

Lecture 12- Pre-lecture reading

Frequency, Wavelength and Coverage:

Part 1: Free space and the antenna effect

To really understand radio systems, we need an intuitive understanding of radio frequency, propagation and antennas. This lecture and the following lecture are intended to provide that understanding to a non-technical audience, but even radio engineers may find that the ideas presented here may help them to understand radio in new and useful ways. After a general discussion of the available frequencies, this lecture will focus on radio waves in free space. The “free space” loss of signal power with distance occurs because the radio energy is spread over an expanding sphere as it moves away from the base station or mobile unit. Antennas are designed to absorb energy from a tiny area of that expanding sphere as it passes by. We call that area the antenna “aperture” and we will see that at higher frequencies, antennas are smaller. [A good antenna is “tuned” to the wavelength it is receiving, so higher frequencies have smaller antennas. Thus they have smaller apertures and absorb less energy.] This results in a more limited range for radio systems using higher frequencies, which becomes a strategic issue for system design. For example, cellular (systems that operate at higher frequencies have more limited radio range and must start-up with smaller cells). For systems like WiFi that have inherently short range, higher frequencies are less of a problem. [Historically, radio engineers would say that “path loss” increases with the square of frequency. This is because it was convenient to include the receive antenna in the “path” when making measurements. The available energy per square inch at a given distance is independent of frequency.]

Lecture 13 (part 2 of frequency, wavelength and coverage) will then focus on the effect of the “real world” physical environment on the radio wave. We will see that hills and buildings and trees and even rain can absorb, scatter, reflect and bend radio waves, with significant effect on their range. We will see that the influence of the environment on the radio wave depends significantly on the size of the object and the “size” of the wave (which we call its “wavelength”). As with the problem of smaller antenna aperture at higher frequencies, the range-limiting effects of the real-world environment also tend to be more significant at higher frequencies. We will see in this and the following lecture that frequency (wavelength) is the primary determinant of the coverage we are able to achieve in a system (for example the maximum cell size at start-up).

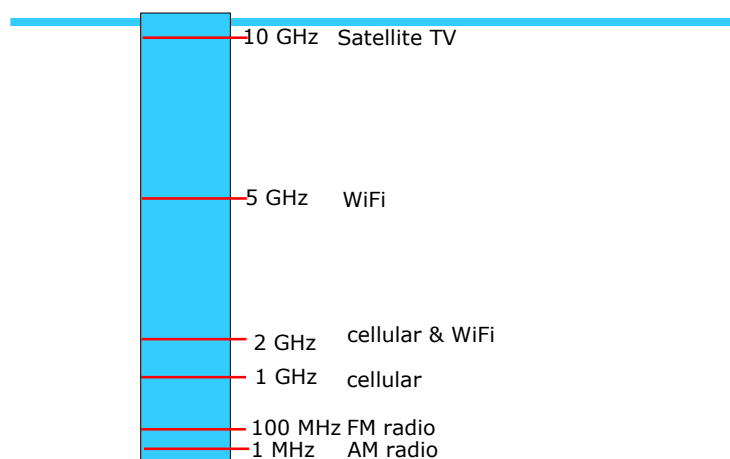
Available frequencies

At the low end of our frequency bands (at about 1 MHz) we have AM broadcast radio (one of the earliest applications). FM broadcast came later, at about 100 MHz. Cellular systems are at about 900 MHz and 2000 MHz (roughly 1 GHz and 2 GHz). WiFi is at 2.4 GHz and 5 GHz. TV satellites like DIRECTV use frequencies near 10 GHz. Cellular “5G” (fifth generation) technology uses some very high frequencies (near 30 GHz and 60 GHz). To some extent those choices of a particular frequency for a particular purpose were driven by the availability of spectrum when the new services were proposed and the capabilities of affordable radio equipment. As we saw earlier, the highest frequencies that we could use for low-cost consumer radios has moved steadily higher with the passing decades, so periodically new frequencies have become

available, and it was logical to use these for new services, but there are also some natural constraints in terms of what certain frequencies are useful for.

In this and the following lecture, we will see why some frequencies are better or worse than others for a given purpose. Some frequencies allow greater range, while others use smaller antennas, which may be important as well (a pocket phone with a large antenna is problematic). Some provide better coverage in hilly terrain, or work better in forests. Some are affected by rain or snow. At a minimum, a poor frequency assignment can make our system more expensive, and we have seen that even a small disadvantage in cost can limit profitability in a competitive environment. In extreme cases it may be essentially impossible to use a particular frequency for some particular purpose. The FCC must consider such issues in assigning new spectrum, and strategists must be aware of the potential pitfalls of using frequencies that are not as desirable as the frequencies used by our competitors. There are many examples of companies who tried to start a new system with poorly chosen spectrum and were unable to compete.

Current “consumer” radio frequencies (10 times more than in 1970-80)



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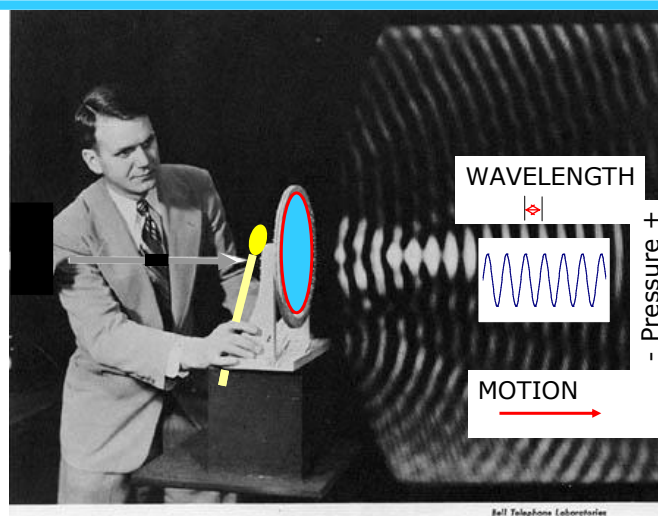
Because of antenna effects and sensitivity to real-world environments, a cellular system using frequencies near 10 GHz would have very limited range. For instance, some of 5G uses mmWave frequencies in the 28 GHz and 60 GHz range and the cells that use these frequencies are by necessity small. The largest cells would be very small, so many more base stations would be needed at start-up. With small cells the immediate capacity of the system would be very large (cell-splitting might never be needed), but the cost at start-up would be prohibitive. In less populated areas the cells would be unnecessarily small forever (so the system would always be much more expensive than its existing competitors). Even a smaller increase in frequency such as doubling the frequency from 900 MHz to 2 GHz (the first auctions) resulted in doubling the number of cells at startup and therefore doubling the initial investment for the new competitors (and as we have seen, the new competitors had to match the coverage areas those competitors had achieved after a decade of expansion). And of course the new competitors had to pay for their spectrum as well (another investment that the existing

systems did not have to make). Thus, while the 2 GHz frequencies used for second-generation cellular systems were quite practical, the systems they led to were more expensive to create than the systems of their competitors. This created an important competitive disadvantage for the new service providers. It's hard enough to compete with entrenched competitors on an equal footing. They already have lower SG&A per user and we don't need additional systemic disadvantages. Decades later, the first systems that got those free channels at 900 MHz (primarily Verizon and AT&T) are still the dominant cellular providers. T-Mobile and Sprint have struggled to compete.

To understand why one frequency or another is better for a given purpose, we need an intuitive understanding of wavelength, antennas and radio propagation. We will be helped in this understanding by the similarities in the behavior of radio waves and other waves we have more direct experience of, such as sound waves and light waves.

What happens when we hit a drum? As shown in slide 4, the surface of the drum vibrates at some “frequency”—which is just the number of times the surface moves back and forth in a second. Each time the surface moves forward, it compresses the air in front of it, and a pressure wave moves away from the drum at the speed of sound (about 1100 feet per second, which we will approximate as 1000 feet per second). When the surface of the drum moves backward, it produces a reduced pressure that also moves away, so the moving wave has “peaks” of higher pressures and “troughs” of lower pressure that move away from us like ripples in water. We can also see the peaks and troughs of pressure in this photograph, which used special techniques to make the sound wave visible.

What we call wavelength



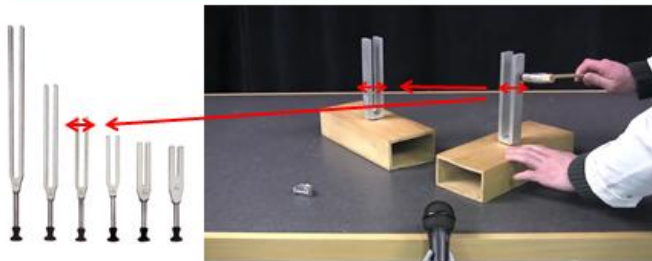
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The wave is often depicted as a “sine wave” (as shown on the slide) and the distance between those peaks is the “wavelength.” One key thing to remember is that the drum will always produce the same wavelength (because of its size) and the speed of the

wave doesn't depend on how hard we hit the drum. If we hit the drum harder, we can make the sound louder (have greater energy), but it will have the same frequency and move at the same speed through the air.

To "receive" the signal we need something that will absorb that energy from the sound wave. We can do that with a drum of the same diameter, which will resonate to that same frequency that was produced by the first drum. We can do the same thing with tuning forks. If we strike a tuning fork, other tuning forks of the same length will absorb that energy and resonate. Other forks will absorb much less. This is much the way a good antenna works. It absorbs a maximum of the electromagnetic energy in the passing radio wave.

Tuning forks are like good antennas;
they will absorb maximum energy



Other tuning forks will not absorb the energy

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Energy on the expanding sphere

Let's first consider the weakening of these waves in "free space" with no obstructions. If we think of the light energy from a star, or a radio wave from Mars, no energy is actually lost as the signal moves through space. We can think of the total energy from a voice, or a star, or a radio as being spread over the surface of an expanding sphere, and our eyes or ears, or radio antennas will capture the energy on a tiny fraction of that surface.

The energy per square inch on the surface of that expanding sphere is independent of frequency. It is simply the transmitted energy (say 1 watt) divided by the surface of the expanding sphere. At 2 miles from the transmitter the surface of the sphere is .2 trillion square inches. The energy density on the surface of the sphere at 2 miles is the transmitted energy (say 1 watt) divided by the surface area of the sphere. Thus, the energy density at 1 mile is

$1 \text{ watt} / .2 \text{ trillion square inches} = 5 \times 10^{-12} \text{ watts per square inch.}$

The purpose of a radio antenna, like that of the eye or the ear, is to absorb energy from the radio wave and pass it to the radio receiver for processing. We refer to the antenna as having an "aperture" of a certain size. In the above case, if an antenna absorbed a signal of 5×10^{-12} watts we would say it had an aperture of 1 in^2 . This becomes important because the aperture of the antenna is proportional to its size, which is proportional to the square of the wavelength it is designed to receive. Higher

frequencies have shorter wavelengths, resulting in smaller antennas with smaller apertures that absorb less energy.

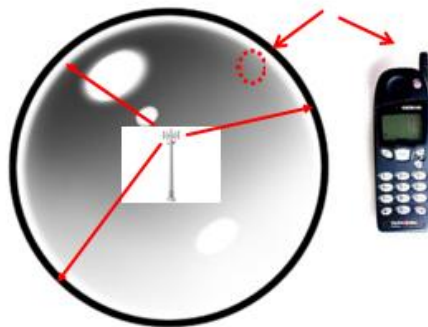
The antenna that is used for products like cell phones (and many other consumer products) is called a “quarter wave whip.” It’s basically just a wire with a length of $\frac{1}{4}$ of the wavelength being received, and it is almost “omnidirectional” (it has pretty good transmission and reception in most directions). That matters because we don’t want to have to “point” the cell phone in different directions to find the best reception and keep changing the direction as we move. Longer whips often “telescope” for convenient handling, and short ones are often hidden in the device (as with smart phones). Ideally, the quarter wave whip should be mounted on a large metallic “ground plane” (like the roof of a car) which reflects additional energy to the antenna. Unfortunately, car phones became pocket phones without ground planes, so their antennas don’t work as well as they used to. The “effective aperture” (A) of a quarter-wave whip of length L without a ground plane, is calculated as

$$A = .5 \times (2L)^2 = 2 \times L^2.$$

For a 3 inch whip at 1 GHz, the effective aperture would be 18 in²

At 2 miles, the sphere has a surface area of .2 trillion square inches. 1 Watt becomes an energy density of 5×10^{-12} Watts/in²

If the antenna has an “aperture” of 18 in², it gathers a signal power of 10^{-10} watts, or -100 dBw



The term L^2 is important, since if we double the frequency to 2 GHz the antenna length (L) becomes 1.5 inches. The aperture becomes 4.5 in² and the absorbed power at any distance is reduced by a factor of 4 (6 dB), so the maximum cell size at start-up is reduced.

An additional reason for the energy loss in a radio (or even sound) wave is that real-world obstructions along the path it travels will scatter and absorb and reflect some of its energy. This effect is also frequency-dependent, and can affect the suitability of a frequency for some particular purpose. We will consider those real world effects in lecture 13.

Over the centuries, people have figured out how to use larger “antennas” of various types to capture more energy from the surface of that expanding sphere. We used “ear

horns” to capture more sound and telescopes to capture more light. A variety of radio antennas have been used for the same purpose, like those old multi-element and dish antennas used for TV.

We can use larger “antennas” to capture more energy



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We could even put two whip antennas on our cell phones and combine them to get a stronger signal. In our radio system, however, there are two limitations to this approach. The first limitation is physical. Large antennas are obviously not desirable on portable phones that we carry in our pockets, and even at the base station there are practical limits on the size of antennas we put at the top of a mast. The second limitation is that when we make an antenna larger, it becomes more “directive.” Our eyes see a fairly wide field of vision, while a telescope, which can gather more light, sees a much smaller “field of vision”. The telescope and ear horn must be pointed at the source of the light or sound.

Similarly, when we make a radio antenna larger to gather more energy, it becomes more “directive” (it begins to focus in a particular direction). This is not a problem for the dish antenna we use for direct satellite TV on our roof, because it is a stationary antenna focused on a “stationary” satellite in space (the satellites are in “stationary” positions 22,000 miles above the equator, in 24-hour orbits that appear to be stationary on the surface of the earth). Such an antenna is not desirable, however, for a portable device like a cell phone. Even if we were willing to carry a device with multiple antennas, it would work better in some directions and worse in other directions. We might have to aim the antenna in a particular direction to get a good signal, which would be difficult or impossible to do with a portable cell phone.

A better possibility would be a “steerable” antenna for cell phones that would automatically point in the best direction. Such antennas are possible and could improve

the future usability of higher frequencies. In fact, 4G and 5G systems do use advanced antennas as do some of the advanced WiFi access points.

Because some radio systems need more range than others and others need compact radios with small antennas, and still others require the greatest possible capacity, we try to pick the best frequencies for different purposes when we can. A police system may need only a few channels but want maximum range in hilly terrain and has no problem putting long whip antennas on its patrol cars. It might therefore opt for 100 MHz channels. WiFi users might be happy with short range but demand a lot of capacity, so the huge frequency bands at 5 GHz would be attractive. Cellular providers might want frequencies that allow reasonable range for start-up investment and small antennas for attractive phones. They might prefer 900 MHz spectrum. A good designer considers all these things when deciding which frequencies to use for various services.

The economics of cellular systems for the new competitors

The following may seem to be a digression (a sudden shift from antennas and coverage to profit and loss) but it is really a reflection of the nature of strategy. Strategists need to see all aspects of a system all the time. We have already seen (in Lecture 8) that the new systems **had to pay for spectrum** that the original systems got for free, but they had to match the price per month that the original service providers were charging. We saw that the cost of spectrum would reduce their profits to less than 6%.

We have now discovered another serious problem. The new systems will need **many more cells at start-up** than the original systems needed). The original service providers, with 900 MHz spectrum, were able to start with larger cells (say 5-mile radius) than the new service providers who are using 2 GHz spectrum. The difference means that the new service providers would need about twice as many cells to cover any service area at start-up. To make matters worse, the original systems had a decade to gradually expand their coverage areas from (say) 1500 to 3000 square miles. The new competitors would need to match that increased system size immediately (who will want to buy service in a smaller system?). A third possibility might be that the original systems (having split to smaller cells for growth), were better able to provide in-building service for the lower powered pocket phones that were replacing car phones. We will ignore that possibility in our calculations, but smaller cells and larger coverage areas might demand 4 times as many cells (say 80 cells at start-up, rather than 20) costing \$80M.

And while this was happening, **the old systems were dropping their prices fast**, as we can see in the CTIA data. When the new competitors began planning (perhaps in 1993), users were still paying \$57/month. While they were bidding for spectrum a year later, revenues were falling to \$49/month! By the time the “lucky” winners were starting to offer service, the revenues they were forced to charge had fallen to \$45/month (on their way to \$40/month in the next few years). And the benefits of 2G they might have counted on to reduce future investments had evaporated with the new calling packages.

These are very serious problems but **the worst problem was SG&A**. SG&A expense is always a problem at start-up, but looking at the CTIA data, we see that the original systems were able to charge more at startup (\$101/month in 1984). With fewer cells and free spectrum, they were almost immediately profitable. The new systems had no

such benefits, and they were competing with established systems that had much lower SG&A per user.

If we assume that a typical existing system had 500,000 users in 1996 (when the new systems were actually starting to offer service), the SG&A expense for the existing systems would be \$250M, or **\$500/user**. We will assume that all four competing systems will be growing equally, at 60,000 users per year. According to our SG&A chart, for year one the new competitors would have SG&A expenses of \$90M (much more than their revenues). Since they are growing at 60,000 users/year, their average number of revenue-producing users will only be 30,000, providing total revenues of 30,000 users x \$45/month x 12 months = \$16M to support an SG&A of \$90M, so **they will need to borrow \$74M** just to pay things like salaries and rents). In slide 8, we see that a new service provider would have lost \$94M in year 1.

Profitability was a problem for the new cellular systems. They needed more base stations; they had to pay for their spectrum; their SG&A/user was very high; and they could only charge \$45/month

Balance Sheet YEAR 1		P&L for year 1	
Number of cells=	80	60K users at the end of year 1 = an average of 30K users	
(startup with 3-mile cells)		Rev/user /month = \$45	
Inv @ \$1M/cell	\$80M	30K users @ \$45/mo = \$16M	
25 MHz of spectrum		Tot Expenses	\$110M
@ \$1 /MHz/POP=	\$250M	Est SG&A for 100,000 users	\$ 90M
Assets (cells & spectrum) \$330M		10% Depreciation	\$ 8M
		5% Amortization \$	12M
Shareholders equity \$330M		BT Earnings	-\$94M

The result was a disaster.
They would have had to borrow about \$74M just to pay salaries

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We might expect this problem to quickly disappear as the new systems grow and SG&A per user falls, but the old systems are growing as well. By the time the new systems get to 500,000 users and an SG&A of \$500/user, the old systems will have 1,000,000 users and an SG&A of only \$350/user, so they can continue to reduce their monthly charges and put pressure on the new competitors. At the end of year 5, with 300,000 users (and 300 base stations), things are even worse (as shown in slide 9, below). Their total investment has risen to \$550M (new base stations for growth) but according to the CTIA data, competition from the original systems has driven revenues down to \$43/user/month. Their revenues are still less than their SG&A and now they are paying at least 10% interest on the accumulating debt they have been taking on to pay salaries. They would have borrowed more than \$300M at (say) 10% interest, so they would actually be losing more than \$120M per year. Realistically, we should assume that they

are borrowing money for the new base stations as well (why would anyone invest in the shares of such a disaster?) but the numbers are so bad that it hardly matters.

The use of financial calculations makes it clear that the problems for new competitors were huge and continuing, and as strategists we could clearly see what would happen before it happened! The new companies that the FCC allowed in 1994 have never overcome the disadvantages of being smaller and paying more for their systems and spectrum.

5 years later things are actually worse

Balance Sheet YEAR 5 (300K users)		P&L	
Number of cells=	300	300K users at end of year 5 (an average of 270K during year 5)	
Inv @ \$1M/ cell	= \$300M	Rev/user = \$43/month	
25 MHz of spectrum	= 250M	270K users @ \$43/mo = \$139M	
Assets (cells & spectrum)	\$ 550M	Tot Expenses	\$262M
Shareholders equity	\$ 550M	SG&A (\$500/user)	~190M
Accumulated debt	\$ 300M	10% Depreciation	30M
		5% Amortization	12M
		Interest on debt	30M
		BT Earnings	-\$123M

They are still losing money on "operations" and are now paying interest on the money they have borrowed to pay for things like salaries, so their losses are actually increasing!

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Having explored the problems of creating new cellular competition in 1994, we will now return to the world of technology and our discussion of antennas and wavelength in the next few lectures.