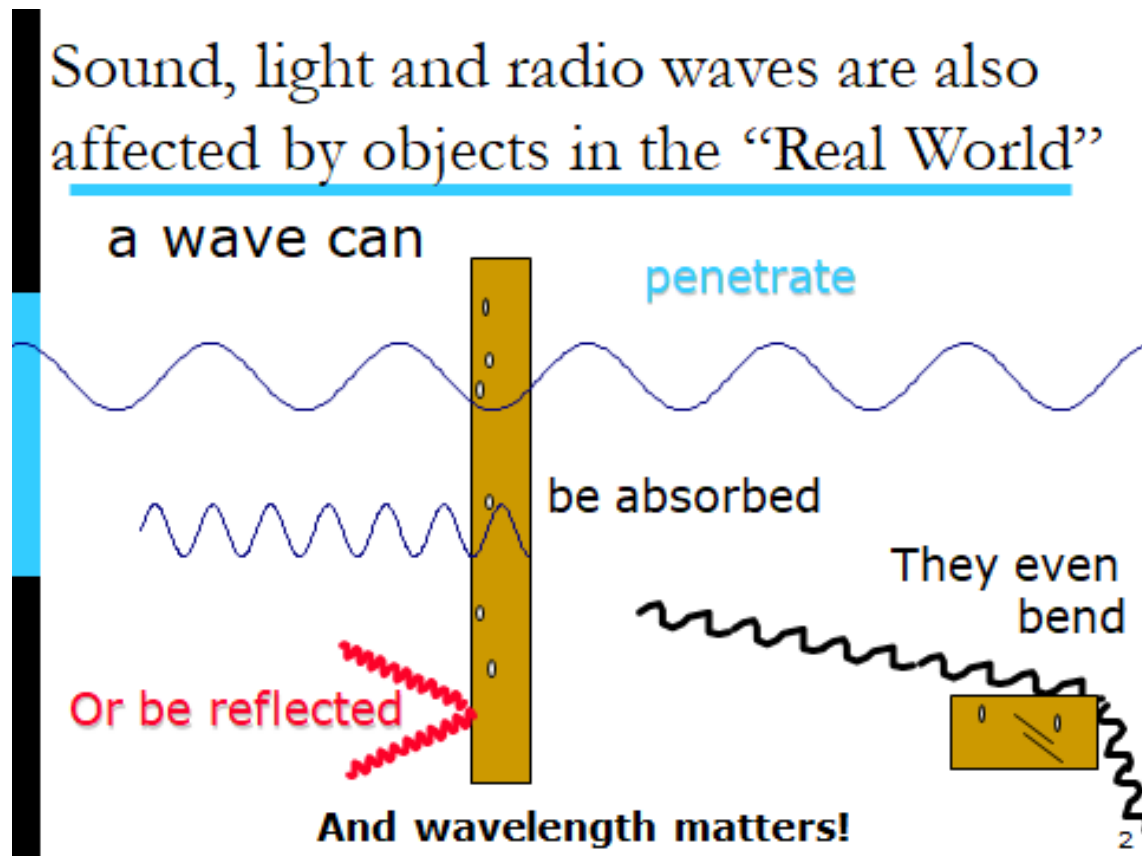


Lecture 13- Pre-lecture reading

Frequency, Wavelength and Coverage: Real World

So far, we have been discussing idealized “free space” environments without obstructions. Now let’s consider some real-world obstructions between the transmitter and the receiver. Depending on the wavelength and size of the obstruction, waves can pass through it, bounce off it, bend around it, or even be absorbed [slide 2]. Since we depend on the energy of the radio wave reaching the receiver, the real-world environment affects the performance of a radio system. We will see that different frequencies are affected in different ways by obstacles like buildings, hills, trees and rain or snow, so that must be considered in the choice of spectrum for a given purpose in a given environment.

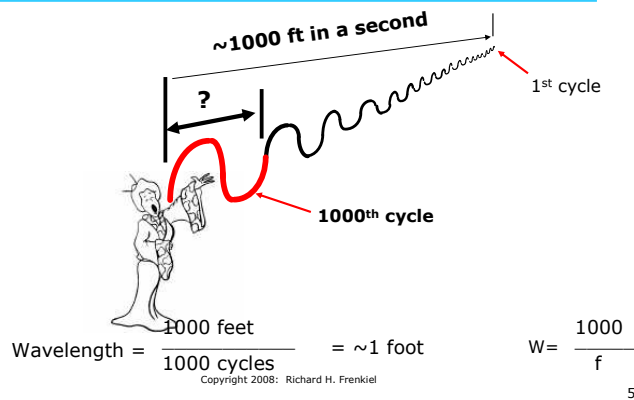


Analogy with Sound Waves

We cannot see or feel radio waves, so we begin with little intuition about how they behave. On the other hand, we have a good deal of experience with other waves, like sound waves and light waves. Sound waves are physical waves at very low frequencies, but their wavelengths can be similar to the radio frequencies we are considering (slide 3)

Let's look at the frequency we call "Soprano C" (two octaves above middle C), in this case produced by the voice of a singer [slide 5]. It has a frequency of about 1000 cycles per second, or 1000 Hz. The wave is moving away from the singer at about 1000 ft/sec, so one second later that first wavelength is 1000 feet away. We also know that the soprano's vibrating vocal chords have produced 1000 of these wavelengths in that same second, so we have 1000 wavelengths lined up in that 1000 feet. It's easy to see that each wavelength is about 1 foot long. Any wavelength can be easily calculated if we know the speed of the wave and the frequency being produced.

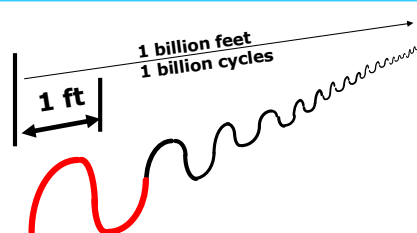
The wavelength of a sound wave at soprano C
(~1000 "cycles"/sec = 1000 Hertz)



5

Now let's consider a radio wave [slide 6]. It moves at the speed of light, which is about 1 billion feet per second (a million times faster than sound waves) but the frequencies we are interested in are also about a million times higher than sounds we can hear. Cellular uses frequencies of about 1 billion Hz (1 GHz), which is one million times higher than soprano C. Thus, the wavelengths of cellular radio and Soprano C sound are both about 1 foot.

The wavelength of radio at 1 GigaHertz



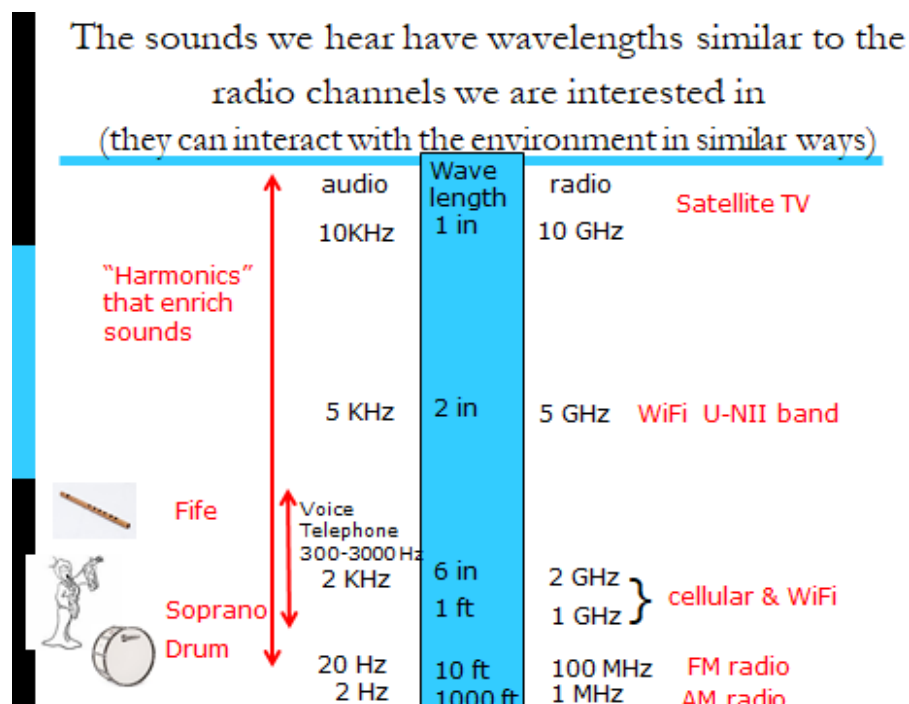
A million times faster than Soprano C; and a million times higher in frequency as well. Result? Same 1 ft wave

The radio waves we are talking about are similar in size to the audio waves— similar physical effects of environment?

Copyright 2008: Richard H. Frenkiel

6

In fact, the familiar radio waves we use for television, mobile radio, WiFi and direct satellite TV have the same range of wavelengths as the sound waves we hear (from about 1 inch for direct satellite TV at 10 GHz to 20 feet for VHF-TV channel 2 at 50 MHz). [see slide below]. Humans hear a range of 20 Hz to 20,000 Hertz, or wavelengths of a half inch to 50 feet. This is important because waves interact with the real world in ways that depend on the sizes of the wave and the sizes of the things they interact with, like walls and hills and leaves and even raindrops. Radio waves tend to interact with somewhat different objects than sound waves (they “see” objects that conduct electricity, like metals and things containing water), so the analogy to sound is not perfect, but our experience with sound can give us good intuition about how radio waves behave in the real world. As we look at the familiar effects of real objects on sound waves we are learning something about the behavior of radio waves in those same environments. Light waves (which are electromagnetic waves, like radio waves), are also useful in some analogies, but their wavelengths are extremely small so they are less instructive for our purposes than sound waves.



When a wavelength is much greater than the thickness of a solid obstruction, the wave tends to pass through the obstruction. We experience this when we hear the bass frequencies from a loud sound system in a passing car through the walls of our homes. The low frequency sound wave is many feet long, and the walls of our homes are only a few inches thick, so the low frequency sound passes through with little “loss.” High frequencies, like the treble from the same car system, have shorter wavelengths and bounce off or absorbed by the walls of our home, so we don’t hear them inside. Thus we hear the bass from a passing car but not the treble.

The colonial “fife and drum corps” (slide 5, below) can be used to compare the behaviors of low frequency waves that are many feet long (the drums) and high frequency waves that are inches long (the fifes).

Fifes and drums: very different wavelengths (inches and feet)

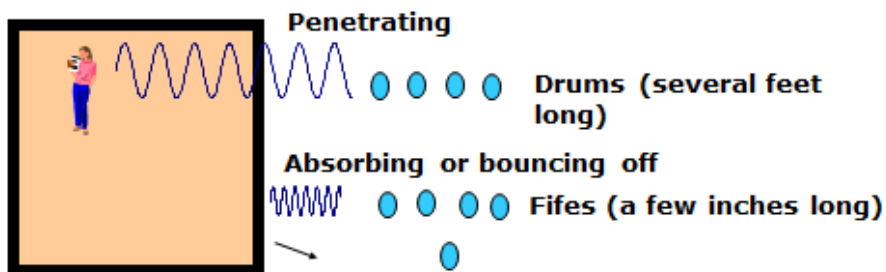


5

If we stand in the street as they pass, we hear both, but if we go inside, we hear the drums much better than the fifes. [slide 6] We hear the bass (wavelengths of several feet) through the walls, but not the higher frequencies.

Passing through and bouncing off walls

Long waves from the drums pass through walls
Short waves bounce off (or are absorbed)

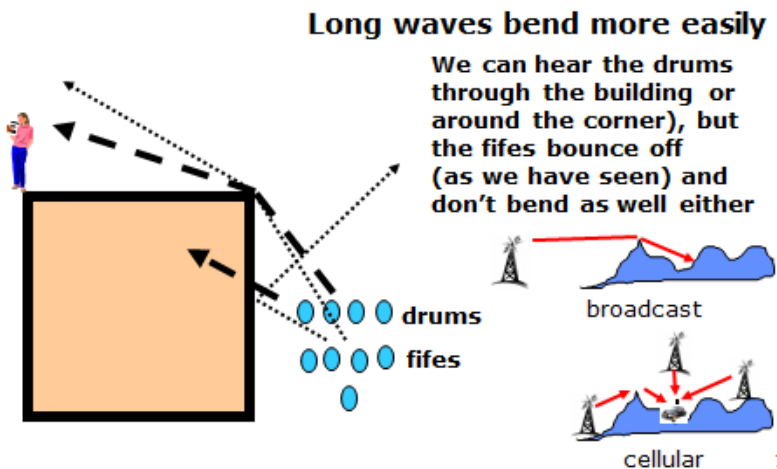


Is the wave much longer than the thickness of the wall? **What about "5G" millimeter waves?**

6

Diffraction (the bending of a wave around a corner) creates other possibilities. If we are outdoors listening to the fife and drum corps and we go around a the corner of a heavy building that stops even the drums from passing through, we still hear the drums better, because the longer waves “bend” around the edges of the building more easily than the high frequencies of the fifes [slide 7]. This also allows low frequency radio frequencies like AM or FM broadcast to bend over the tops of hills, so they provide better coverage in hilly terrain. Cellular frequencies do not bend over hills as well, but cellular systems have smaller coverage area than broadcast systems, and have many base stations that can provide coverage from different directions.

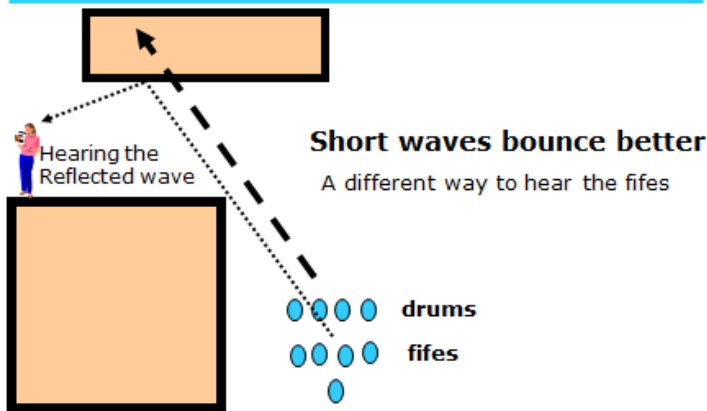
Bending around corners (diffraction)



On the other hand, higher frequencies tend to be reflected by walls, which creates a new path around that building (slide 8). The streets of an urban center may be better served by higher frequency signals that bounce off buildings and are “channeled” down streets, than by lower frequencies that must pass through many buildings to get to the same place. On the other hand, the inside of buildings will be served better by low frequencies. A powerful example of waves being reflected is sunlight (light waves are electromagnetic waves, just like radio waves, but they are many times higher in frequency, with wavelengths less than a millionth of a meter). We know that sunlight, with its tiny wavelength, will be completely blocked by walls and won't bend around corners very well, but the world around us is still visible. Sunlight reaches us by bouncing off all the things we can see (if light waves didn't bounce off all the objects around us, we couldn't see those objects). Wherever we walk, sunlight reaches us through myriad reflected pathways. In a complex environment, there is no perfect wavelength, but frequencies near 1 GHz seem to work pretty well in many environments.

Bouncing of objects is actually a good thing

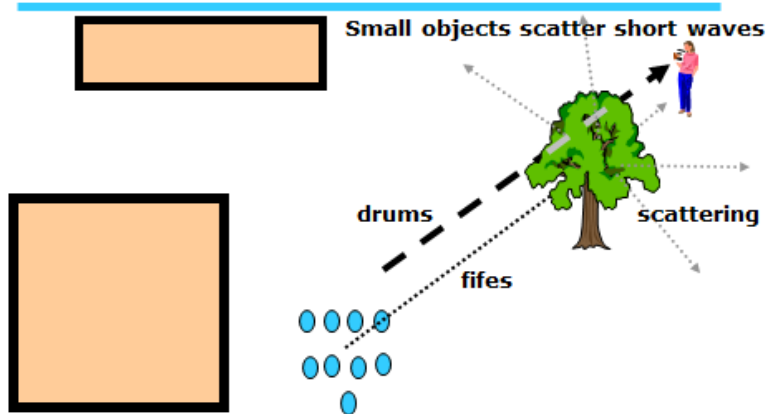
It fills the world with light and offers useful paths for radio



8

For high-frequency sounds (like a fife) or high-frequency radio waves with wavelengths of only an inch or two, the leaves of trees can also cause significant attenuation [slide 9]. Each leaf will scatter or absorb a little of the energy, so many millions of leaves will significantly scatter and attenuate the wave. Lower frequencies, on the other hand, have much longer waves and are relatively unaffected by foliage. This is why low frequency “jungle drums” can be heard through miles of rain forest, but a high frequency tone will not travel very far. For even higher frequencies, such as radio waves above 10 GHz, even raindrops and snowflakes can provide significant attenuation. They affect the frequencies used for satellite TV (10+ GHz) and would be much more of a problem for 5G “millimeter wave” frequencies.

Many small objects like leaves (especially wet leaves) can absorb and scatter small waves like 5 GHz (2.5 inch waves)
(long waves are less affected)



Raindrops can scatter satellite radio (12-18 GHz) (1 inch waves) and more so for “5G” millimeter waves

9

Choosing the right frequency for some example purposes

Having reviewed a variety of factors that could influence system design, we will now apply that understanding to some practical problems. We will find, of course, that the best frequencies might not be available. Lower frequencies were assigned decades ago, though in some cases earlier frequency assignments have been changed. The reassignment of UHF-TV spectrum to cellular systems is the best example of a major reassignment with important results. In general, however, new spectrum assignments have involved increasingly higher frequencies, sometimes with disadvantages for the new user. Such disadvantages might limit the performance or increase the cost of a system, and when a competing system is given less desirable frequencies it creates a competitive problem. We saw that in the last lecture, when new cellular competitors were given spectrum at 2 GHz. It reduced the radius of startup cells by 30%, which doubled the cost of their systems at startup. Disadvantages in competitive situations are always important.

The earliest uses for spectrum were broadcast TV and radio, and they got the lower frequencies that were actually the best match to their needs. In particular, TV was a problem because it required long range with wide channels, and had to contend with urban buildings and terrain issues like hills and foliage. Even with low frequencies it often required transmitters with 50 Kilowatts of power (or more). A simple antenna at the TV set might not work very well at the most distant locations, particularly because the channels were widely spread over such different frequencies (from 50 MHz to 200 MHz for VHF-TV and then to 800 MHz for UHF-TV. Fortunately, large and complex rooftop antennas could be both directive and multi-band.



A police radio system needed a smaller but significant range and tended to use a single base station near the dispatcher at the headquarters building. It had to work in a variety of terrains, including hills, woodland, and cities, so lower frequencies were preferred. Antennas were generally mounted on vehicles, so a quarter-wave whip several feet long was not a problem. Frequencies near 100-200 MHz were preferred.

Car phones were like police phones, powered by car batteries with antennas mounted on the roof of the car. When they became pocket phones, they needed to use less power (small batteries). Small antennas were easier to use on a hand-held cellphone, but they also needed to achieve several-mile range and they were used inside buildings, so larger antennas offered better coverage, so a compromise was beneficial.

Frequencies from 700MHz to 2 GHz were used, with the lower frequencies being more desirable at start-up, and inside buildings. Frequencies like 5 GHz would have posed significant problems at startup.

WiFi didn't need much range, but 100-300 feet was desirable for convenient access. In fact, longer range usage would have been a problem, as it was with Citizen's Band Radio—it would have limited all-important reuse and download capacity. Since WiFi is now used by cellphones, antennas can't be very large and power is limited, but a fairly wide range of frequencies could be used. What WiFi did need was a lot of spectrum for downloading large amount of information at high speeds. The ISM bands at 900 MHz and 2 GHz were a good option, and then the huge band allocated by the FCC at 5 GHz became the primary band for WiFi.

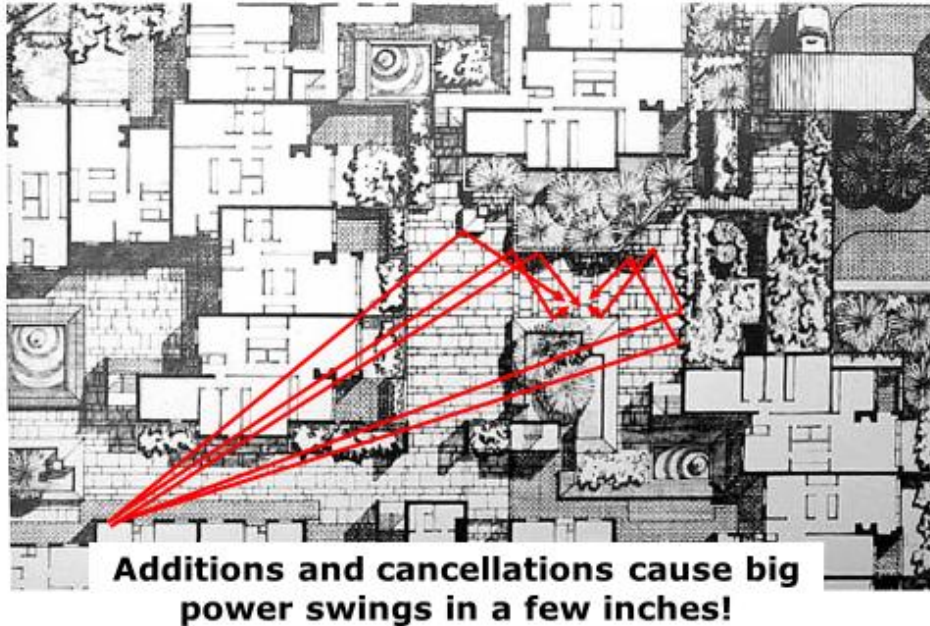
Satellite TV requires long range (25,000 miles) because of the high orbits of geosynchronous satellites, and they use very wide channels. On the positive side, they have a (generally) unobstructed path from satellite to rooftop, and they transmit only in one direction. Both the geosynchronous satellite and the home have the advantage of fixed positions, so very directive antennas can be used, and the satellite can use a large solar array to generate significant power for their transmitters. As a result, these systems are able to operate at high frequencies like 12 GHz. This was not an ideal frequency, since TV quality can be affected by heavy rain or snow, and rooftop antennas have to be carefully placed to avoid obstacles like hills and trees, but as with WiFi, that's where the available spectrum was. The smaller dish antenna on rooftops was an advantage.

In general, the “real world” delivers much less radio energy than “free space”. The “expanding sphere” in free space led to a “square law” for path loss (our antenna receives $1/4^{\text{th}}$ the power when we double the distance ($p \sim 1/d^2$). Obstructions of many kinds in the “real world” cause much larger losses. For “real world” radio systems we generally assume a “fourth power law” for path loss (our antenna receives $1/16^{\text{th}}$ the power when we double the distance ($p \sim 1/d^4$). Higher frequencies are usually more affected by real world losses (e.g., leaf scatter) as well as by the smaller antennas we have discussed.

In this and the previous lecture, we have considered how antennas and real-world conditions affect the coverage provided by radio systems, and why different frequencies may be better for different purposes. We sometimes refer to these as “technology” lectures, but they are more about the reality of coverage than they are about cellular technology. Radio waves expand into space and interact with the world of hills, and buildings and trees, and our technology can't change the world we operate in.

In fact, there is another aspect of “real world” radio coverage that makes system design even more difficult and causes a special type of noise and interference. As shown on slide 11, below, there are many paths of different lengths between transmitter and receiver, and they add together to produce the radio signal that we receive.

And another “real world” problem for designers
The signal arrives as “rays” by many paths with
different lengths



11

Sometimes they add together “constructively” to produce a stronger signal and sometimes they “cancel” each other and can dramatically reduce the signal, as shown on slide 12. These cancellations are called “Rayleigh fades” as shown at the bottom of slide 12. We see the resulting signal strength variations when those many signals, from different directions, come together at a cellphone or base station antenna. We also see that the signal is much stronger than the interference on average but can actually be weaker than the interference for few milliseconds during a Rayleigh fade.

This causes a “click” that may be repeated every half-wavelength (many times a second, depending on how fast we are moving). The result can be a fast clicking sound like “popcorn.” Rayleigh fading limits the voice quality we experience and leads to a requirement for more power and greater re-use distance than would otherwise be needed (to minimize the number and intensity of audible clicks). The early analog cellular systems used 2-antenna “diversity” receivers at the base stations (the receivers could instantaneously select the better antenna to avoid much of the worst effects of Rayleigh fading, or even add the signals in-phase for the best performance). These techniques were not used in the cellphones for cost reasons, and because the antennas couldn’t be sufficiently separated on a cellphone.

Adding many waves that have traveled different distances causes “Rayleigh fading”
(sharp variations in power on a few inches)



In “phase”
addition

>

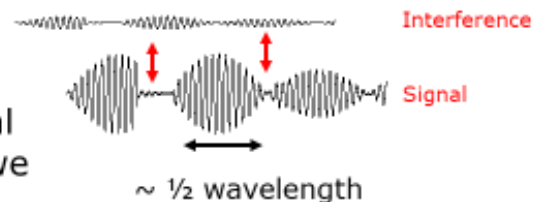


Out of “phase”
cancellation

>



Signal below interference causes “click”



The phase changes in inches because the cell phone is moving, so the signal has sharp and frequent “fades” that we Hear as “clicks”

12

In summary, sound or light or radio waves have energy that is spread over an expanding sphere, so even in “free space” the energy received by our eyes, ears, or radio antennas is reduced by a factor of 4 (6 dB) each time the distance from the source is doubled. Larger antennas can gather more power, but they are directive. Thus, they are useful for point-to-point communications such as direct satellite TV, but for mobile devices we use omni-directional antennas like the quarter-wave whip, which are proportional in size to wavelength. As a result, the antennas used for higher frequencies are smaller and absorb less energy, so range is reduced. Lower frequencies inherently provide better range. A system using 30 GHz frequencies could benefit from having many tiny antennas with complex phase shifting that (in effect) “pointed” the antenna array at the strongest signal.

In real-world environments, obstructions further reduce the energy of the wave, and signals reach us along different paths. Depending on wavelength and the size of the obstruction, waves can pass through walls or bounce off them or be absorbed, bend around corners, and even be scattered by leaves and raindrops. They can also be absorbed by objects of a certain “resonant” size. Thus, the best frequency for a given situation will depend on the type of system and the environment.

In general, lower frequencies will be better for applications needing long range, such as military and broadcast systems that cover large areas and rely on a single base station. The longer waves pass through walls more easily, are less affected by foliage, hills and small objects in the environment, and they use larger antennas that inherently capture more energy. They require antennas several feet in length, but these are not a problem

in homes and on vehicles. The best TV coverage (before broadcast TV was replaced by cable) was provided by the lower VHF channels between 50 MHz and 100 MHz. The UHF-TV channels between 500 MHz and 1 GHz provided much poorer range. (The upper ones that went to cellular were good for cellular but poor for TV.)

For hand-held devices like cell phones, range is important for larger cells at start-up (but not as important as for broadcast systems, since we can use a number of cells in our coverage area. This means we want lower frequencies, but smaller antennas are also desirable on cell phones. As discussed, cellular systems at 900 MHz or 2 GHz use an antenna 1.5-3 inches long, which is a good size for a pocket phone. It receives less power than a 100 MHz antenna, but enough to allow start-up cells several miles in radius. These frequencies are also low enough that they are not affected by foliage or rain.

A cellular system at 5-10 GHz would have very poor range. Its very small antennas would capture less energy, while the waves would be more attenuated by walls, hills and trees, so start-up cells would be quite small. Strategic planners who are unaware of these effects can make serious errors. In 1991, before buying McCaw's cellular systems, AT&T wasted about \$100M on early planning and design for a cellular system that would have used 6 GHz channels, because their strategists didn't understand the economic penalties of working at such high frequencies.

WiFi, as we will discuss later, needs a lot of spectrum because of the high-speed Internet information it carries, and it only needs up to a few hundred feet of range, so higher frequencies like 5 GHz are not a problem. WiFi started in the 2 GHz ISM bands with many other devices (including later generation cordless phones), but recognizing huge potential of wireless access to the Internet, the FCC later made huge new frequency bands exclusively available for WiFi at 5 GHz.

Direct satellite TV also needs a lot of spectrum, which was available at 10 GHz, but it also needs range (the satellites are 25,000 miles above the earth). Fortunately, a fixed, very directive antenna on the roof can be aimed at a "stationary" satellite (which can also use a very directive transmitting antenna). This is like a flashlight pointing toward a telescope, and it allows good performance even at these very high frequencies and long range, as long as there is a clear "line-of-sight" between the rooftop and the satellite. Positioning of the rooftop antennas is therefore important. Foliage, and even heavy rain, can cause damaging loss for satellite systems at 10 GHz.

We can see that designing radio systems to provide good service at attractive prices is quite a complex problem, but a little knowledge and intuition drawn from sound and light can cause us to ask good question and see potential costs and quality problems. These propagation impairments affect not only range; they affect information capacity as well. In previous lectures we have mentioned that radio channels in mobile radio systems have been limited to an information rate of about 1.5 bits/second/Hz (the 30 KHz cellular channel could carry about 45,000 bits/second). According to "Shannon's Law" (a foundation of information theory) the capacity of a radio channel depends on both the channel bandwidth and the signal-to-noise ratio, which could allow many more than 1.5 bits/second/Hz if the channel were free of noise and interference. In our "real world", however, we do have noise and interference, and impairments like Rayleigh fading. Near the base station the channel might support more than 1.5 bits/second/Hz, but at startup (for example) we want maximum range (so we accept noise) and throughout growth we want minimum channel-reuse distance (so we accept interference), and we are always experiencing fading. To control cost and maximize capacity we must live

with channels that are “just good enough.” We accept 1.5 bits/second/Hz because it leads to the best overall design.

As discussed earlier and again in the next lecture, this condition continued in 2G digital cellular systems. The 3x increase in voice capacity for 2G systems was achieved through voice compression (needing only 15,000 bits/second for good quality voice, compared to 64,000 bits/second used in the telephone network). The channel itself was still delivering only 1.5 bits/second/Hz. During the planning for 3G systems, however, the technological possibilities were beginning to improve. Some improvements were accomplished through digital coding and others through elaborate antenna arrays and complex signal processing that could use those many “rays” to maximize signals and minimize interference. New ideas and improved equipment led to improving standards (3G>4G>LTE). Somewhat exaggerated performance claims for these new standards led to unrealistic expectations of capacity for smart phone service (as they had for 2G standards), but a 5x improvement (to 7.5 bits/second/Hz) was finally achieved.

It remains true that smaller cells increase capacity as they have for past cellular technologies, but the comfortable understanding of individual channels in individual cells serving individual users is no longer realistic. Today, advances in cloud and edge computing allow information to be carried for each user as a cloud of radio signals, involving multiple base stations. Both access technology and network architecture have made significant advances during the evolution from 3G and 4G/LTE. These advances are well beyond what can be explained in this course but we will attempt to provide a high-level overview in a future lecture.

The performance that can be achieved is also dependent on the type of data and the real-world environment in which the system operates, so the capacity of a system has become more difficult to predict before installation and can be difficult to measure even after a system is in operation. Demonstrations involving particular data in selected environments can show much higher data rates than might be achieved in a real system, but the 7.5 bits/second/Hz we have reported is based on measurements in an operating system and is probably realistic. The evolution from 3G to 4G/LTE has been a dramatic technological success that has changed the world of radio communications, but as we will see, the capacity that was needed has been even greater than the technology could provide.

As we will see in Lecture 14, the capacity increase needed for Internet access by smart phones was much larger than the 5x improvement actually achieved by 3G/4G/LTE technology. The demand for information has now increased by 100x (compared to 2G), so the service providers have had to make huge additional investments in additional base stations and spectrum to meet the demand, as we will see in subsequent lectures.