

Lecture 14- Pre-lecture reading

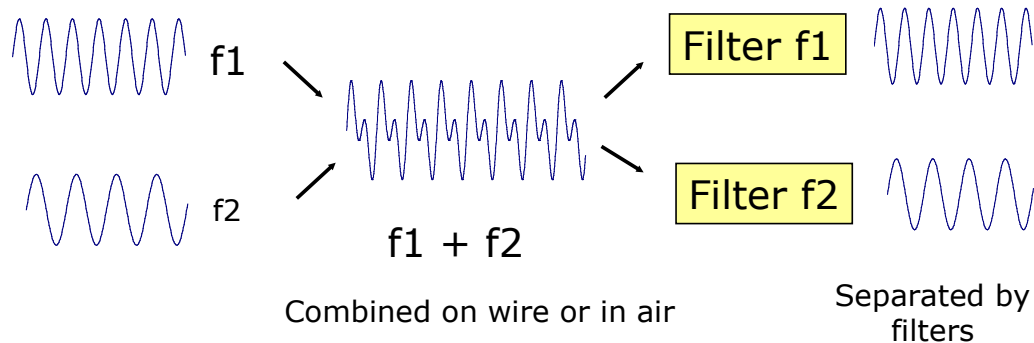
Spectrum, Bandwidth, Capacity and Cost

In Lectures 12 and 13 we talked about “frequencies”—how sound waves and light waves and radio waves are affected by distance, and by objects in real, cluttered environments—and how particular frequencies can create strategic advantages and disadvantages for different types of systems. Earlier, we discussed the shortage of “channels” or “spectrum” that limited mobile telephony before cellular, and how cellular systems were specifically intended to deal with that spectrum shortage by reusing channels many times in each system. But what determines how much “bandwidth” a channel needs to be useful (how much spectrum we need for each channel), which determines the number of channels we can create from any given amount of spectrum? Why do TV broadcast channels and WiFi channels require much more spectrum than cellular channels (recall that each UHF-TV channel that was reassigned to cellular produced 100 two-way cellular channels)? Today we will explore those questions, and find they are central to understanding strategies in the world of radio.

Before radio, as we have seen, telegraph signals traveled through a wire. When we put a battery voltage on one end of that wire and attached the other end to “ground,” an electric signal travels down the wire. At the other end, we used a coil in the wire to produce a magnetic force that pulled down an iron bar and made a tapping sound. By connecting and disconnecting the battery with a switch at one end of the wire, we produced the dots, dashes and spaces of Morse code at the other end. If we were to put two Morse code messages together on the same wire, however, we would get gibberish—the “wire channel” can carry only one telegraph message at a time. If we wanted to send two telegraph messages at the same time we had to use two wires. The same was true of Marconi’s first demonstration of a radio-telegraph message, which sent pulses of noise. Only one telegraph message at a time could be sent at any location without causing interference.

Telephone was a similar technology, except that the electrical signal that traveled down the wire was an “analog” of someone’s voice (the voltage varied in the same way as the pressure wave of the voice). As with the telegraph, one wire could carry only one voice at a time. As telephone traffic grew, and the long distance network began to carry millions of conversations for long distances, it became important to put many conversations on each wire, so that we wouldn’t need millions of wires. The key to doing that, on wires and with radio, was to use “channels” at higher “frequencies.” Slide 3 shows how two frequencies can be put together (on a wire or in the air) and be separated at the other end with filters and radio receivers. By sending pulses of frequency we could put multiple telegraph signals on the same wire, or on radio at the same location.

Using frequencies to carry telegraph

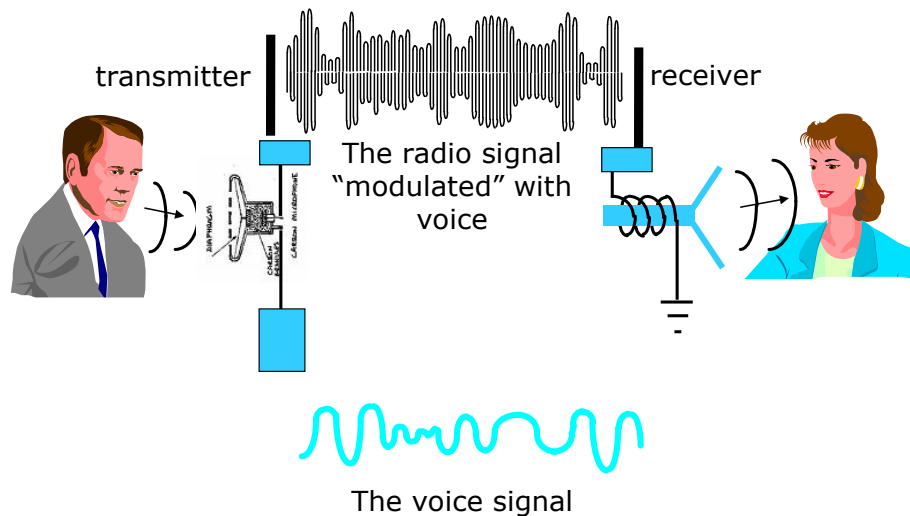


Morse Code on different frequencies

As we saw in Lecture 2, Lee De Forrest's "vacuum tube" allowed radio designers to "modulate" those frequency "carriers" with an "analog" voice signal. You can see the electrical voice signal at the bottom of slide 4, and you can see that it has been used to shape the "amplitude" of the radio wave above. This is called "amplitude modulation" or AM. Later, in 1933, Edwin Armstrong invented "frequency modulation" (FM), which was another way to put voice or music on the radio frequency. Different frequencies could now carry different voices (even thousands of conversations) on the same wire (generally a "coaxial cable"). This is called "multiplexing." In the same way, different radio channels could carry different voices or music in the air and be separated by "receivers." Today we have millions of radio channels in the air around us at any time. We separate out the channel we want with our radio receivers, and we "de-modulate" that channel to recover the voice or music (or other information) that is carried on the channel.

Lee De Forrest's "vacuum tube"

Putting voice on a radio frequency



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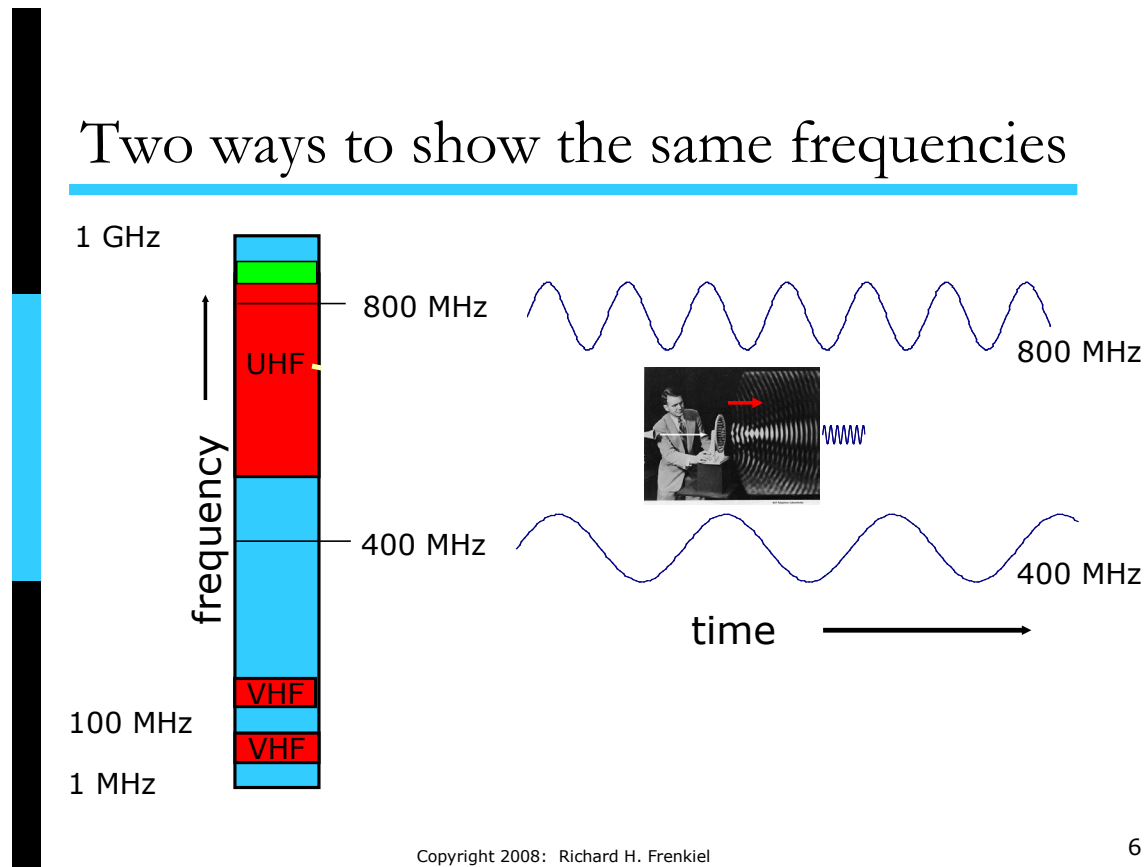
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One useful analogy to the use of different frequency channels can be imagined with visible light. Imagine that we send a Morse Code signal with flashes of light, as war ships do. If we are sent many signals from the same place at the same time, we would see a confusion of flashing lights and no information would be recovered. Now suppose we use different colors of light for the different messages. We can then see the message we want by wearing color-filtering glasses. This example seems very different from our radios because the frequencies and method of receiving are so different, but it's exactly the same. The different colors of light are different frequencies, and the colored glasses filter out the frequency we want just as our radios do. Our eyes and brains then demodulate the signal and receive the information.

So now we see the radio spectrum as many frequency channels, with each carrying different information. Receivers are designed to separate one of those channels from all the others, and "demodulate" it to recover the information it carries. But why is there a shortage of channels? We have seen that the practical limit of frequency for systems like cellular is set by propagation and antennas at about 2 GHz, but there seem to be an infinite number of different frequencies below 2 GHz, so why is there always a shortage of channels? The answer is fundamental to physics and information theory. When we put any kind of information on a frequency it spreads out over a "band" of spectrum, and the more information we want it to carry, the more it spreads out.

To illustrate this we need to represent our frequency in two different ways, as we have in earlier lectures. Both of these are shown in slide 6. On the right are two frequencies shown as sine waves, with the higher frequency about twice the lower frequency. For example, the lower frequency might be 400 MHz and the upper frequency would then be 800 MHz. The left side shows a vertical bar representing spectrum, which includes

all the frequencies from 1 MHz to 1 GHz. In this representation, those two sine waves become horizontal lines at 400 and 800 MHz (with no thickness at all, except that we give them thickness so we can see them). These two representations of frequencies mean the same thing, but they are useful in presenting different ideas. The time-based representation can be used to show a modulated frequency, while the frequency-based representation allows us to see the spectrum that a channel (or a group of channels) occupies.

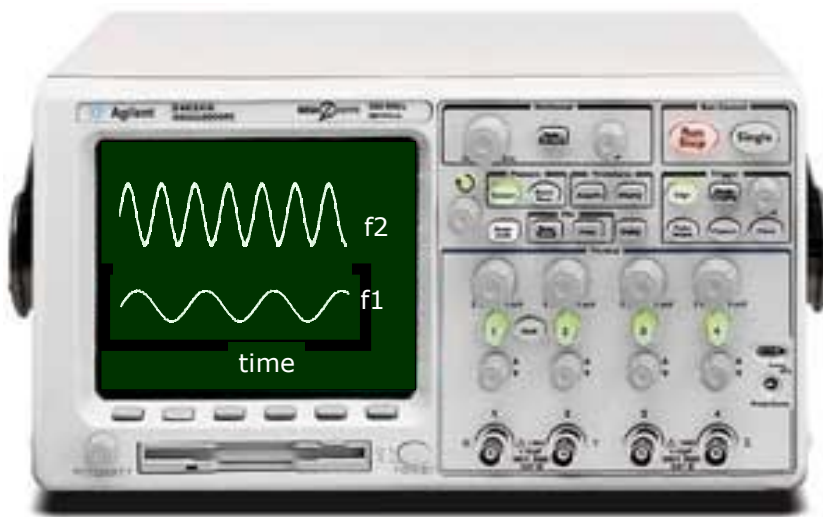


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These two representations of our frequencies can be displayed on the screen of an oscilloscope, as shown below. The first image is the time scale, shown on slide 7, which shows the frequencies as sine waves. The second is the frequency scale, shown on slide 8, which shows the two frequencies as horizontal lines.

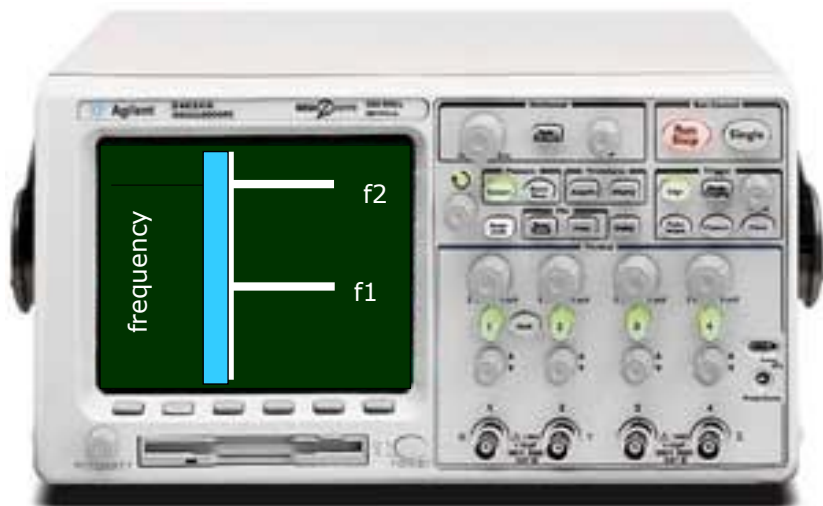
A time display of two frequencies



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A frequency display of the same signals



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Now let's use our oscilloscope to look at a familiar picture—our voice-modulated radio frequency [slide 9]. When we look at the time display, it looks like it's still just a single frequency, with only the amplitude of the wave varying to carry the voice signal.

A time display of voice on a channel



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When we look at the same signal on our oscilloscope as a frequency display, however, we see something surprising. The narrow line that depicted a single frequency has spread out—it now has a “bandwidth” [slide 10]. This is a tremendously important issue in communication systems. When you add information to a radio frequency, the signal spreads out over a range of frequencies, and you need to receive the full “bandwidth” of spectrum it occupies to send and recover the information. The more information you put on a channel, the wider it gets.

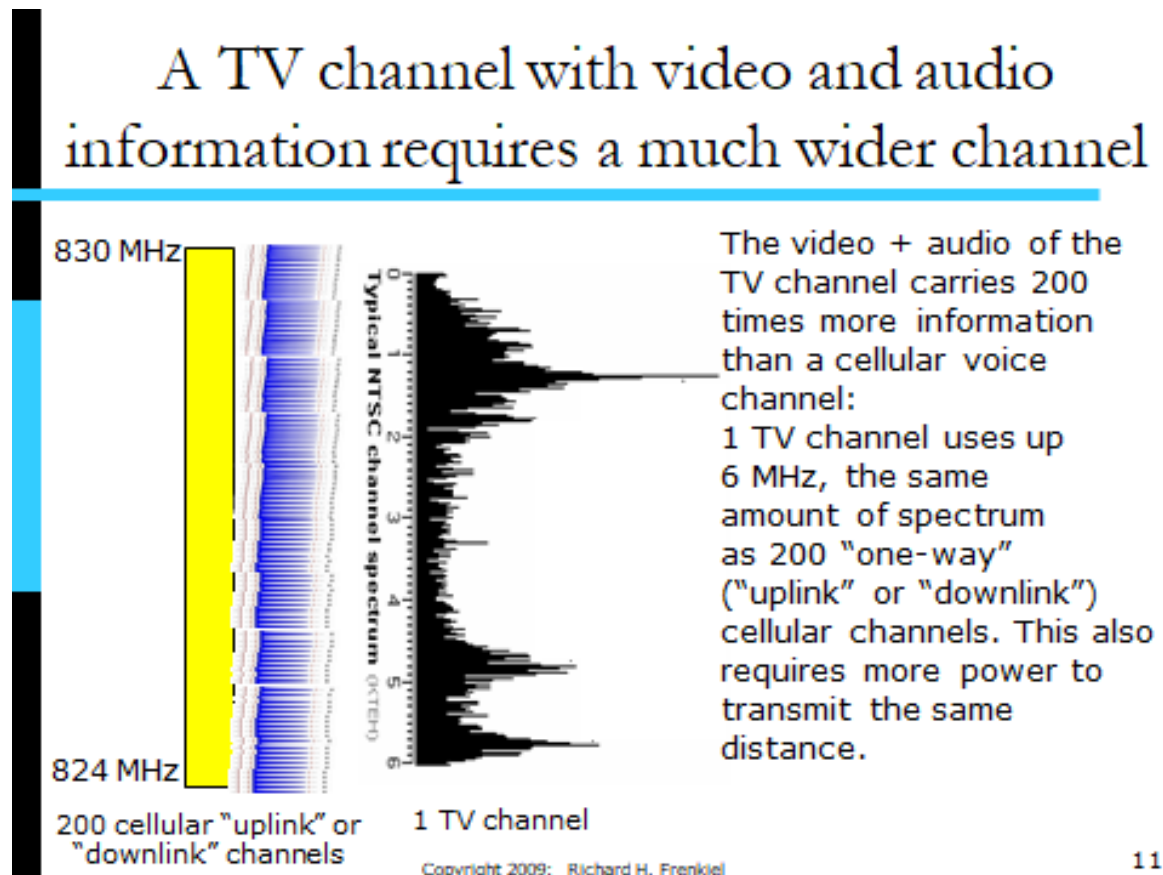
A frequency display of voice on a channel



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That's why a TV channel is so much wider than a cellular channel [slide 12]. It has to carry information about color and intensity that renews each pixel on your screen 60 times a second. HD TV channels are even wider, because they have to deal with more pixels. The figure below shows one of those UHF-TV channels compared to the narrower cellular channels that replaced it (there should be many more cellular channels than are shown, but it would not be possible to see them all in a figure of this type).

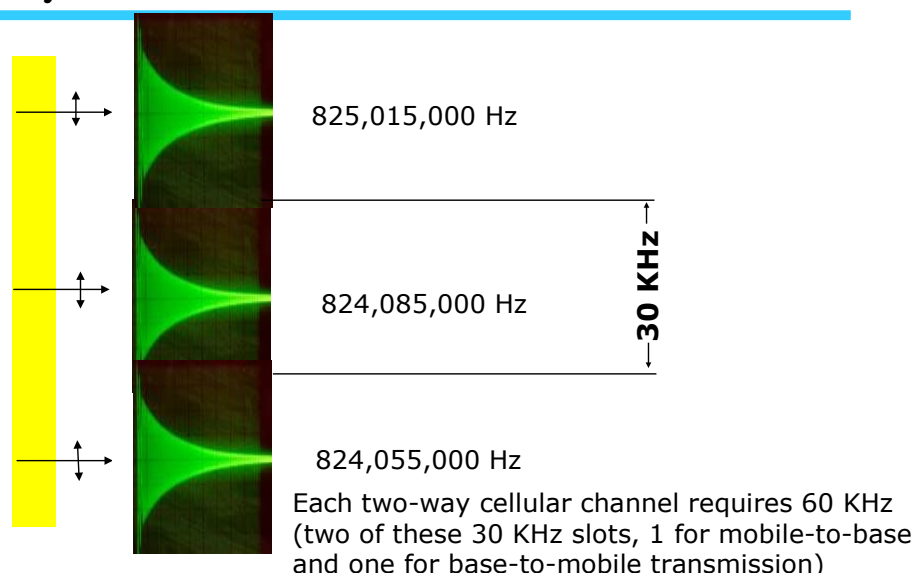


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There is also a practical design issue that makes us put channels a bit further apart than we would need to for information capacity. One of the difficulties of radio design is creating the precise frequencies that we need to transmit and receive our channels. These frequencies are generally based on resonances in crystals, which are established by how the crystals are cut in manufacture. This is a physical process with tolerances, and other circuit elements have tolerances as well, so the frequencies are never exact. Moreover, crystals and other components "drift" over time, and with changes in temperature. This uncertainty can be reduced by various techniques but this adds cost, which is undesirable in consumer products. Some uncertainty must be allowed, and we must allow for this uncertainty by increasing the spacing between channels. In early radio systems, this uncertainty was quite significant, and large spaces between channels were required to allow for drift and uncertainty. By the 1980s, crystals and circuit designs had gotten more sophisticated, but cellular systems had to allow for a variation of about plus or minus 2500 Hz in the placement of channels.

Information content plus uncertainty

Early cellular channels need 30,000 Hz slots



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So we have seen that radio channels require some “bandwidth” of spectrum rather than just a frequency. The more information they have to carry, the wider the assigned slot has to be, and practical design tolerances make the assigned slot even wider. The amount of spectrum that allowed four UHF-TV channels (24 MHz) will allow a cost-effective cellular system with 400 voice channels. Auctions are now used to decide which cellular operator gets the spectrum, but the FCC must still make fundamental decisions about how much spectrum goes to TV and how much goes to cellular. Some economic benefits can be calculated, but such decisions are basically a matter of judgment. In the 1950s, TV seemed more important than cellular. In the 1970s, attitudes began to shift. More recently, with most TV being delivered on “cable” or from satellites at higher frequencies, and with cellular service having great popularity and economic impact, the FCC has continued to reassign channels from UHF-TV to cellular. Some economists believe that even this decision could be based on auctions—that the decision of TV vs. cellular could be based on “willingness to pay,” but there remains a belief that government has a role in determining a “social value” for such decisions, and in setting rules that prevent chaos. It would be a problem, for example, if TV won the auction in one city and cellular won it in a nearby city.

As we saw in Lecture 8, the FCC soon learned that it could auction off blocks of additional spectrum for what was an increasingly popular service. When additional spectrum was auctioned at 2 GHz in the 1994, bidding led to unexpectedly high prices (about \$2/MHz/POP). In 2001, it went for an average of about \$5 per MHz per “POP”, and Verizon paid more than \$10 per MHz per POP for spectrum in the New York area. We saw that Verizon’s large investment for New York may have been based on their existing system reaching the limits of cell-splitting. The high prices in Europe may have been based on an overly optimistic assessment of the economic potential of new “3G” information services that emerged some years later. We have seen, however, that even for conventional cellular systems that have not reached the limits of growth, added

spectrum will mean more channels per cell and thus fewer cells. In effect we can calculate a value for spectrum as an alternative to expensive cells. Since spectrum was free for the first cellular systems, AT&T had a powerful argument for monopoly. If the FCC had set a high price for spectrum (like \$5 /MHz/POP) the first systems would have been more expensive, and the advantage of monopoly would have been lessened.

This calculation is quite complex, as shown in the following examples, because the value of spectrum depends on how much we are considering buying. As we have seen, if we had only 200 channels our investment in base stations would have been \$2000 per user. If we had 400 channels our investment would have been \$1000 per user, and with 800 channels our investment would have been \$500 per user. Thus, if we have only 12.5 MHz of spectrum (200 channels) to start with, we can reduce our investment by \$1000 per user (from \$2000 per user to \$1000 per user by buying just 12.5 MHz of additional spectrum. If we already have 25 MHz, on the other hand, we need to buy twice as much spectrum (25 MHz) to reduce our investment by half as much (\$500 per user). If we have more spectrum, we are willing to pay less for additional spectrum. Conversely, competitors with less spectrum should be willing to pay more for additional spectrum.

In the example below [slide 16], we look at investment and profit for a proposed system with 1 million users in a region like New York with 20 million POPs. Suppose we have an opportunity to buy spectrum at \$4/MHz/POP, and we can buy either 12.5 MHz (for \$1.25B) or 25 MHz (for \$2.5B). We will depreciate our equipment over 10 years and amortize our spectrum over 20 years. The 12.5 MHz case is shown on the right and the 25 MHz case is shown on the left. The calculation shows that when we consider investment, depreciation and amortization, it is slightly more profitable to buy 25 MHz for a system of 1M users. [The investment is the same but the amortization expense of 5% for spectrum is less than the 10% depreciation expense for cells].

Cellular system with 1M subscribers and 12.5 MHz
or 25 MHz. 20M POPs; Spectrum at \$4/MHz/POP

Balance Sheet				P&L			
Channels	400	200		Monthly Rev/sub	\$60	\$60	
Subscribers/cell	1000	500					
Number of cells	1000	2000		Oper Revenue	\$720M	720M	
				Expenses	\$550M	600M	
Inv in cells	\$1.0B	\$2.0B		SG&A	350M	350M	
Inv in spectrum	\$2.0B	\$1.0B		Depreciation	100M	200M	
Tot Assets	\$3.0B	\$3.0B		Amortization	100M	50M	
				BT Earnings	\$ 170M	120M	
Liabilities	\$3.0B	\$3.0B		Tax	\$ 57M	40M	
Equity	3.0B	3.0B		Profit	\$ 113M	\$80M	
				Return on equity	3.8%	2.6%	

An operator should buy 25 MHz @ \$4+ /MHz/POP

On the other hand, suppose 50 MHz is being offered. If we do the same comparison between 25 MHz and 50 MHz of spectrum (see below), we find that the situation is reversed. The operator is worse off buying 50 MHz at \$4/MHz/POP. In fact, the break-even price is now less than \$2/MHz/POP. [slide 17]

Cellular system with 1M subscribers and 25 MHz
or 50 MHz. 20M POPs; Spectrum at \$4/MHz/POP

Balance Sheet			P&L		
Channels	800	400	Monthly Rev/sub	\$60	\$60
Subscribers/cell	2000	1000			
Number of cells	500	1000	Oper Revenue	\$720M	720M
Inv in cells	\$0.5B	\$1B	Expenses	\$600M	550M
Inv in spectrum	\$4.0B	\$2B	SG&A	350M	350M
Assets	\$4.5B	\$3B	Depreciation	50M	100M
			Amortization	200M	100M
Liabilities	\$4.5B	\$3B	BT Earnings	\$ 120M	170M
Equity	\$4.5B		Tax	\$ 40M	57M
			Profit	\$80M	113M
			Return on equity	2.6%	3.8%

**An operator with 25 MHz should not pay \$4+ /MHz/POP
for another 25 MHz**

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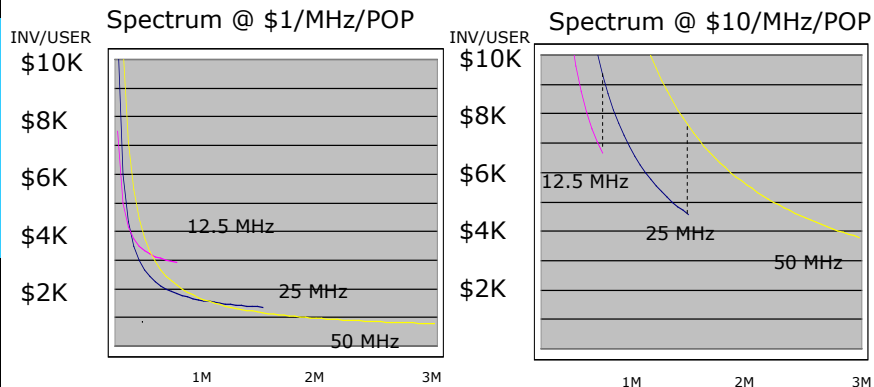
To make things still more complex, the calculation of break-even price for spectrum also depends on the size of the system, and how fast it grows. We pay for spectrum up front and for cells more gradually. Thus, for a slow-growing system there is more of a reason to grow with cells (a huge investment in spectrum will take longer to pay off). It would be nice to buy spectrum as we need it, but we don't know when it will be offered and how much it will cost. Base stations might cost more (eventually) but it might take a long time to get there.

On the other hand as shown in Slide 19, a system with only 12.5 MHz would not be able to serve 3M users— it would probably reach the limits of cell-splitting between 600K and 1M users. A 25 MHz system would probably only serve 1.5 to 2M users, while a 50 MHz system might serve 3-4M users. Once again, at the low price \$1/MHz/POP we would probably buy 50 MHz right away, but even at \$10/MHz/POP, we would be forced to buy more spectrum over time, as Verizon did, to keep growing, no matter what the cost (as shown on the right). We would need to raise the price of service to make a profit, and if the price was already established at \$50, we would probably not be

profitable until we reached more than 3M users. We saw in an earlier example that Verizon's profit was reduced significantly for several years after its expensive purchases of spectrum in 2000.

Cost of equipment plus spectrum for a growing system in a region with 20M POPs

These curves show Investment PER USER with a limit on number of cells
1500 cells yields 600K users for 12.5MHz; 1.5M users for 25 MHz; 3M users for 50 MHz



How much spectrum would you buy at \$1? At \$10? What other factors would you consider?

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Verizon's true investment for New York would have first been based on the 25 MHz of free spectrum it got at 900 MHz, so its investment would have been low and it would have quickly become profitable. It would have remained profitable until it was forced to buy expensive spectrum in the 2000 to keep growing. It lost its profitability for a while, followed by a gradual return to profitability as the system reached 3-4 M users. In 2008, it then jumped at the chance to buy more spectrum at \$1/MHz/POP (even though growth had slowed, people were talking more, and Verizon wanted to offer 3G services).

So how much is spectrum really worth? We saw that Verizon's large investment for New York may have been based on their existing system reaching the limits of cell-splitting. The high prices in Europe may have been based on an overly optimistic assessment of the value of new "3G" information services. Even for conventional cellular systems that have not reached the limits of growth, added spectrum will mean more channels per cell and thus fewer cells. In effect we can calculate a value for spectrum as an alternative to expensive cells. Finally, we know that scarcity increases the value of a commodity, and we don't know how much spectrum there will be. They could not have predicted that the FCC would auction off more TV channels, as they have done.

We need frequencies between about 700 MHz and 3 GHz for a good compromise between antenna size and cell size, but this is still a lot of spectrum. If the FCC were auctioning the last good spectrum for cellular we would pay more for it. In the 1990s, operators may have believed they were bidding on the last cellular spectrum that would be made available, and they bid high. Then Cable TV and digital TV made UHF-TV

channels less important. In 2008, the FCC was able to auction off more TV spectrum for cellular, and the price dropped to \$1 per MHz per POP. It remains possible that even more spectrum will be auctioned off in the future, so prices could drop again. On the other hand, additional spectrum needed for 3G services could push the price back up. As a result of all this uncertainty, it is very difficult to decide at any given time what spectrum is really worth. It is clear that the problems are very complex, that they vary from one time-period to another, and that they are very important to the cellular providers.