Pacific Island Schools Connectivity, Education, and Solar Project

Fundamentals of telecommunications

The Abdus Salam International Centre for Theoretical Physics

Friday, July 27, 2012

Will cover basic concepts of telecommunication systems

Goals

To present the basics concepts of telecommunication systems with focus on digital and wireless, and the most important features of the propagation of telecommunication signals

Basic Concepts

- Signal
  - Analog, Digital, Random
- Sampling
- Bandwidth
- Spectrum
- Noise
- Interference
- Channel Capacity
- BER
- Modulation
- Multiplexing
- Duplexing

Telecommunication Signals

Telecommunication signals are variation over ***time*** of voltages, currents or light levels that carry information.

For analog signals, these variations are directly proportional to some physical variable like sound, light, temperature, wind speed, etc.

The information can also be transmitted by digital signals, that will have only two values, a digital ***one*** and a digital ***zero***.

Telecommunication Signals: Features

Amplitude is the maximum excursion from the zero value, and is generally measured in volts (**V**) or amps (**A**).

For *periodic* signals, the number of repetitions of the signal in one second is called the *frequency* of the signal, measured in **H**z and its multiples.

The *power* of an electric signal is given by the product of its voltage and current and is measured in watts (**W**).

The *energy* of the signal is give by the product power over the time considered and is measured in joules (**J**), and also in **Wh**, with its multiple, the **kWh** (kilo watt hour) most commonly used.

Telecommunication Signals

Any analog signal can be converted into a digital signal by appropriately ***sampling*** it.

The sampling frequency must be at least twice the maximum frequency present in the signal in order to carry ***all*** the information contained in it.

Random signal are the ones that are unpredictable and can be described only by statistical means.

Noise is a typical random signal, described by its mean power and frequency distribution.

Examples of analog signals are voice and video, examples of digital signals are written text and the morse code used in telegraphy. Any analog signal can be converted to a digital one containing the same information. Digital signals are more robust and easier to store and transport, that is why nowadays digital signals prevail

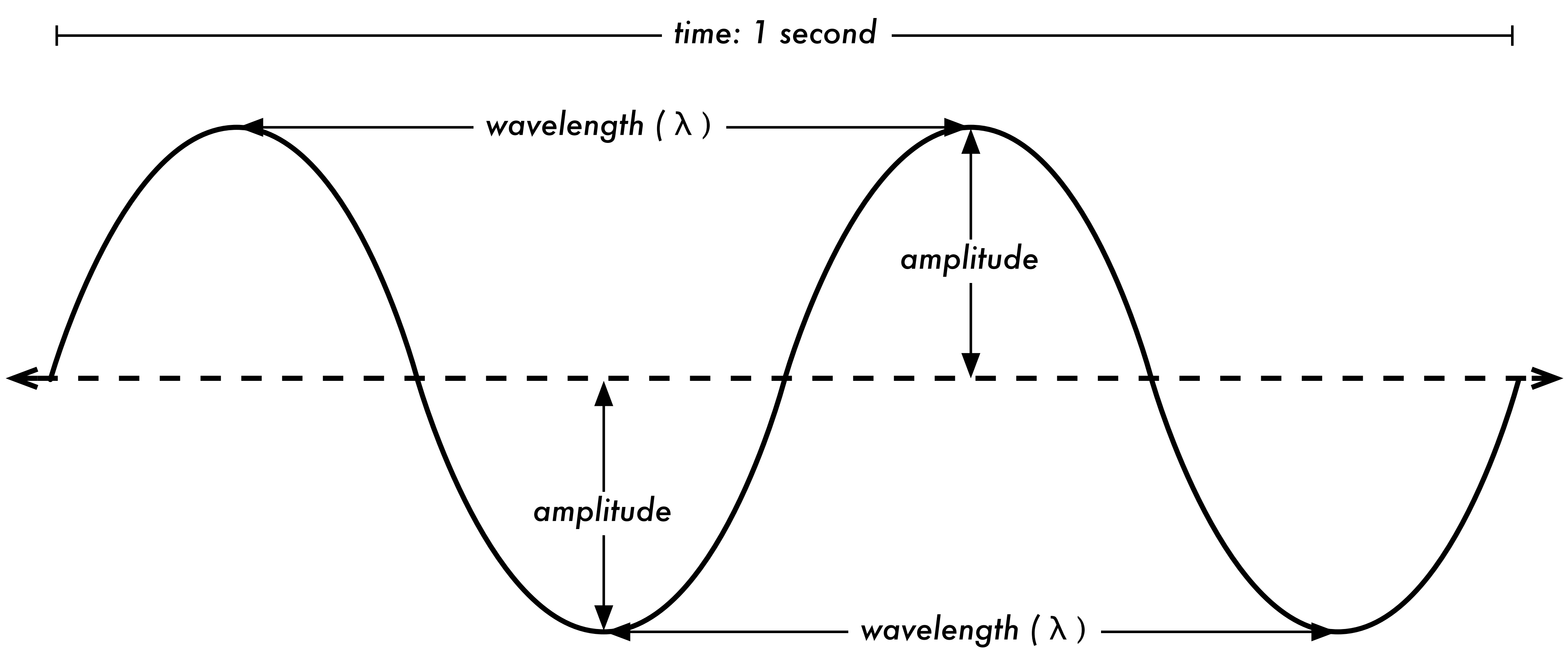
Quick review of unit prefixes

pico-	10^{-12}	1/1000000000000	p
nano-	10^{-9}	1/1000000000	n
micro-	10^{-6}	1/1000000	µ
milli-	10^{-3}	1/1000	m
centi-	10^{-2}	1/100	c
kilo-	10^{3}	1 000	k
mega-	10^{6}	1 000 000	M
giga-	10^{9}	1 000 000 000	G

In physics, math, and engineering, we often express numbers by powers of ten. We will meet these terms again, e.g. in giga-Hertz (GHz), centi-meters (cm), micro-seconds (µs), and so on.

Example of signals: Electromagnetic Waves

- Characteristic wavelength, frequency, and amplitude
- No need for a carrier medium
- Examples: light, X-rays and radio waves



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The wavelength (sometimes referred to as ***lambda***, **λ**) is the distance measured from a point on one wave to the equivalent part of the next, for example from the top of one peak to the next. The frequency is the number of whole waves that pass a fixed point in a period of time.

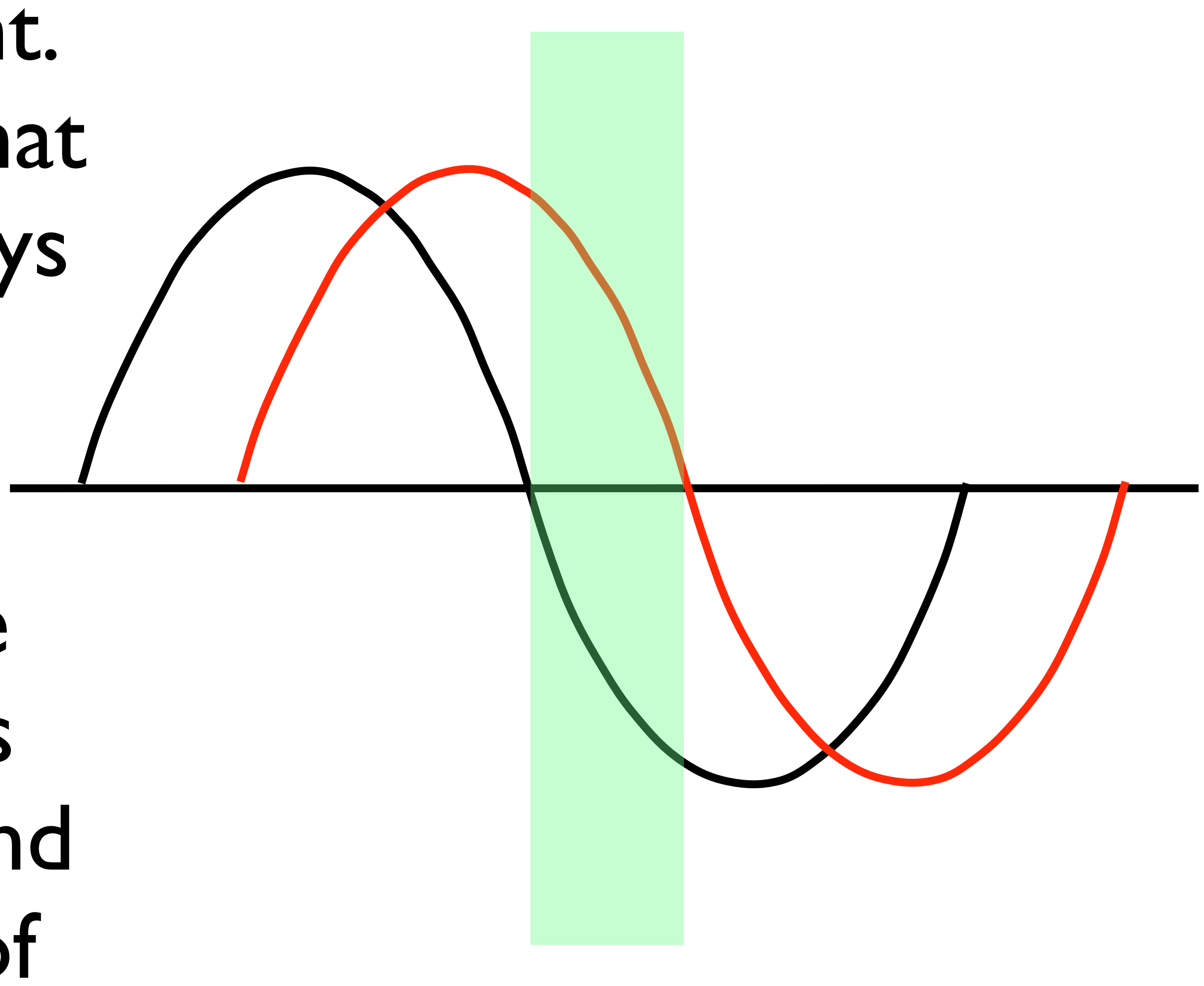
Waves also have a property called ***amplitude***. This is the distance from the center of the wave to the extreme of one of its peaks, and can be thought of as the "height" of a water wave.

Unlike waves in water, electromagnetic waves require no medium to carry them through space. It may be said that the media that oscillates is the electromagnetic field.

Phase

The **phase** of a wave is the fraction of a cycle that the wave is offset from a reference point. It is a relative measurement that can be express in different ways (radians, cycles, degrees, percentage).

Two waves that have the same frequency and different phases have a **phase difference**, and the waves are said to be out of phase with each other.



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from Wikipedia http://en.wikipedia.org/wiki/Phase_(waves)

A phase difference is analogous to two athletes running around a race track at the same speed and direction but starting at different positions on the track. They pass a point at different instants in time. But the time difference (phase difference) between them is a constant - same for every pass since they are at the same speed and in the same direction. If they were at different speeds (different frequencies), the phase difference is undefined and would only reflect different starting positions.

Java applet for a demo: http://phy.hk/wiki/englishhtm/phase.htm

Interference (constructive and destructive) will be explained in the next slide using the concept of phase difference between the interfering waves.

Wavelength and Frequency

$$c = f * \lambda$$

c = speed (meters / second)

f = frequency (cycles per second, or Hz)

λ = wavelength (meters)

If a wave on water travels at one meter per second, and it oscillates five times per second, then each wave will be twenty centimeters long:

```
1 meter/second = 5 cycles/second * λ
λ = 1 / 5 meters
λ = 0.2 meters = 20 cm
```


A wave has a certain ***speed***, ***frequency***, and ***wavelength***. These are connected by a simple relation:

Speed = Frequency * Wavelength

The wavelength (sometimes referred to as ***lambda***, λ) is the distance measured from a point on one wave to the equivalent part of the next, for example from the top of one peak to the next. The frequency is the number of whole waves that pass a fixed point in a period of time. Speed is measured in meters/second, frequency is measured in cycles per second (or Hertz, abbreviated ***Hz***), and wavelength is measured in meters.

Wavelength and Frequency

Since the speed of light is approximately 3×10^8 m/s, we can calculate the wavelength for a given frequency.

Let us take the example of the frequency of 802.11b/g wireless networking:

```
f = 2.4 GHz
  = 2,400,000,000 cycles / second

wavelength (λ) = c / f
               = 3 * 10^8 m/s / 2.4 * 10^9 s^-1
               = 1.25 * 10^-1 m
               = 12.5 cm
```

Therefore, the wavelength of 802.11b/g WiFi is about ***12.5 cm***.

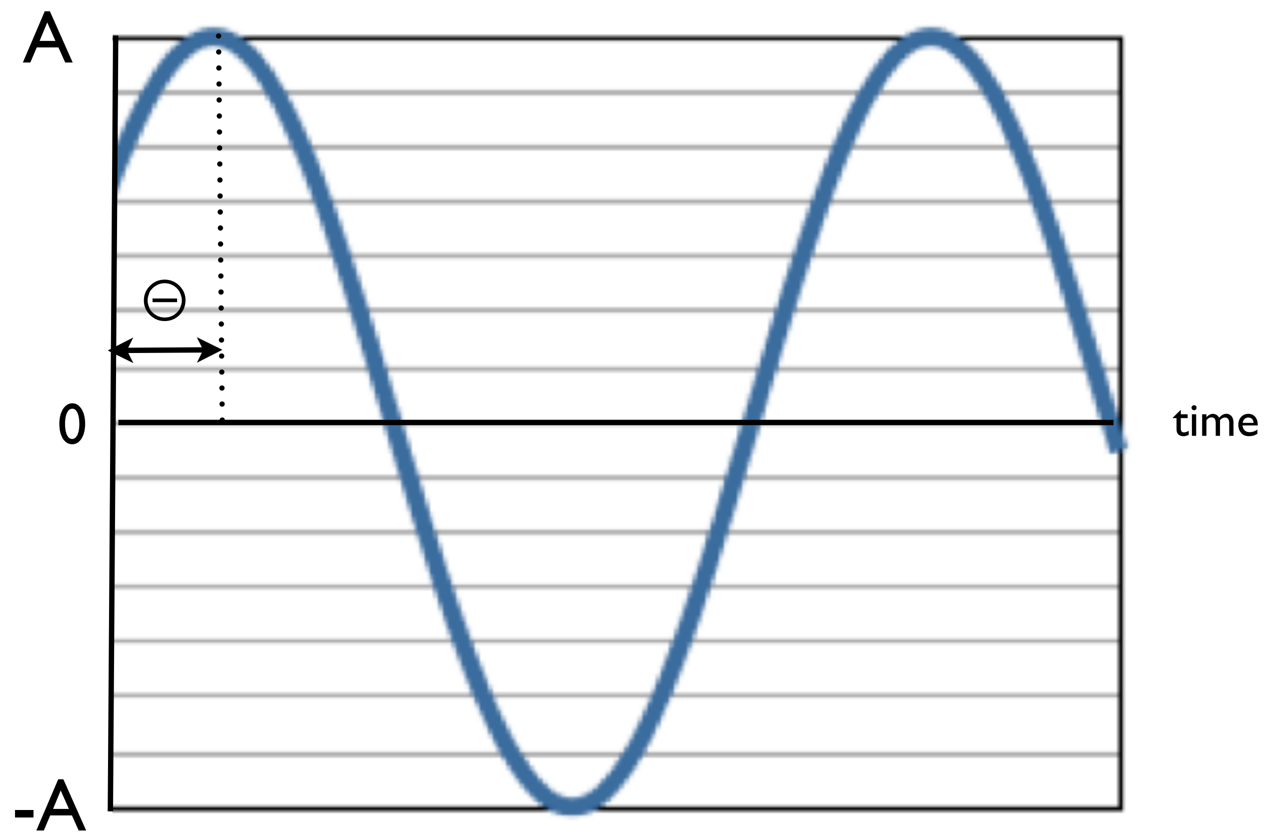
There are many more frequencies used in WiFi networking: one possible range spans over 85 MHz, starting at 2400 MHz and ending at 2485 MHz (but note that the ending value may be different in different countries).

What is the wavelength of 5.3GHz 802.11a?

$\lambda = 3 * 10^8 / 5.3 * 10^9 = 5.66$ cm

Sinusoidal Signal

$$v(t)= A\cos(wt - \Theta)$$



A = Amplitude, volts

w = 2*πf, angular frequency in radians

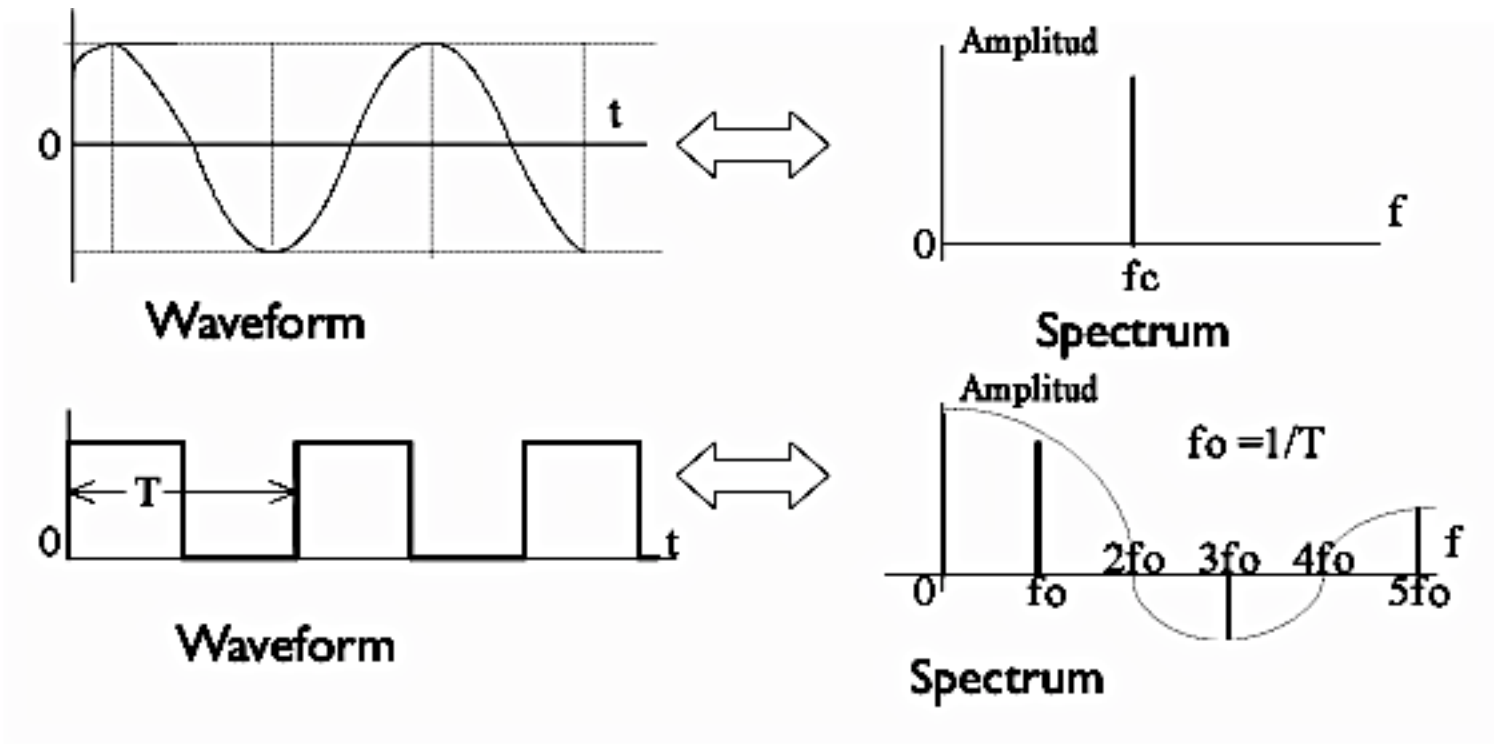
f = frequency in Hz

T = period in seconds, T= 1/f

Θ= Phase in degrees or radians

The sinusoidal signal is very important and can be expressed by a simple mathematical formula.
It contains a single frequency.
The phase is the offset from zero of the signal, when the offset is 90° we can also express the signal as v(t)=A*sin (w t)

Signals and Spectra



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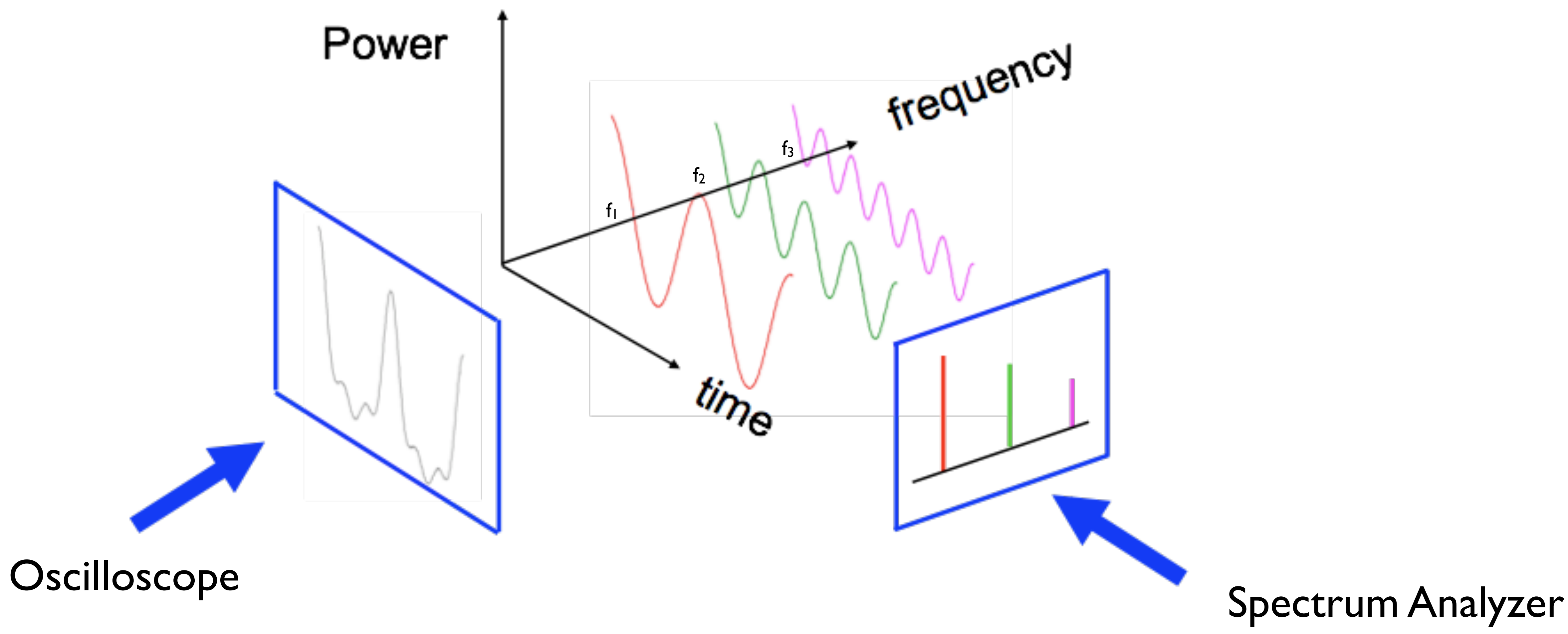
A signal can be characterized by its behavior over time or by its frequency components, which constitute its spectrum.
Any periodic signal is composed of many sinusoidal components, all of them multiples of the fundamental frequency, which is the inverse of the period of the signal.

Spectrum of a signal



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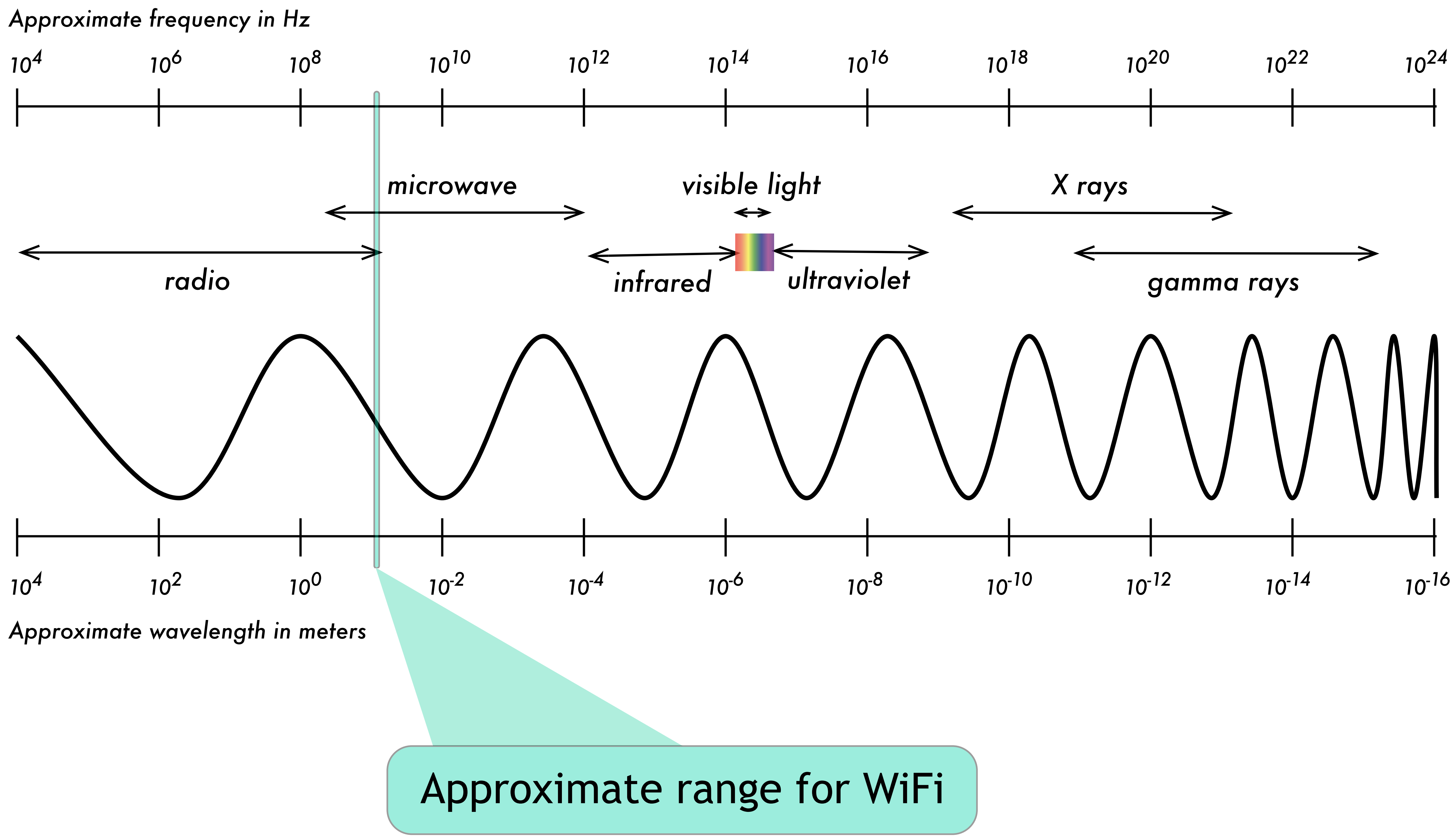
The graph shows that we can look at a signal from the perspective of its evolution over time, or we can look at it from the perspective of its frequency component, when we look at it from this perspective, we are dealing with the spectrum of the signal.
The spectrum distribution relays very important information about a the signal and allows for the intuitive understanding of the concept of filtering electrical signals.
In the example shown, the signal is formed by the superposition of 3 sinusoidal components of frequency f_1,f_2 and f_3.
If pass this signal through a device that will remove f_2 and f_3, the output is a pure sinusoidal with the f1 frequency. We call this operation "**Low Pass filterin**g" because it removes the higher frequencies.
Conversely, we can apply the signal to a "**High Pass Filte**r", a device that will remove f_1 and f_2 leaving only a sinusoidal signal at the f_3 frequency.
Other combinations are possible, giving rise to a variety of filters.
No physical device can transmit all the infinite frequencies of the electromagnetic spectrum, so it will always perform some kind of filtering in the signal that goes through it.
The bandwidth of a signal is the difference between the highest and the lowest frequency that it contains and is expressed in Hz.

Electromagnetic Spectrum



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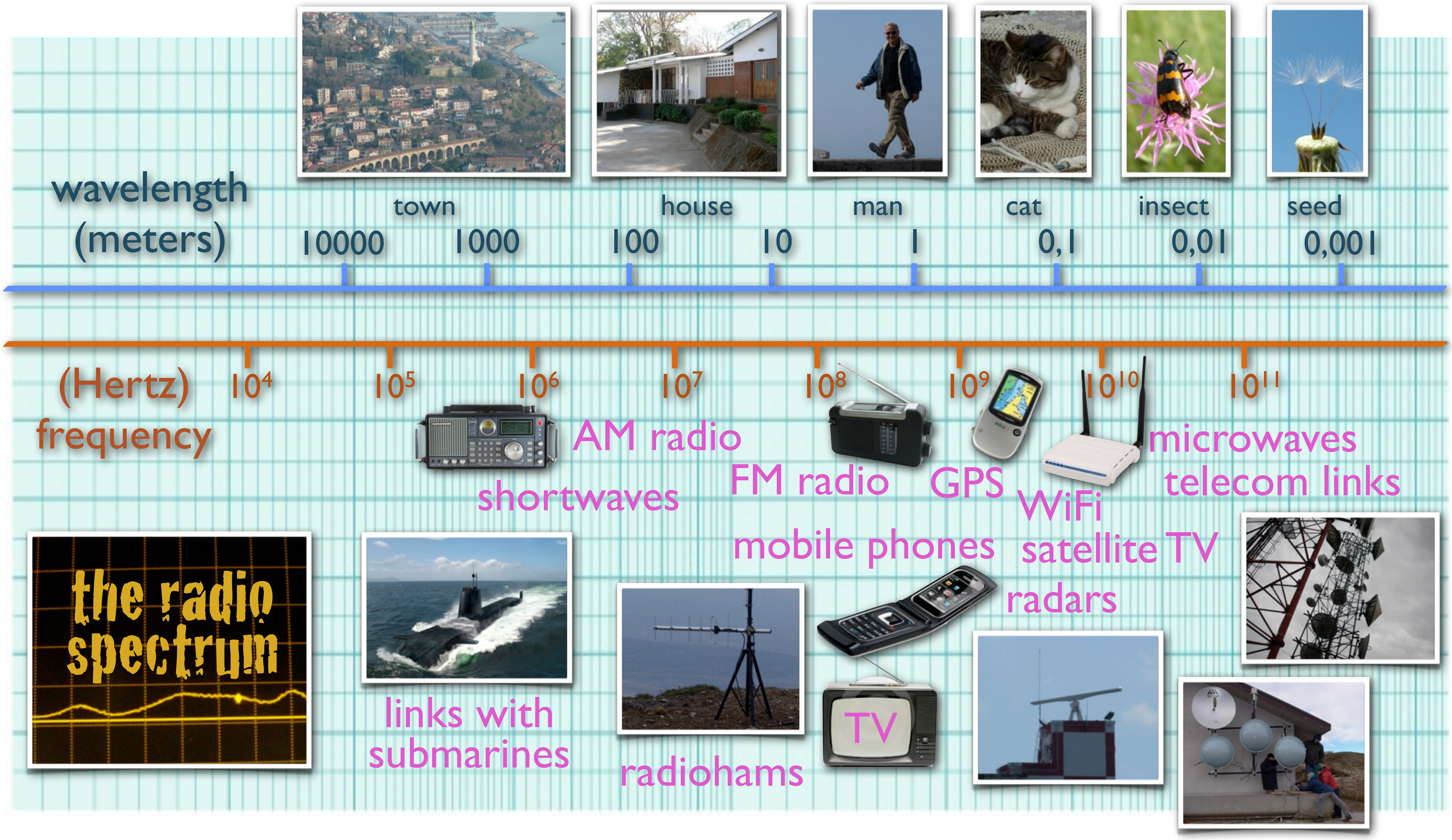
This picture represents the entire electromagnetic spectrum. It goes all the way from very low frequency radio waves on the left, to very high frequency X-rays and gamma rays on the right.

In the middle, there's a very small region that represents visible light. In the scope of the entire electromagnetic spectrum, the range of frequencies that we can actually perceive with our eyes is very small. You can see on either side of visible light is infrared and ultraviolet.

But the area that we are interested in is the very narrow range of frequencies used by WiFi equipment. That is the very thin sliver at the low end of the microwave range.

Perspective



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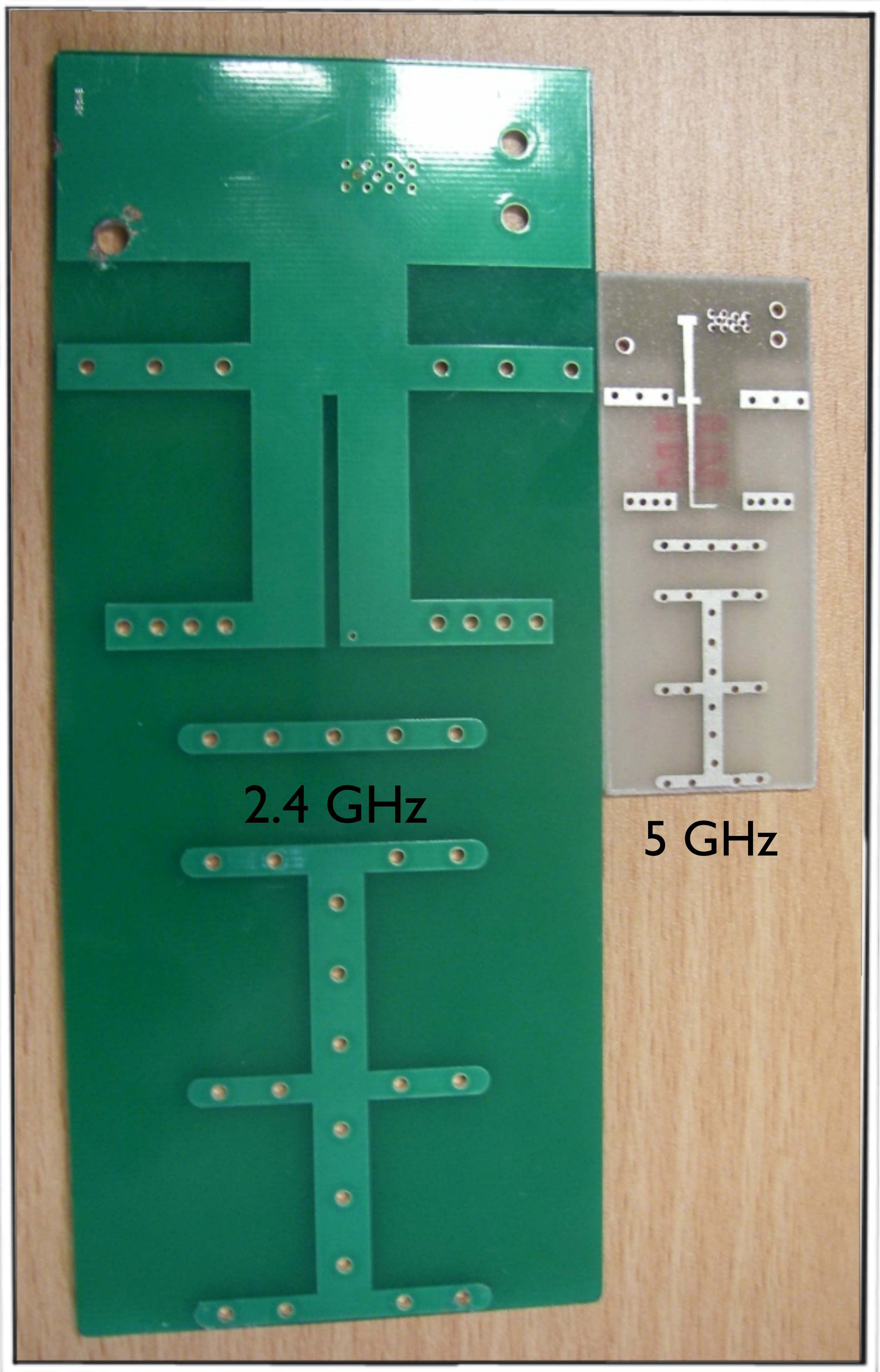
This picture represents some of the many different usages of the e.m. spectrum, from low frequency radio up to microwaves.

E.m. communications with **submarines** are forced to use very low e.m. frequencies, because of the difficulties of propagation of higher frequency RF signals under water. Most of the other usages are concentrated on higher frequencies, because of the wider capacity available there (more channels and more data per channel). Examples are:

shortwaves (international AM broadcast, maritime communications, radio amateurs HF bands, etc.): from 1 to 30 MHz
FM radio: from 88 to 108 MHz
TV broadcast: VHF channels in many bands from 40 to 250 MHz; UHF channels in many bands from 470 to 885 MHz (depending from the country)
VHF and UHF **radio ham** bands: around 140-150 and 440-450 MHz, together with many other users (services, security, police, etc...)
mobile phones: 850, 900, 1800, 1900 and 2100 MHz for GSM and CDMA cellular networks;
GPS: 1227 and 1575 MHz
WiFi: 2400-2485 MHz and 4915-5825 MHz (depending from the country). See *http://en.wikipedia.org/wiki/List_of_WLAN_channels* for details.
radars: common bands for radars are: L band (1–2 GHz), S band (2–4 GHz), C band (4–8 GHz), X band (8–12 GHz) but others are also used.
satellite TV: C-band (4–8 GHz) and Ku-band (12–18 GHz)
microwave telecom links: for example in the United States, the band 38.6 - 40.0 GHz is used for licensed high-speed microwave data links, and the 60 GHz band can be used for unlicensed short range data links with data throughputs up to 2.5 Gbit/s. The 71-76, 81-86 and 92–95 GHz bands are also used for point-to-point high-bandwidth communication links.



WiFi frequencies and wavelengths

Standard	Frequency	Wavelength
802.11 b/g/n	2.4 GHz	12.5 cm
802.11 a/n	5.x GHz	5 to 6 cm

This photo shows two Yagi antennas made from PC-board materials. The Yagi (sometimes referred also as Yagi-Uda, from the names of the two inventors) is one of the many designs for antennas.

The antenna on the left is designed to work at 2.4 GHz, while the antenna on the right works for 5 GHz. The two antennas have similar characteristics and gain at their respective frequencies.

You may notice that the ratio of the typical dimensions of the two antennas is the inverse ratio of the two frequencies:

5000:2400 = 12,5 : 6 = circa 2

It's almost always true that antennas of comparable characteristics at 2.4 and 5 GHz have this same dimensional ratio of 2, i.e. a 5GHz antenna is half the size of a 2.4GHz antenna (with approx. the same gain).

Communication System

The basic communication system is formed by a transmitter TX, a communication channel and a receiver RX

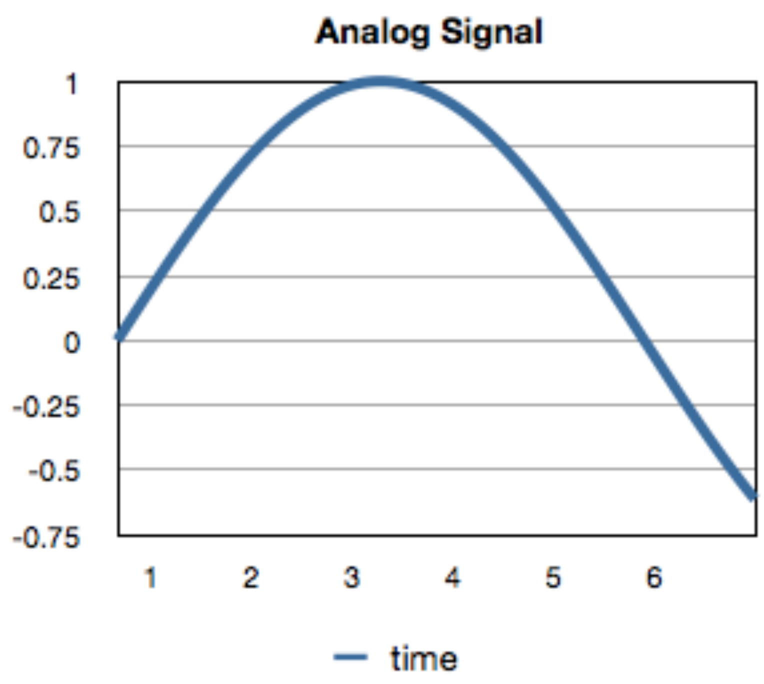
The Transmitter injects a signal into the channel that delivers it to the receiver.
The receiver must recover the information contained in the receiver signal despite the limitations introduced by the channel.

The channel can be a physical one, like a copper cable and an optical fiber, or simply air or even vacuum that transmits electromagnetic waves.

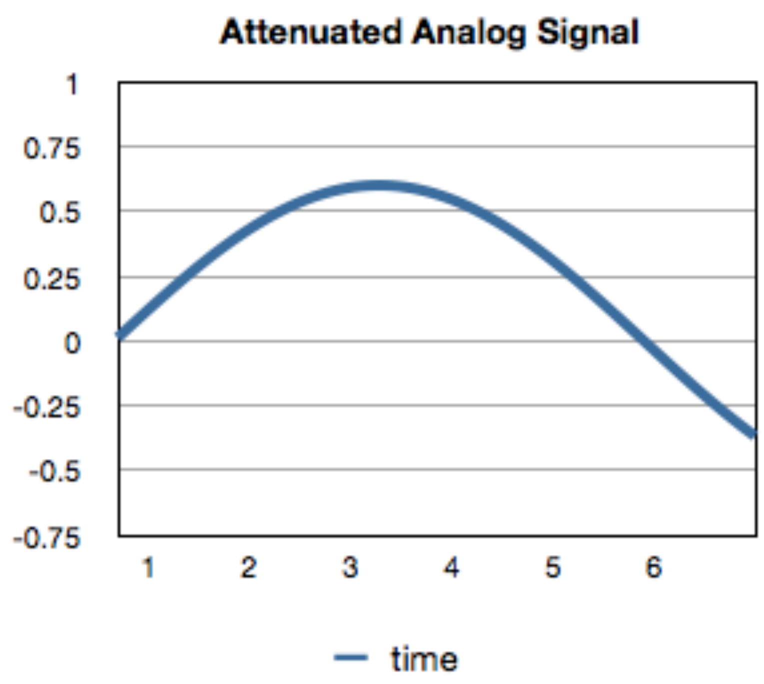
Any channel is subject to some kind of electromagnetic “noise” and interference, will attenuate the signal and will change its shape (distorsion).

Since it takes some time for the signal to traverse the channel, the received signal will have some latency with respect to the transmitted signal. This “latency” might change over time and contribute to “jitter” in the received signal.
The signal might also reach the receiver by means of different trajectories, and in this case the different received versions will interact as a consequence of the “multipath”.
Multipath can completely obliterate a signal but it can also used advantageously in some modern communications techniques.

Attenuation



Transmitted Signal



Received Signal

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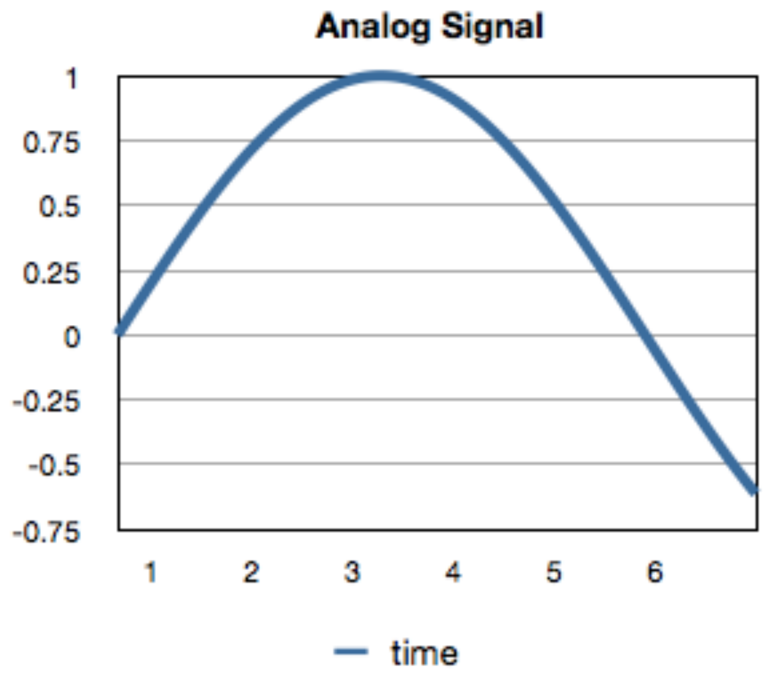
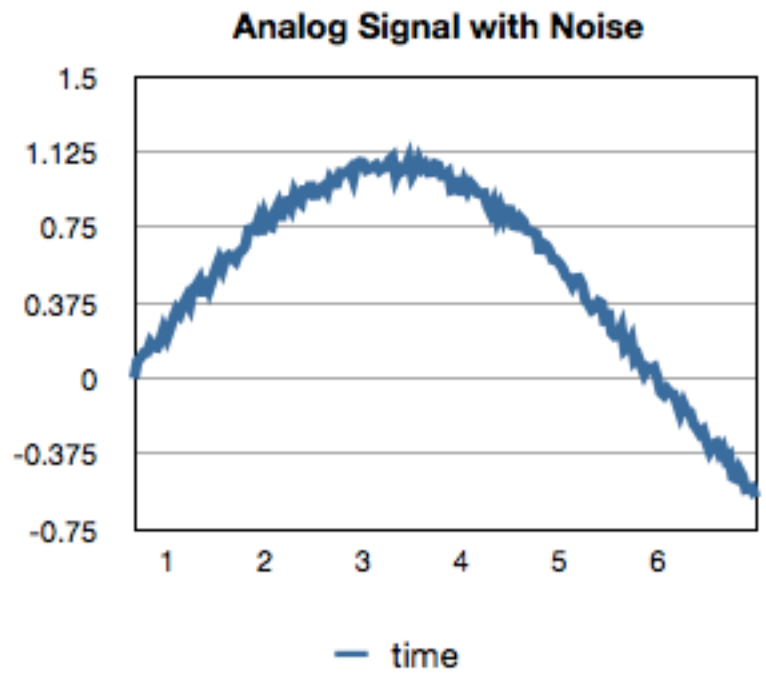
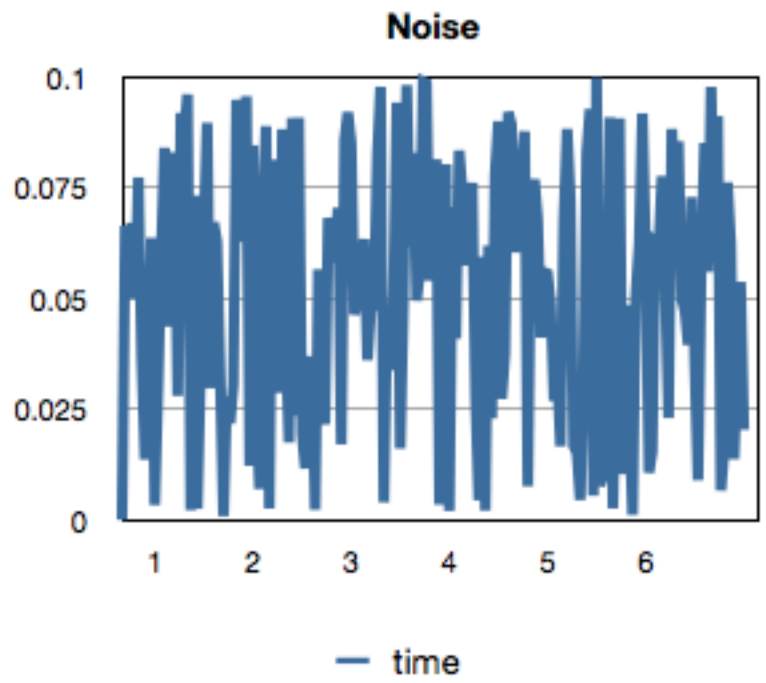
Although the effect of attenuation can easily be overcome with an amplifier, the amplifier will also enhance any noise introduced by the channel and inevitably introduce some extra noise of its own.

Noise in an analog Signal







Noise can completely masquerade the transmitted signal. Telecommunications engineers have strived for a century to find better ways to recover the information contained in the signal contaminated by noise.

Interference

Any signal different from the one that our system is designed to receive that is captured by the receiver impairs the communication and is called interference.

Intra-channel interference originates in the same channel as our signal.

Co-channel interference is due to the imperfection of the filters that will let in signals from adjacent channels.

Channel Capacity

$$C = B*\log_2\{1 + [S/(N_o*B)]\}$$

Noise power density, W/Hz

Received signal power, W

Bandwidth, Hz

Capacity (maximum throughput), bit-per-second

- The capacity and and bandwidth efficiency [C/B (bps/Hz)] decreases with the noise

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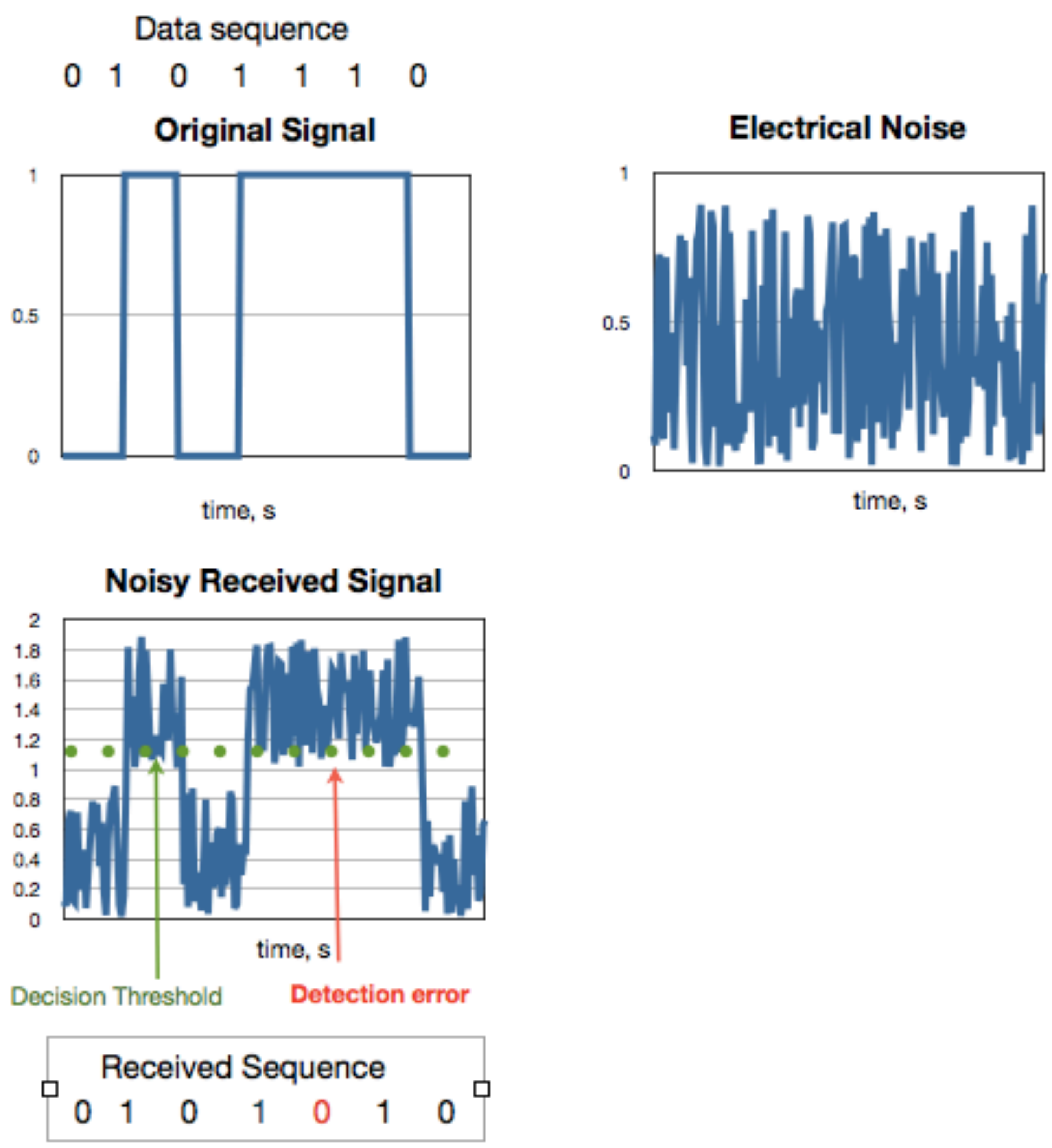
The bandwidth efficiency, or spectral efficiency, is an important figure of merit for communication systems because bandwidth is a scarce and valuable assessment, so designers strive to pack as many bits/s in a certain amount of bandwidth as possible. This increases the complexity of the system and also the required S/N in order to correctly decode the received signal. That is why many systems provide greater capacity at shorter distances where the signal power is greater.

Since capacity in bits/s is proportional to bandwidth in Hz, it is common to speak of “bandwidth” in bits/s. Bear in mind that the number of bits carried by each hertz can be as low as 1/2 or as high as 8.

Detection of a noisy signal



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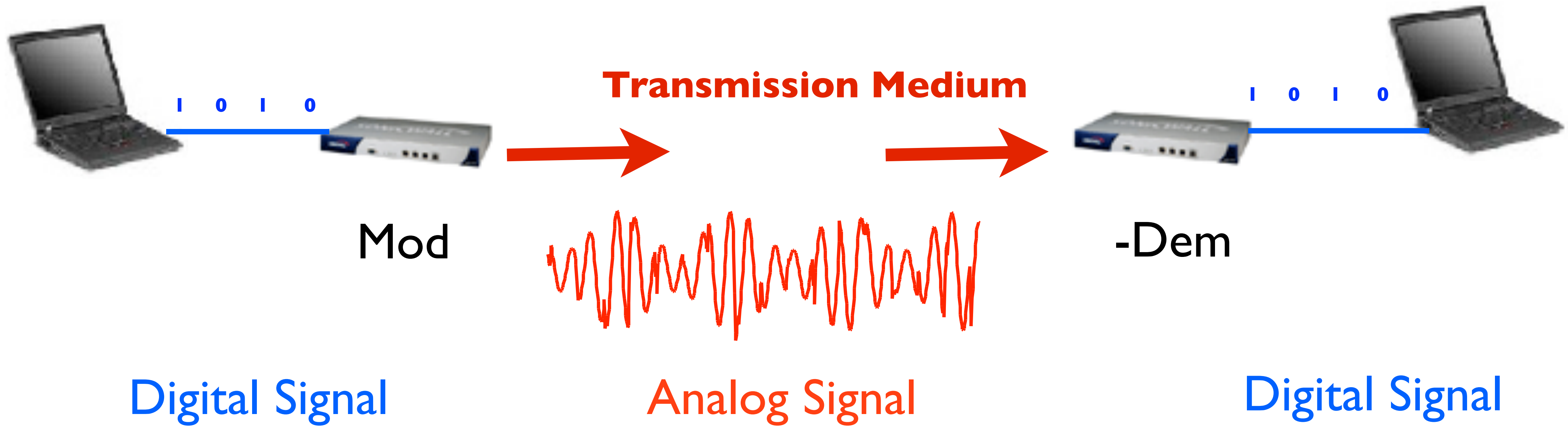
In the figure, the original data consists of the **0 1 0 1 1 1 0** sequence. The **0**'s are represented as zero voltage and the **1**'s as 1 V. As the signal moves towards the receiver, its amplitude will diminish. This effect is called "attenuation" and is shown in the figure. Likewise, there will also be a delay as the signal moves from the transmitter to the receiver. Each of these impairments, if severe enough, can cause a detection error.

An amplifier can be used to overcome the attenuation, but the electrical noise always present in the system will add to the received signal. The noisy received signal is therefore quite different from the original signal, but since it is a digital system we can still recover the information contained by sampling the received signal and comparing the value at the sampling time with a suitable threshold voltage. In this example the noise received signal has a peak of 1.8 V, so we might choose e threshold voltage of 0.9 V. IF the received signal is above the threshold, the detector will output a digital **1**, otherwise, it will output a **0**. In this case we can see that because of the effect of the noise the fifth bit was erroneously detected as a zero.

Transmission errors can also occur if the sampling signal period is different from that of the original data (difference in the *clock rates)*, or if the receiver clock is not stable enough (*jitter*). Any physical system will have an upper limit in the frequencies that will transmit without attenuation (the *bandwidth* of the system) , so the abrupt rise and fall of the voltage will be smoothed out as the signal goes through the channel. Therefore, we must make sure that each of the elements of the system has enough bandwidth to handle the signal. On the other hand, the greater the bandwidth of the receiver system, the greater the amount of the noise that will affect the received signal.

MoDem



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In order to transmit a digital signal at a reasonable distance it has to be processed by a modulator.
The modulator can:

Select the frequency at which the signal will be transmitted over the channel.

Allow for different signals to share the same modulation channel, in a process known as multiplexing.

Adapt the signals parameters to suit the requirements of a given channel (bandwidth, spectral properties, noise robustness, etc.).

Provide the flexibility to exchange spectral efficiency for robustness, as needed.

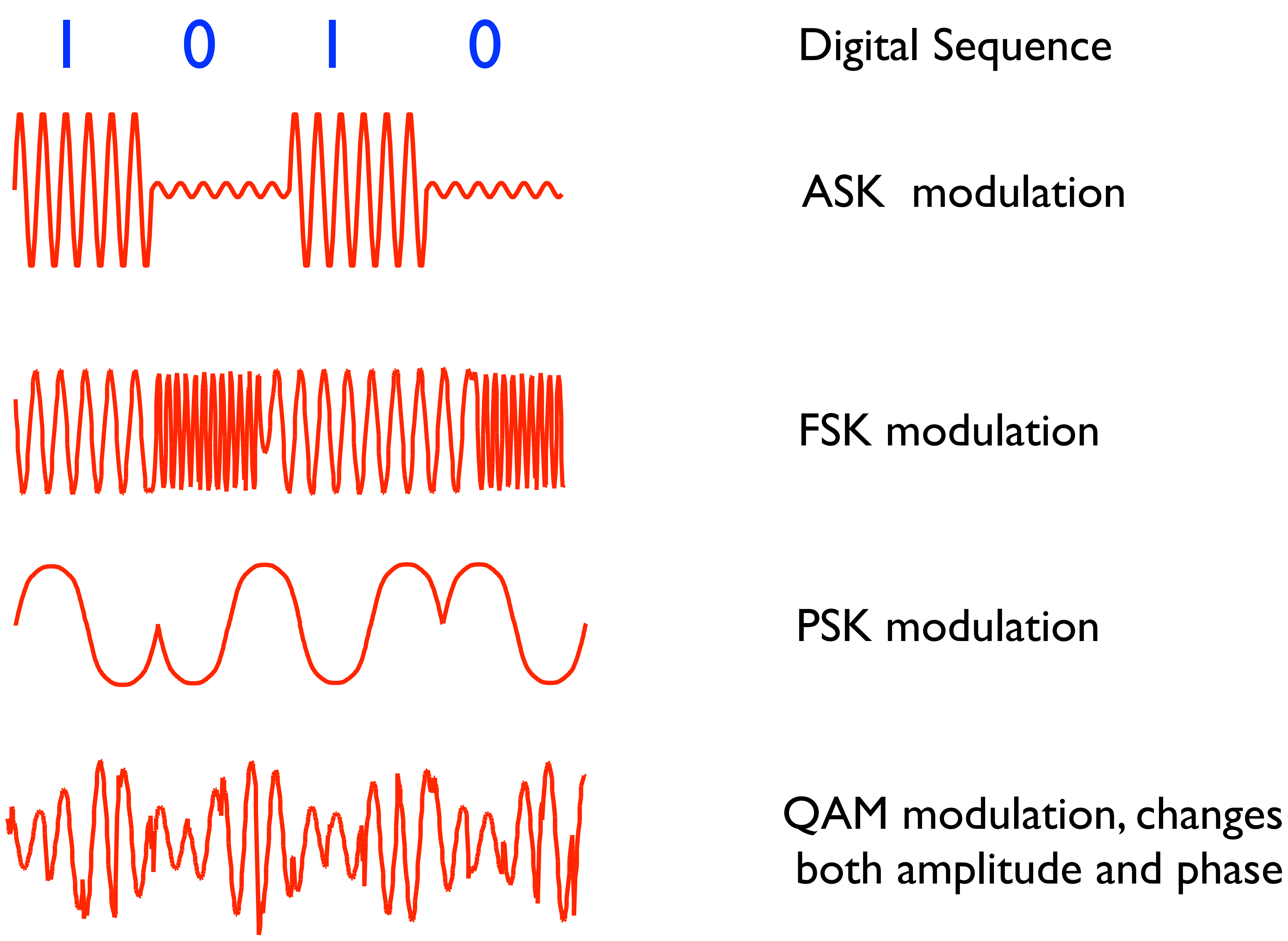
Of course, at the receiving end, the inverse operation, called demodulation, needs to be performed. So in bidirectional systems a single device will perform both operations and therefore be called a modem.

The word modem is a combination of the words modulation and demodulation which is precisely what a modem does. A modem can also be viewed as a device that takes information, transfers it on to a medium to allow transportation of the information, and at the other end, removes the information from the medium and restores it to it's original form. This brings up two distinguishing characteristics of a modem, the type of information it accepts and the media that it operates upon. In the case of WiFi modems, the information is data 10BT or 100BT Ethernet format and the media radio.

The type of medium employed by the modem dictates the type of modulation it will employ, The medium can be a copper cable, an optical fiber or an electromagnetic wave in free space.

Although the modem is a separate building block, it is often embedded in a laptop or in a wireless router-

Comparison of modulation techniques



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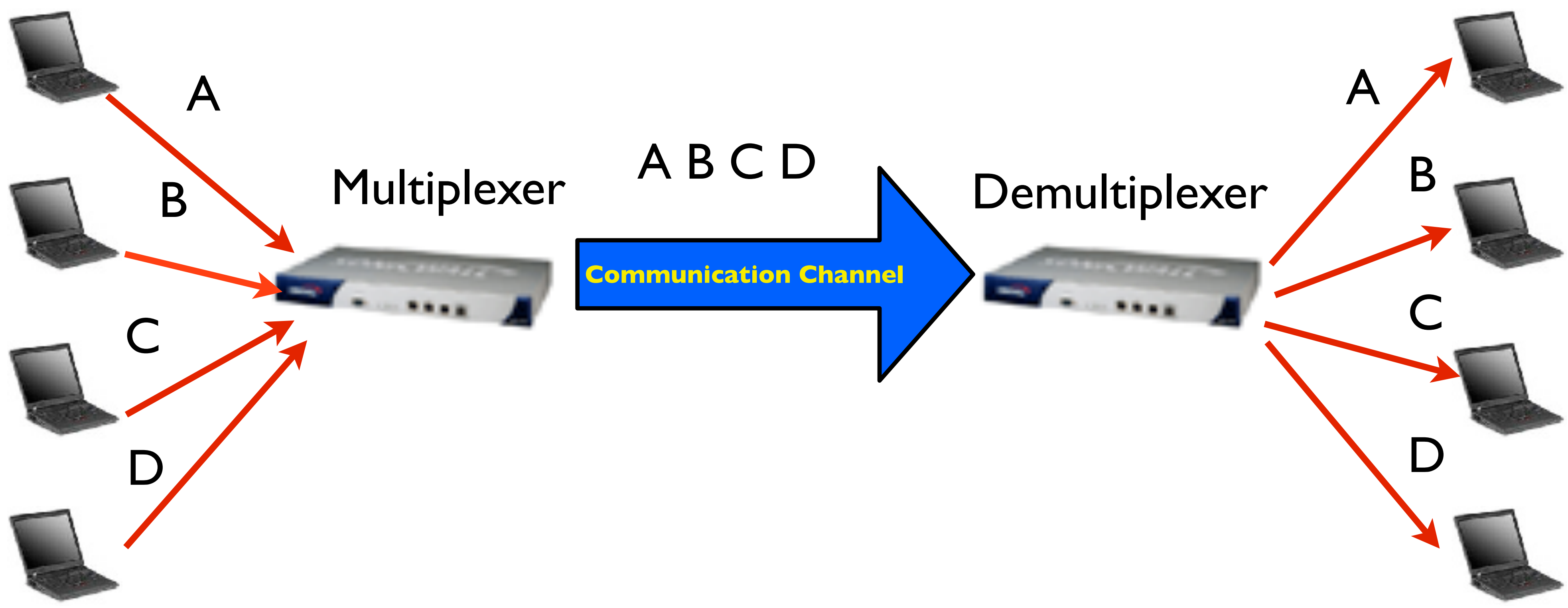
The digital sequence 1 0 1 0 is shown modulating a sinusoidal carrier in ASK (Amplitude Shifting Keying), FSK (Frequency Shifting Keying), PSK (Phase Shifting Keying) and QAM (Quadrature Amplitude Modulation). Quadrature modulation is another term used for binary phase modulation. There is a great number of modulation techniques derived from these basic schemes.

Multiplexing



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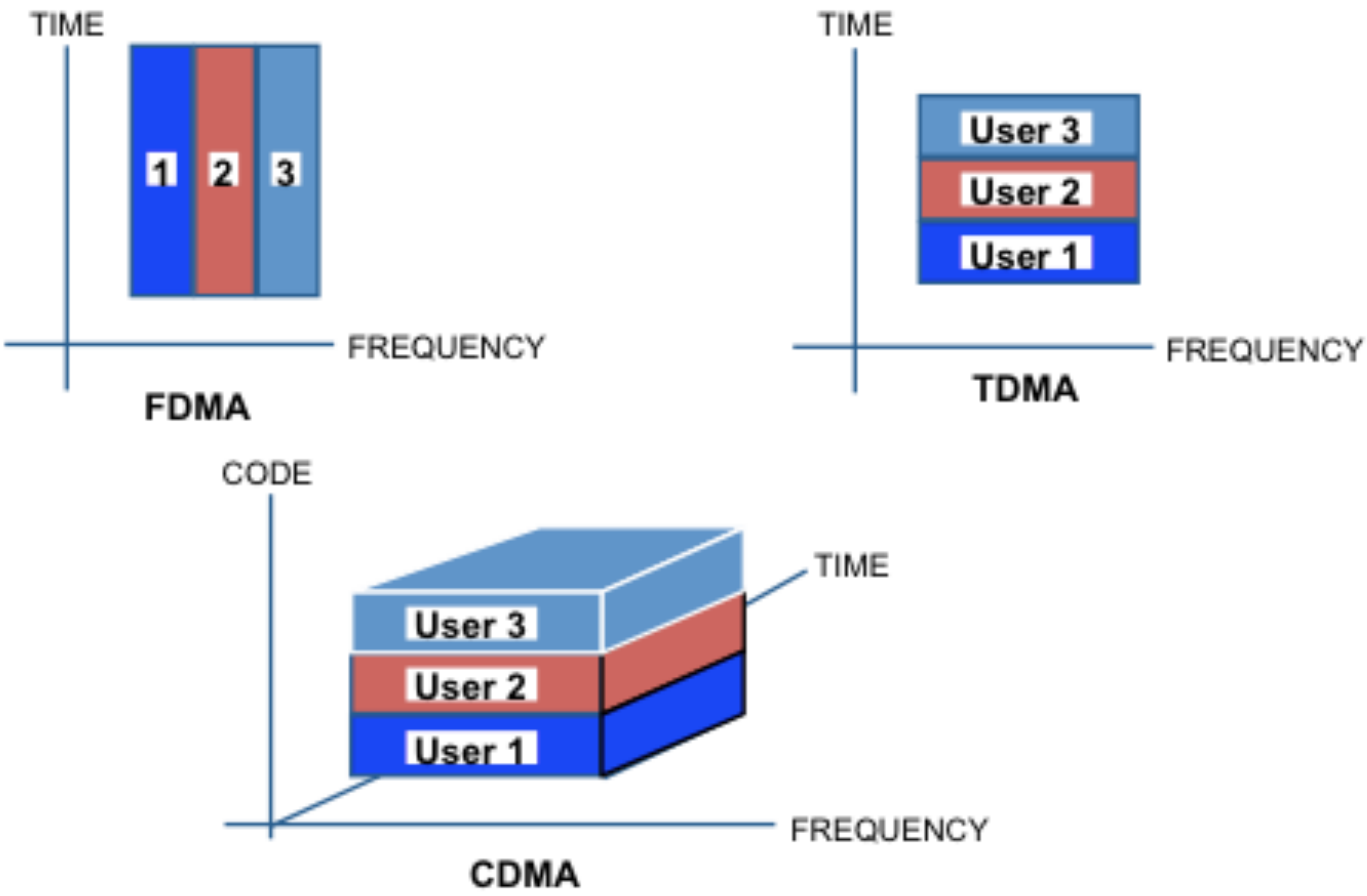
Multiplexing is the sharing of a single communication channel among different users. The communication channel can be a copper wire, an optical fiber or the space between a transmitting and a receiving antenna.

Different users can be distinguished by means of different frequencies, time slots, codes or regions of space.

At the receiving end

Medium sharing techniques



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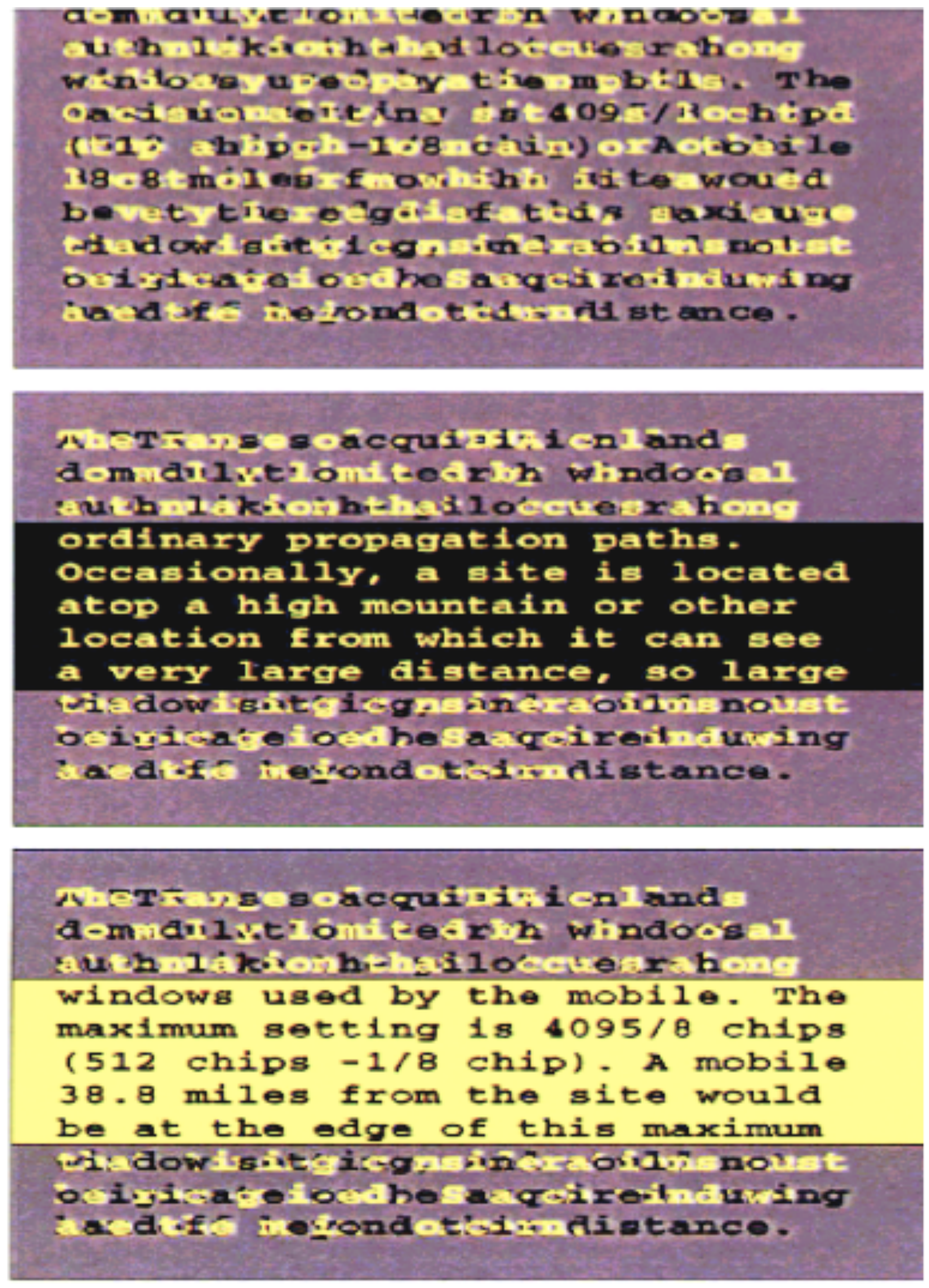
In FDMA (Frequency Division Multiple Access), each user has a different frequency band allocated.
In TDMA (Time Division Multiple Access), each user has d different time slot allocated, while the same frequency is shared among all the users of the service.
IN CDMA (Code Division Multiple Access), the users are distinguished by means of a special mathemathical code, while sharing the same frequency and time slots.

CDMA analogy

Two messages superposed, one in yellow and one in blue

A blue filter reveals what is written in yellow

A yellow filter reveals what is written in blue



This visual analogy is aimed at explaining how two different messages can be superimposed in the same medium and later separated by the proper decoding technique.

Types of transmissions

Simplex:
one way only, example, TV Broadcasting

Half-duplex:
the corresponding stations have to take turns to access the medium, example walkie-talkie. Requires hand-shaking to coordinate access. This technique is called **TDD** (Time Division Duplexing)

Full-duplex:
the two corresponding stations can transmit simultaneously, employing different frequencies. This technique is called **FDD** (Frequency Division Duplexing). A guard band must be allowed between the two frequencies in use.

Behavior of radio waves

There are a few simple rules of thumb that can prove extremely useful when making first plans for a wireless network:

- The ***longer*** the wavelength, the further it goes
- The ***longer*** the wavelength, the better it travels through and around things
- The ***shorter*** the wavelength, the more data it can transport

All of these rules, simplified as they may be, are rather easy to understand by example.

Assuming equal power levels, waves with longer wavelengths tend to travel further than waves with shorter wavelengths. Lower frequency transmitters can reach greater distances than high frequency transmitters at the same power.

A wave on water which is 5 meters long will not be stopped by a 5 mm piece of wood sticking out of the water. If instead the piece of wood were 50 meters big (e.g. a ship), it would easily stop the wave. The distance a wave can travel depends on the relationship between the wavelength of the wave and the size of obstacles in its path of propagation.

It is harder to visualize waves moving "through" solid objects, but this is the case with electromagnetic waves. Longer wavelength (and therefore lower frequency) waves tend to penetrate objects better than shorter wavelength (and therefore higher frequency) waves. For example, FM radio (88-108MHz) can travel through buildings and other obstacles easily, while shorter waves (such as GSM phones operating at 900MHz or 1800MHz) have a harder time penetrating buildings. This effect is partly due to the difference in power levels used for FM radio and GSM, but is also partly due to the shorter wavelength of GSM signals.

The faster the wave swings or beats, the more information it can carry - every beat or cycle could for example be used to transport a digital bit, a '0' or a '1', a 'yes' or a 'no'.

Traveling radio waves

Radio waves do not move in a strictly straight line. On their way from “point A” to “point B”, waves may be subject to:

- Absorption
- Reflection
- Diffraction
- Refraction

We are going to examine all of these effects in detail in the next slides.

Absorption

When electromagnetic waves go through some material, they generally get weakened or dampened.

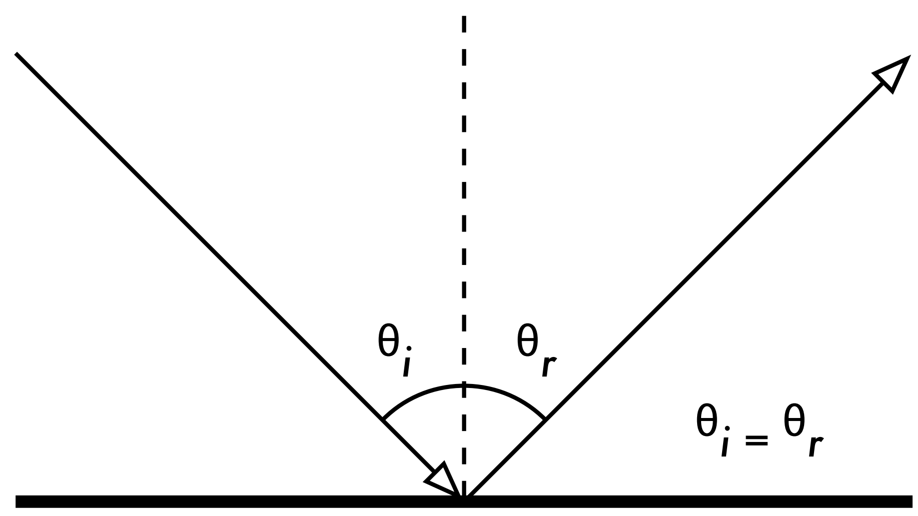
Materials that absorb energy include:

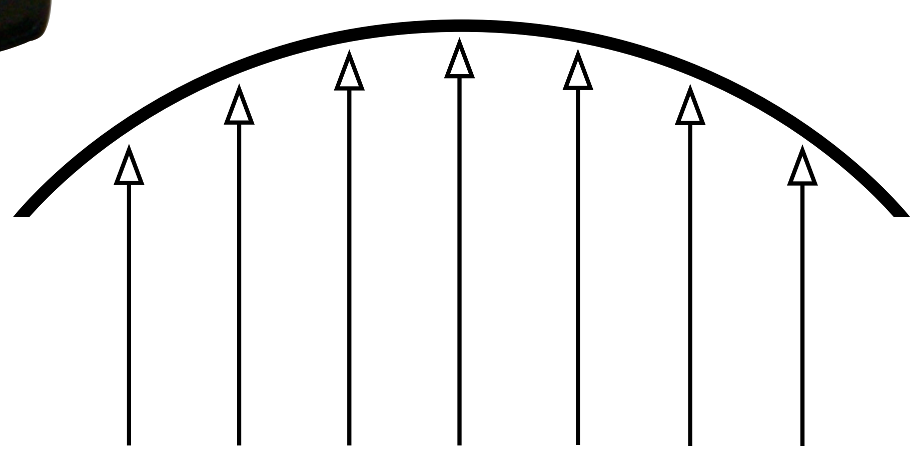
- ***Metal***. Electrons can move freely in metals, and are readily able to swing and thus absorb the energy of a passing wave.
- ***Water*** molecules jostle around in the presence of radio waves, thus absorbing some energy.
- ***Trees*** and ***wood*** absorb radio energy proportionally to the amount of water contained in them.
- ***Humans*** are mostly water: we absorb radio energy quite well!

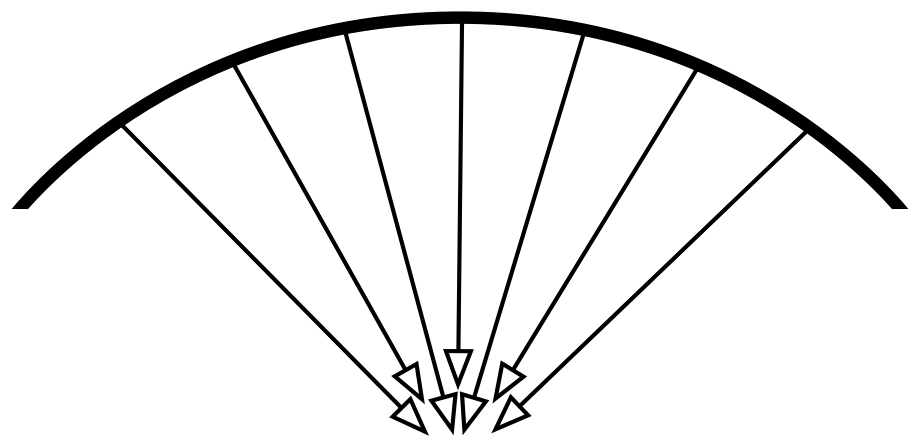
Plastics and similar materials generally do not absorb a lot of radio energy- but this varies depending on the frequency and type of material. Before you build a component from plastic (e.g. weather protection for a radio device and its antennas), it is a good idea to verify that the material does not absorb radio energy around 2.4 GHz. One simple method of measuring the absorption of plastic at 2.4 GHz is to put a sample in a microwave oven for a couple of minutes. If the plastic heats up, then it absorbs radio energy and should not be used for weatherproofing.

Reflection

The rules for reflection are quite simple: the angle at which a wave hits a surface is the same angle at which it gets deflected. **Metal** and **water** are excellent reflectors of radio waves.







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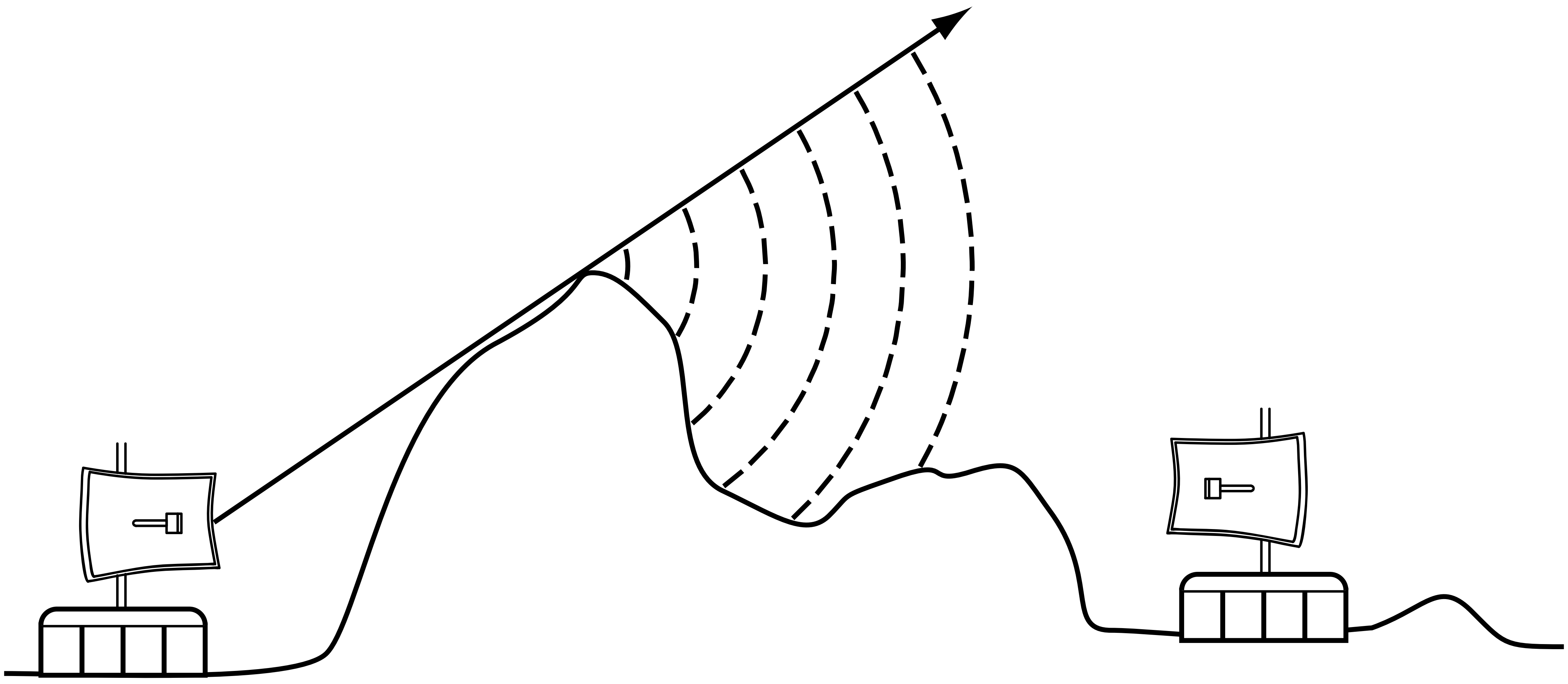
Although the rules of reflection are quite simple, things can become very complicated when you imagine an office interior with many many small metal objects of various complicated shapes. The same goes for urban situations: look around you in city environment and try to spot all of the metal objects. This explains why **multipath** effects (i.e. signal reaching their target along different paths, and therefore at different times) play such an important role in wireless networking. Water surfaces, with waves and ripples changing all the time, effectively make for a very complicated reflection object which is more or less impossible to calculate and predict precisely.

We use reflection to our advantage in antenna building: e.g. we put huge parabolas behind our radio transmitter/receiver to collect and bundle the radio signal into a fine point.

Big metallic panels can be used as *passive radio reflectors* to cover areas that cannot be normally reached using a straight path, this is sometimes done to increase the TV coverage in mountain and valley areas.

Diffraction

Because of the effect of diffraction, waves will "bend" around corners or through an opening in a barrier.



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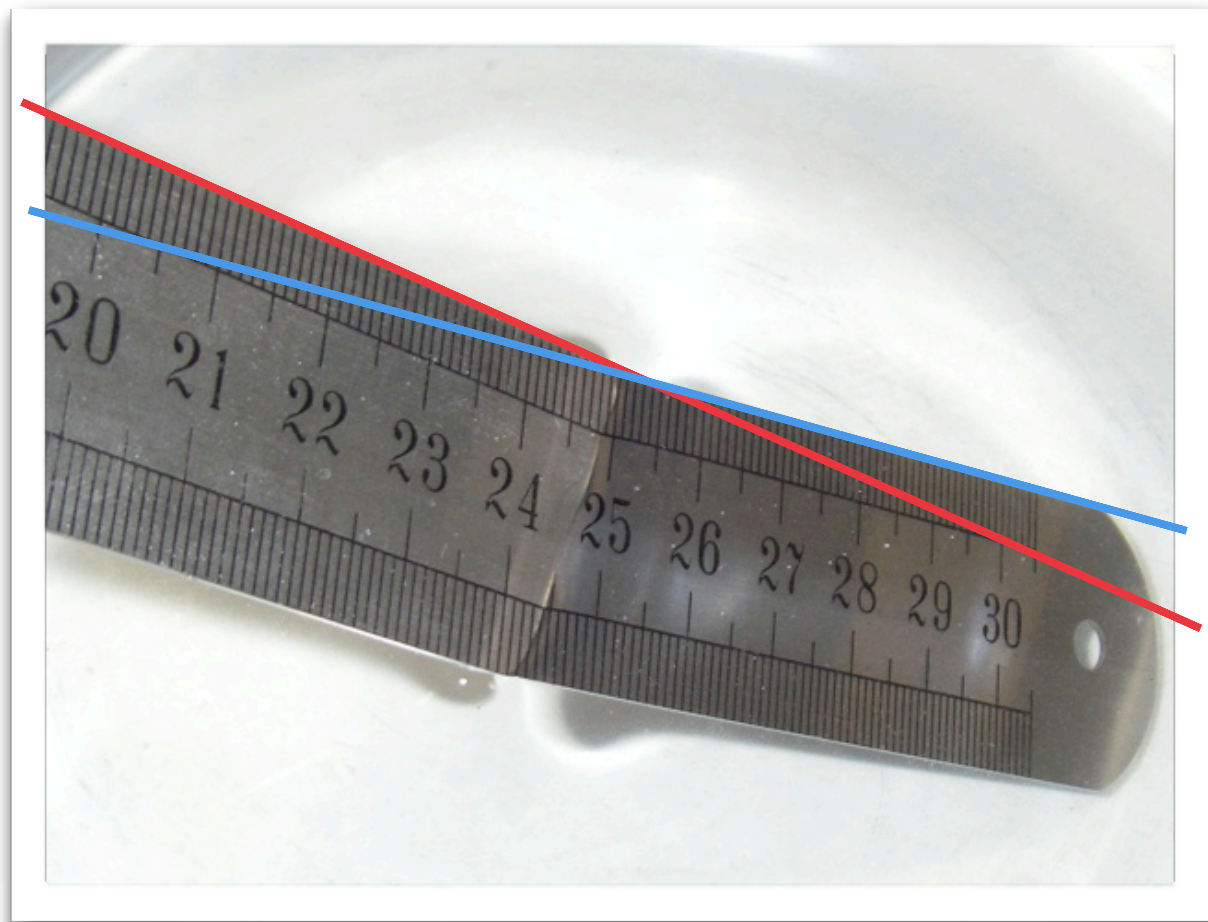
The wavelengths of visible light are far too small for humans to observe this effect directly. Microwaves, with a wavelength of several centimeters, will show the effects of diffraction when waves hit walls, mountain peaks, and other obstacles. It seems as if the obstruction causes the wave to change its direction and go around corners.

Note that diffraction comes at the cost of power: the energy of the diffracted wave is significantly less than that of the wavefront that caused it. But in some very specific applications, you can take advantage of the diffraction effect to circumvent obstacles.

Refraction

Refraction is the apparent "bending" of waves when they meet a material with different characteristics.

When a wave moves from one medium to another, it changes speed and direction upon entering the new medium.

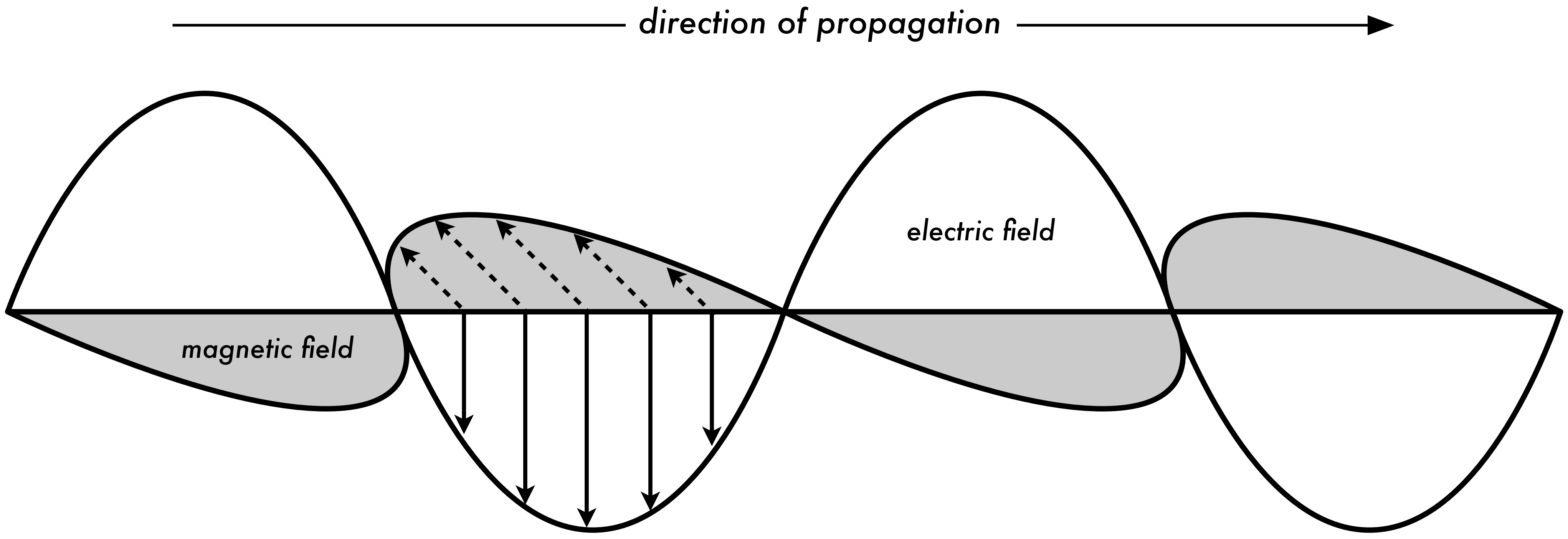


This is a common effect when a ray of light is passing trough materials with different refractive indexes (like air and water).

Refraction is described mathematically by Snell's law (http://en.wikipedia.org/wiki/Snell's_law), which states how the angle of incidence is related to the angle of refraction and take into consideration the refractive indexes of the two media. Basically the ratio of the sin functions of the two angles is equal to the ratio of the two indexes.

Polarization

- Electromagnetic waves have *electrical* and *magnetic* components that oscillate perpendicular to each other and to the direction of the propagation.
- The *polarization* of the wave corresponds to the plane in which the electrical oscillations occur.



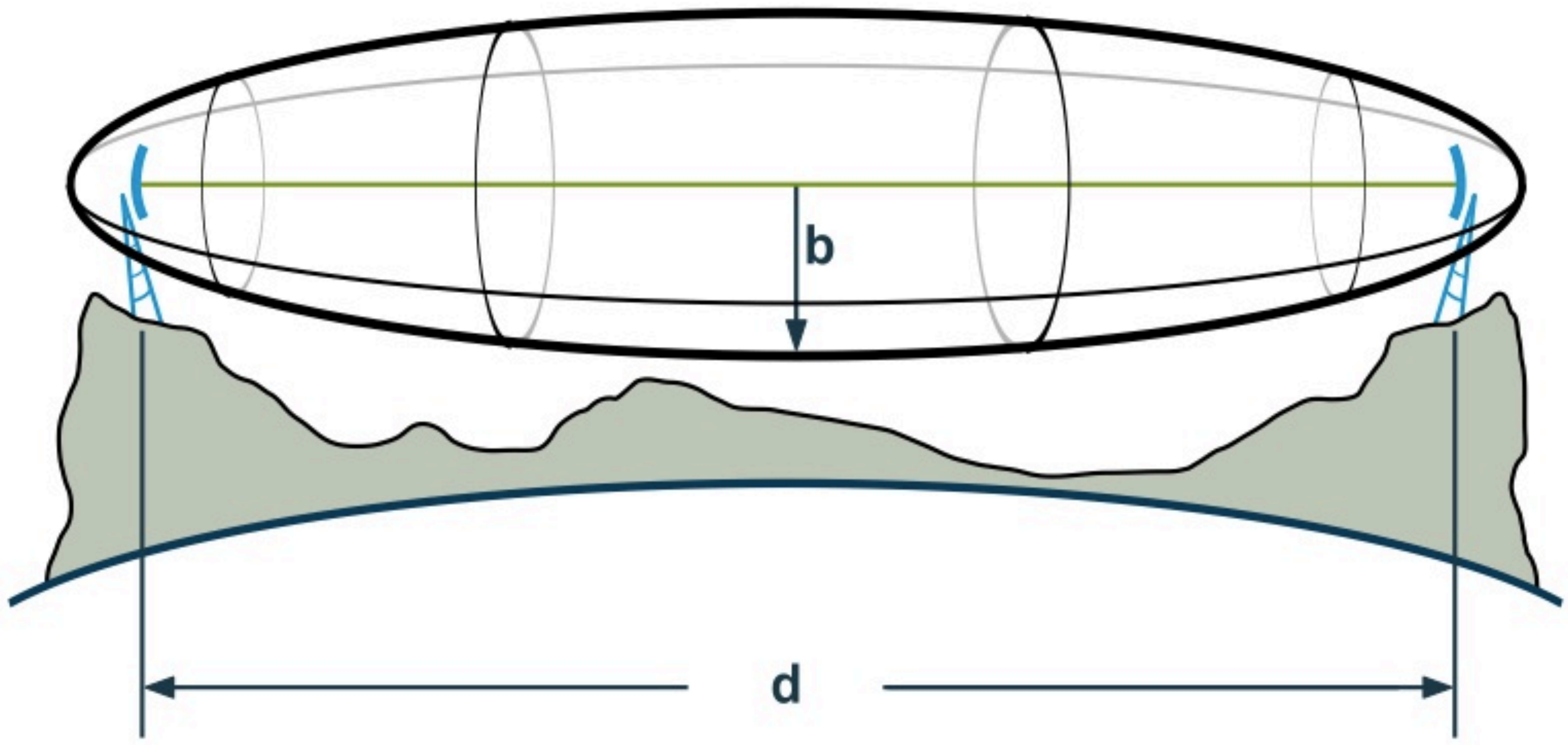
Another important quality of electromagnetic waves is ***polarization***. Polarization describes the direction of the electrical field vector.

If you imagine a vertically aligned dipole antenna (a straight piece of wire), electrons only move up and down, not sideways (because there is no room to move) and thus electrical fields only ever point up or down, vertically. The energy leaving the wire and traveling as a wave has a strict linear (and in this case, vertical) polarization. If we put the antenna flat on the ground, we would find horizontal linear polarization.

Most WiFi antennas we work with are linearly polarized, but circularly polarized antennas are also sometimes used (for special purposes).

The polarization of a transmitting and receiving antenna **MUST MATCH** for optimum communications.

Line of Sight and Fresnel Zones



a free line-of-sight **IS NOT EQUAL TO** a free Fresnel Zone

Simply draw a line between two points, and if nothing is in the way, we have optical **line of sight**.

But radio waves are not confined to a perfectly straight line, they occupy a volume in space. **Fresnel zone** theory describes how a propagating wave can cause interference with itself.

The strongest signals are on the direct line between transmitter and receiver and always lie in the (first) Fresnel Zone. If this zone is partially blocked by an obstruction, the signal arriving at the far end would be diminished.

See wikipedia for more details: *http://en.wikipedia.org/wiki/Fresnel_zone*

Conclusions

The communication system must overcome the noise and interference to deliver the signal to the receiver.
The capacity of the communication channel is proportional to the bandwidth and to the logarithm of the S/N ratio.
Modulation is used to adapt the signal to the channel and to allow several signals to share the same channel.
Higher order modulation schemes allows for a higher transmission rate, but require higher S/N ratio.
The channel can be shared by several uses that occupy different frequencies, different time slots or different codes,

Conclusions

Radio waves have a characteristic wavelength, frequency and amplitude, which affect the way they travel through space.

WiFi uses a tiny part of the electromagnetic spectrumLower frequencies travel further, but at the expense of throughput.

Radio waves occupy a volume in space, the Fresnel zone, which should be unobstructed for optimum reception.

Thank you for your attention

For more details about the topics presented in this lecture, please see the book ***Wireless Networking in the Developing World***, available as a free download in many languages:

http://wndw.net/