1M users.

Thus, if the auction price was \$2/MHz/POP, the purchase of 25 MHz of spectrum for a license area with a population of (say) 10 million people (10M POPS) would be an

added investment of $\$2 \times 25 \text{ MHz} \times 10\text{M POPS} = \$500\text{M}$, and an added amortization expense of $\$500\text{M} \times 5\% = \$25\text{M}$, but revenue would be limited by the existing competition to $\$50/\text{user}/\text{month}$. That calculation is shown in Slide 13, below. The cost of spectrum reduces profit for the new service provider to 5.5%.

Calculating actual profit for a cellular system with 1M users
and 25 MHz costing $\$2/\text{MHz}/\text{POP}$
(Revenue per user is limited by competition to $\$50/\text{month}$)

Balance Sheet spectrum 25 MHz Users/cell 1000 Number of cells 1,000* Assets (1000 cells) = \$1.0B 25 MHz Spectrum @ \$2/MHz/POP = \$0.5B Total assets = \$1.5B We will finance with Stock Shareholders equity = \$1.5B	P&L Rev/user=\$600/year = \$50/month actual revenue \$600M Tot Expenses \$ 475M SG&A 350M 10% Depreciation 100M 5% Amortization 25M BT Earnings \$125M 33% Tax \$ 42M Profit \$83M Return on investment will be 5.5%
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If new competitors are limited to existing charges of \$50/month, their profit will be limited to 5.5%

13

In fact, this is an optimistic view based on a large system with a million users. An even bigger problem is that starting-up a new system in the presence of established service providers that have had ten years to grow and have a much lower SG&A expense per user. Moreover, we will see in lecture 12 that spectrum at a frequency of 2 GHz doesn't work quite as well as spectrum at 900 MHz. It leads to smaller cells at startup, so the investment in the start-up system becomes significantly larger. We will discuss the start-up problem for the new service providers in 1994 in much greater detail in Lecture 13. We can already see that they will find it impossible to return 10% profit to their investors.

Another possibility to consider is that the spectrum could be bought by an existing service provider (as an alternative to cell-splitting). An existing system (in a license area of (say) 10M pops) would already have had about 500,000 users (500 cells) in 1994. The growth in users is strong, and those existing systems could expect to double their users in 5-6 years. This would require 500 new base stations (an investment of \$500M). Finding sites and installing 500 new base stations would be a major effort. If the existing systems could buy another 25 MHz of spectrum at auction, they could double their capacity with the 500 base stations they already had, but how much should

they be willing to pay? The calculation is a relatively simple trade-off that we can calculate. The base stations will cost \$500M. At \$2/MHz/POP in a license area of 10M POPS, 25 MHz will cost $2 \times 25 \times 10M = \$500M$ (the same as cell-splitting). It seems they might be willing to pay \$2/MHz/POP but there is another problem.

The investment in new cells is gradual (over 5 years) but the spectrum must be paid for up-front. If we buy the spectrum, we will come out even in 5 years, but in the early years the \$500M investment would result in less profit. For competing companies this is a serious problem. Management is always focused on this year (even this quarter) so reducing this year's profit for an advantage that would result years from now would be an unlikely choice. Also, as we will see in the next lecture, there was a new "second generation" (2G) technology coming, that promised to triple system capacity. The existing service providers might have been interested in buying more spectrum at the predicted price of 16-64 cents/MHz/POP, but when the bidding went to \$2/MHz/POP they would have dropped out. Auctions go to the "greatest fool" and in this case that was the optimistic new service providers. We will see the unhappy results in detail in Lecture 13.

The tendency to bid too high is more likely when the buyers are new to the business (as in 1994) but even experienced service providers can overpay when they are planning exciting new services. In 1999 and 2000, in the US and around the world, experienced service operators got overly optimistic about 3rd generation ("3G") technology that would allow cellular users to access the Internet with "smart phones." Prices for spectrum in those auctions soared to an average of about \$5/MHz/POP, but a decade later (when the financial problems of Internet access became obvious) they fell to a more realistic \$1/MHz/POP. Also, in 1999, some service operators were having trouble keeping up with current capacity demands in the biggest cities. Verizon paid a record price of \$11/MHz/POP for 20 MHz of spectrum for their NY system. Since the NY license area had 20M POPS, that was an investment of about \$4B and had a significant effect on their profit for several years. It is likely that Verizon was driven to this price because it had reached the practical limit of cell splitting (cells as small as $\frac{1}{4}$ mile were being used in Manhattan) and it had to buy spectrum just to keep growing. In the cellular business (and in many other businesses), growth can be even more important than profitability (recall the SG&A advantage for the larger companies), and pride (being the biggest operator) is a factor as well.

Some important conclusions

These issues are complex, but for now we simply need to recognize the important strategic connections between the cost of spectrum and the profitability of our business. With too little spectrum, we have seen that our investment per user will be high, so we want as much spectrum as our competitors have. If the spectrum is too expensive, on the other hand, our profits will suffer, and we will tend to buy less. The new entrants to the cellular market in 1994 needed at least 20-25 MHz to compete with the established systems, but those old 900 MHz systems had gotten free spectrum, so anything the new competitors paid would make them less profitable than the old systems.

If we assume that spectrum costs \$2/MHz/POP, the "gift" of spectrum for the first systems in the entire US was $\$2 \times 50 \text{ MHz} \times 300M \text{ POPs} = 130 \text{ billion dollars!}$ This was a gift that was not given to the new service providers in 1994, and they have struggled

as a result (and for other reasons). The FCC wanted to encourage more competition by auctioning more spectrum but ended up doing it in an uncompetitive way. As we will see in Lecture 13, it would have been impossible for the new systems to compete with the older systems, even with free spectrum. Large existing systems would already have a lot of users, allowing low SG&A/user. Paying high prices for spectrum on top of that was unfair, but optimistic investors were blind to the risk and lost a lot of money.

We can see that an understanding of the economics of a technology is essential for engineers planning a new product or system, and simple economic calculations using our simplified Balance Sheet and P&L are extremely valuable in that process. We will use those calculations repeatedly in this course to better understand possible strategies.

And finally, we can start to understand the strange economics we have been dealing with, where twice the channels lead to half the investment per user. The spectrum was actually very valuable, but it was a gift for the first systems. If the first service providers had to pay for their spectrum (as they should have), twice the spectrum wouldn't lead to half the investment per user. There would have been a "right" amount of spectrum to buy. In its attempt to create competition, the FCC did some things that actually limited competition.

In Lecture 9, we will complete this segment of the course with a discussion of the most important events in the 35-year evolution of cellular service. These were portability (the pocket phone), digital voice (a big increase in capacity), and the smart phone (Internet access).