CHAPTER 1: Mobile Radio Propagation

Guglielmo Marconi invented the wireless telegraph in 1896: Communication by encoding alphanumeric characters in analog signal; Sent telegraphic signals across the Atlantic Ocean

Communications satellites launched in 1960s: Today satellites carry about one- third of the voice traffic and all of the television signals between countries.

Advances in wireless technology: Radio, television, mobile telephone, mobile data, communication satellites

More recently: Wireless networking, cellular technology, mobile apps, Internet of Things

Cellular telephone

Started as a replacement to the wired telephone; Early generations offered voice and limited data; Current third and fourth generation systems offer:

- Voice
- Texting
- Social networking
- Mobile apps
- Mobile Web
- Mobile commerce
- Video streaming

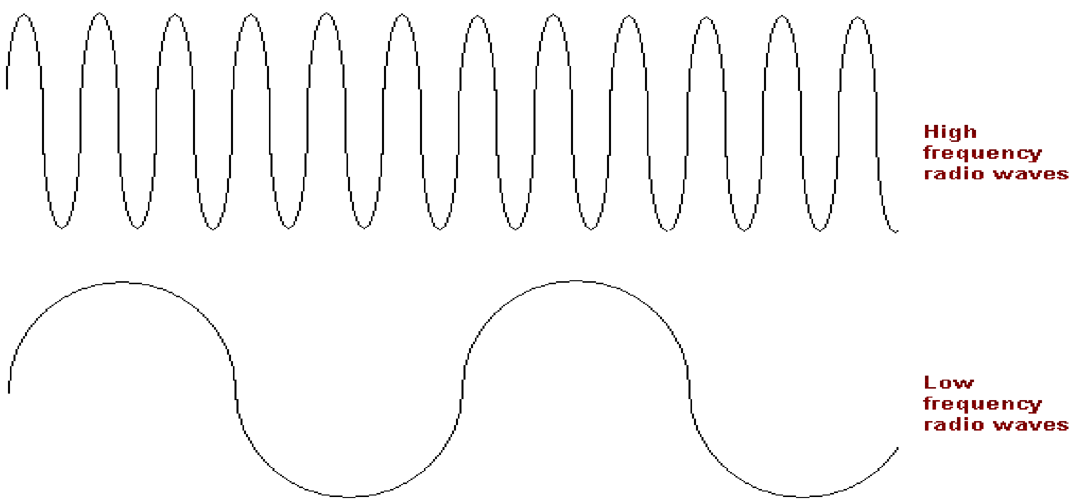
Wireless Impact

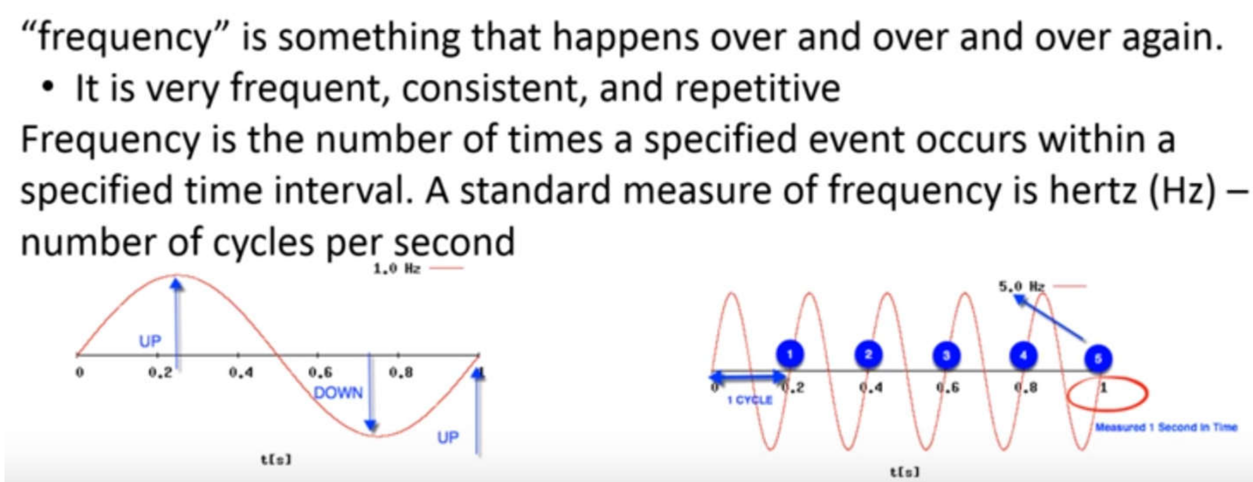
- Profound
- Shrinks the world
- Always on
- Always connected
- Changes the way people communicate
    - Social networking

− Converged global wireless network

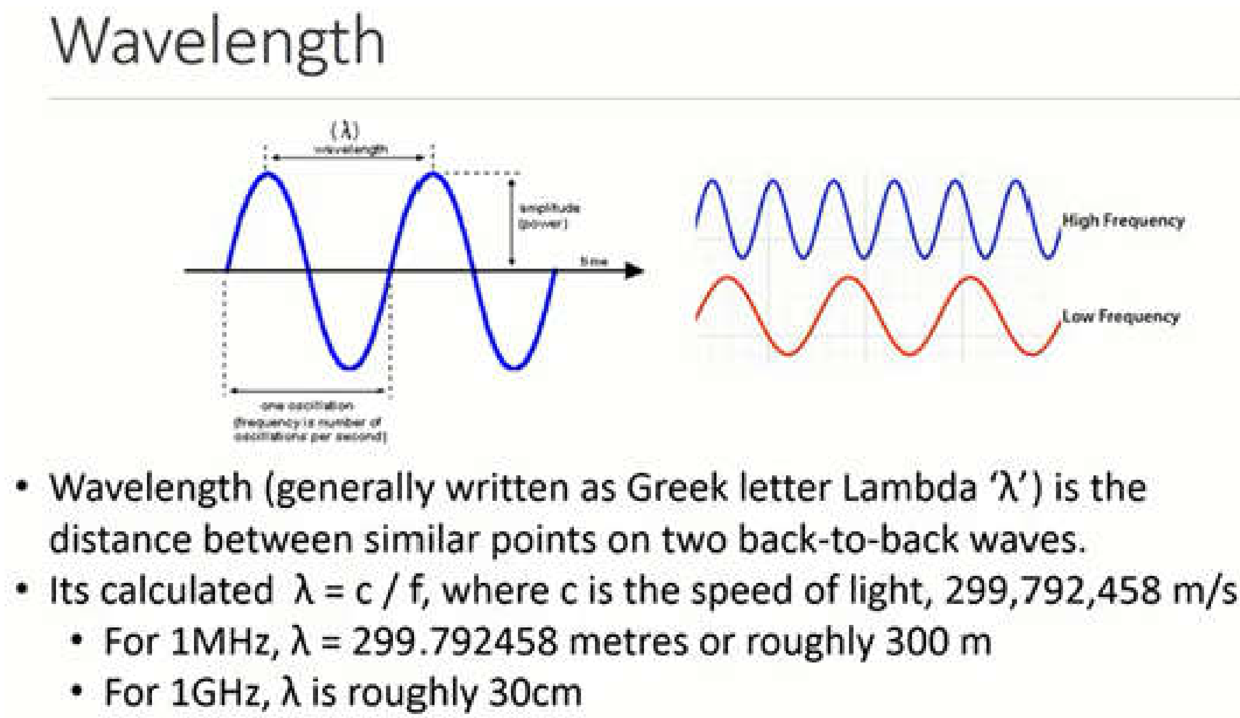
Frequency

Most mobile networks worldwide use portions of the radio frequency spectrum, allocated to the mobile service, for the transmission and reception of their signals. Frequency describes the number of waves that pass a fixed place in a given amount of time. Usually frequency is measured in the hertz unit, named in honor of the 19th-century German physicist Heinrich Rudolf Hertz. The hertz measurement, abbreviated Hz, is the number of waves that pass by per second.

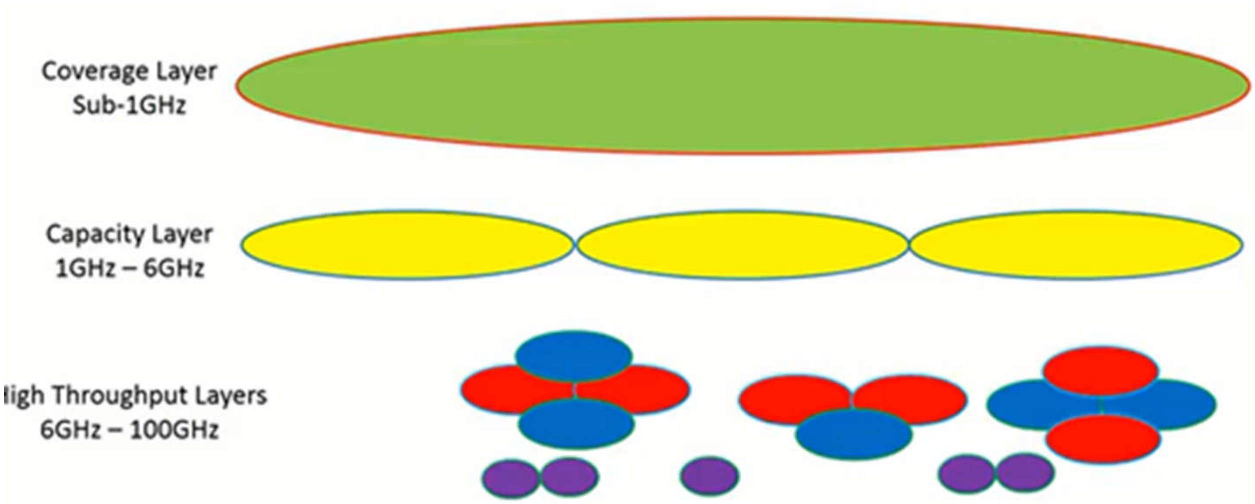


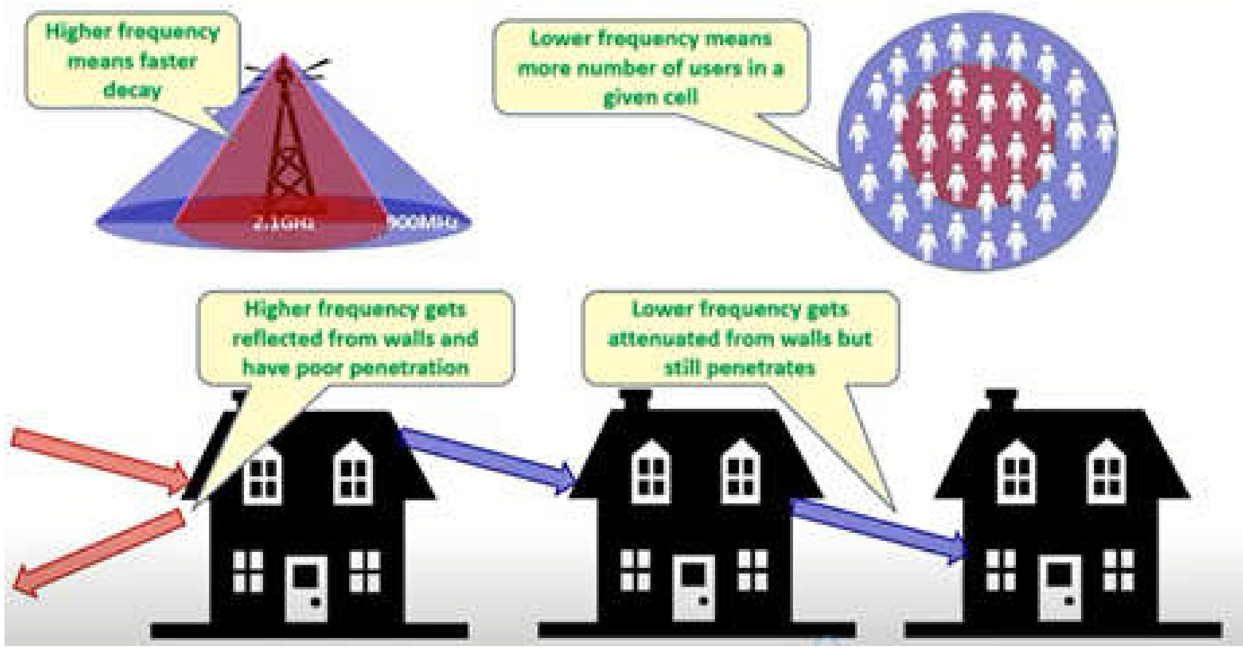


Frequency and Wavelength



Frequency and Coverage





Global cellular network

Growth: 11 million users in 1990; Over 7 billion today (according to 4G Americas)

Mobile devices: Convenient; Location aware; Only economical form of communications in some places.

Generations: 1G – Analog; 2G – Digital voice, Voice services with some moderate rate data services; 3G – Packet networks, Universal Mobile Phone Service (UMTS), CDMA2000; 4G – New wireless approach (OFDM), Higher spectral efficiency, 100 Mbps for high mobility users, 1 Gbps for low mobility access, Long Term Evolution (LTE) and LTE-Advanced.

The dominant first- generation wireless network in North America was the Advanced Mobile Phone System (AMPS). The key second generation wireless systems are the Global System for Mobile Communications (GSM), Personal Communications Service (PCS) IS- 136, and PCS IS-95. The PCS standard IS- 136 uses time division multiple access (TDMA); GSM uses a combination of TDMA and frequency division multiple access (FDMA), and IS- 95 uses code division multiple access (CDMA). 2G systems primarily provide voice services, but also provide some moderate rate data services.

The two major third- generation systems are CDMA(Code-division multiple access)2000 and Universal Mobile Telephone Service (UMTS). Both use CDMA and are meant to provide packet data services. CDMA2000 released 1xRTT (1 times Radio Transmission Technology) and then 1 xEV- DO (1 times Evolution- Data Only) through.

Mobile device revolution

Originally just mobile phones; Today's devices; Multi-megabit Internet access; Mobile apps; High megapixel digital cameras; Access to multiple types of wireless networks; Wi-Fi, Bluetooth, 3G, and 4G; Several on-board sensors. Key to how many people interact with the world around them.

Better use of spectrum; Decreased costs; Limited displays and input capabilities; Tablets provide balance between smartphones and PCs; Long distance; Cellular 3G and 4G; Local areas; Wi-Fi. Short distance; Bluetooth, ZigBee.

Future trends

LTE-Advanced and gigabit Wi-Fi now being deployed; Machine-to-machine communications, The "Internet of Things"; Devices interact with each other; Healthcare, disaster recovery, energy savings, security and surveillance, environmental awareness, education, manufacturing, and many others; Information dissemination; Data mining and decision support; Automated adaptation and control; Home sensors collaborate with home appliances, HVAC systems, lighting systems, electric vehicle charging stations, and utility companies. Eventually could interact in their own forms of social networking.

Machine-to-machine communications: 100-fold increase in the number of devices; Type of communication would involve many short messages; Control applications will have real-time delay requirements; Much more stringent than for human interaction.

Future networks: 1000-fold increase in data traffic by 2020; 5G envisioned by 2020 Technologies: Network densification – many small cells; Device-centric architectures - focus on what a device needs; Massive multiple-input multiple-output (MIMO) – 10s or 100s of antennas; To focus antenna beams toward intended devices.

Millimeter wave (mmWave) - frequencies in the 30 GHz to 300 GHz bands: Have much available bandwidth. But require more transmit power and have higher attenuation due to obstructions

Native support for machine to machine communication: Sustained low data rates, massive number of devices, and very low delays.

The trouble with wireless

Wireless is convenient and less expensive, but not perfect.

Wireless channel: Line-of-sight is best but not required; Signals can still be received; Transmission through objects; Reflections off of objects; Scattering of signals; Diffraction around edges of objects.

Line-of-sight propagation is a characteristic of electromagnetic radiation or acoustic wave propagation which means waves travel in a direct path from the source to the receiver. Electromagnetic transmission includes light emissions traveling in a straight line.

Wireless channel: Reflections can cause multiple copies of the signal to arrive; At different times and attenuations; Creates the problem of *multipath fading*; Signals add together to degrade the final signal; Noise; Interference from other users; Doppler spread caused by movement

Attenuation is a general term that refers to any reduction in the strength of a signal. Attenuation occurs with any type of signal, whether digital or analog. Sometimes called loss, attenuation is a natural consequence of signal transmission over long distances.

Multipath fading occurs when signals reach a receiver via many paths & their relative strengths & phases change.

Propagation

Propagation models have been developed to be able to estimate the radio wave propagation as accurately as possible. Models have been created for different environments to predict the path loss between the transmitter and receiver. How much power needs to be transmitted using the BTS to be able to receive a certain power level from the MS? The complexity of the model affects the applicability as well as the accuracy. Two well-known models are those of Okumura–Hata and Walfish–Ikegami. The first mentioned is created for large cells, i.e. for rural and suburban areas, while the Walfish–Ikegami model is used for small cells, i.e. for urban areas. The basic electromagnetic wave propagation mechanisms are free space loss, reflection, diffraction and scattering.

1.1. Speed, Wavelength, Frequency

The speed of the RF signal is equal to the speed of light, and in this way the distance can be calculated.

Light speed = Wavelength x Frequency

= 3 x 108m/s = 300,000 km/s

Table 3.1. Table for different systems with their frequency and wavelength

System	Frequency	Wavelength
AC current	60 Hz	5,000 km
FM radio	100 MHz	3 m
Cellular	800 MHz	37.5 cm
Ka band satellite	20 GHz	15 mm
Ultraviolet light	10^{15} Hz	10^{-7} m

1.2. Radio Frequency Bands

Table 3.2. Classification of radio frequency bands

Classification Band	Initials	Frequency Range	Propagation Mode
Extremely low	ELF	< 300 Hz	Ground wave
Infra low	ILF	300 Hz - 3 kHz	
Very low	VLF	3 kHz - 30 kHz	
Low	LF	30 kHz - 300 kHz	
Medium	MF	300 kHz - 3 MHz	Ground/Sky wave
High	HF	3 MHz - 30 MHz	Sky wave
Very high	VHF	30 MHz - 300 MHz	Space wave
Ultra high	UHF	300 MHz - 3 GHz	
Super high	SHF	3 GHz - 30 GHz	
Extremely high	EHF	30 GHz - 300 GHz	
Tremendously high	THF	300 GHz - 3000 GHz	

1.3. Radio propagation mechanisms

The basic electromagnetic wave propagation mechanisms are free space loss, reflection, diffraction and scattering. Free space loss describes the ideal situation, where the transmitter and receiver have line-of-sight and no obstacles are around to create reflection, diffraction or scattering. In this ideal case the attenuation of the radio wave signal is equivalent to the square of the distance from the transmitter.

1. **Reflection and transmission.** Specular reflections and transmission occur when electromagnetic waves impinge on obstructions larger than the wavelength.

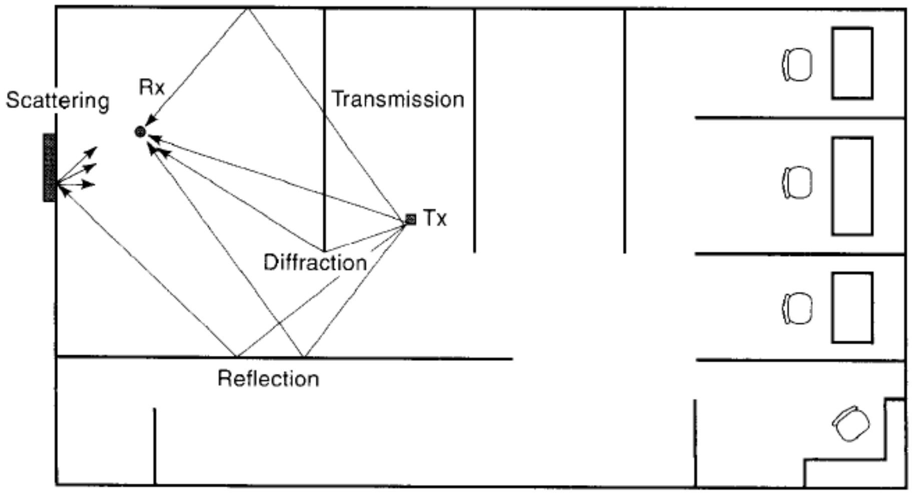


Figure1.1. Radio propagation mechanisms in an indoor area

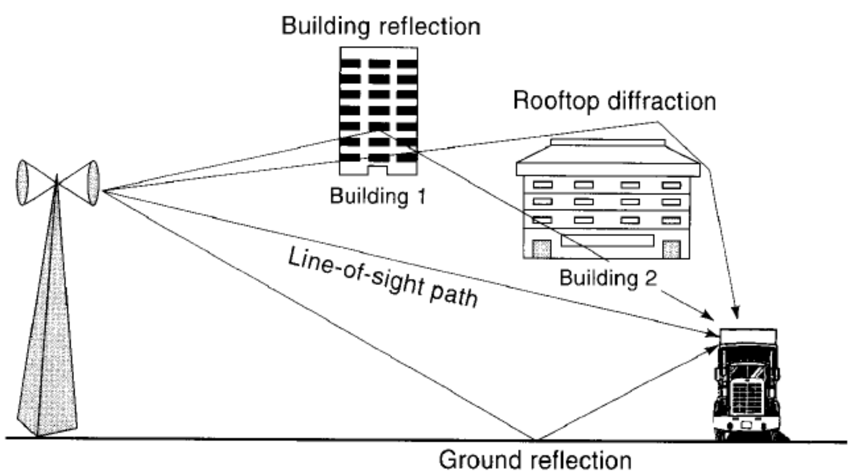


Figure.1.2 Radio propagation mechanisms in an outdoor area

Usually rays incident upon the ground, walls of buildings, the ceiling, and the floor undergo specular reflection and transmission with the amplitude coefficients usually determined by plane wave analysis. Upon reflection or transmission, a ray attenuates by factors that depend on the frequency, the angle of incidence, and the nature of the medium (its material properties, thickness, homogeneity, etc.). These mechanisms often dominate radio propagation in indoor applications. In outdoor urban areas, this mechanism often loses its importance because it involves multiple transmissions that reduce the strength of the signal to negligible values.

2. **Diffraction.** Rays that are incident upon the edges of buildings, walls, and other large objects can be viewed as exciting the edges to act as a secondary line source. Diffracted fields are generated by this secondary wave source and propagate away from the diffracting edge as cylindrical waves. In effect, this results in propagation into shadowed regions because the diffracted field can reach a receiver, which is not in the line of sight of the transmitter. Because a secondary source is created, it suffers a loss much greater than that experienced via reflection or transmission. Consequently, diffraction is an important phenomenon outdoors (especially in microcellular areas) where signal transmission through buildings is virtually impossible. It is less consequential indoors where a diffracted signal is extremely weak compared to a reflected signal or a signal that is transmitted through a relatively thin wall.

3. **Scattering**. Irregular objects such as walls with rough surfaces and furniture (indoors) and vehicles, foliage, and the like (outdoors) scatter rays in all directions in the form of spherical waves. This particularly occurs when objects are of dimensions that are on the order of wavelength or less of the electromagnetic wave. Propagation in many directions results in reduced power levels, especially far from the scatterer. As a result, this phenomenon is not that significant unless the receiver or transmitter is located in a high cluttered environment. This mechanism dominates diffused IR propagation when the Wavelength of the signal is such that the roughness of the wall results in extensive scattering. In satellite and mobile radio applications, foliage often causes scattering.

1.4. Pathloss modeling and signal coverage

1.4.1 Free Space Propagation

In most environments, it is observed that the radio signal falls as some power α of the distance, called the power-distance gradient or path-loss gradient. That is, if the transmitted power is P_γ after a distance d in meters, the signal strength will be proportional to $P_t\, d^{-\alpha}$. In its most simple case, the signal strength falls as the square of the distance in free space (α=2). When an antenna radiates a signal, the signal propagates in all directions. The signal strength density at a sphere, of radiu d is the total radiated signal strength divided by the area of the sphere, which is $4\pi d^2$.

Depending on the radio frequency, there are additional losses, and in general the relationship between the transmitted power p_t and the received power p_r in free space is given by:

$$\frac{P_r}{p_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \qquad (1.1)$$

Here G_t and G_r are the transmitter and receiver antenna gains respectively in the direction from the transmitter to the receiver; d is the distance between the transmitter and the receiver; $\lambda = c / f$ is the wavelength of the carrier; c is the seed of light in free space ($3 \times 10^8 m / s$); and f is the frequency of the radio carrier if we let $p_0 = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$ be the received signal at the first meter ($d = 1\, m$). We can rewrite this question as:

$$P_r = \frac{p_0}{d^2} \qquad (1.2)$$

In Decibels (dB) this equation takes the form

$$10\log(P_r) = 10\log(P_0) - 20\log(d) \qquad (1.3)$$

Where the logarithm is to the base 10. This means that there is a 20dB per decade or 6dB per octave loss in signal strength as a function of distance in free space. The transmission delay as a function of distance is given by $\tau = d / c = 3d\ ns\ or\ 3\ ns$ per meter of distance.

1.4.2. Two-Ray Model for Mobile Radio Environments

The distance-power relationship observed for free space does not hold for all environments. I free space; the signal travels from the transmitter to the receiver along a single path. In all realistic environments, the signal reaches the receiver through several different paths. The simple free space model of the previous section will not be valid for such scenarios and several complex models are required.

We start with the two path or two ray model that is used for modeling the land mobile radio. The propagation environment and the two-ray model are shown in figure 1.3. Here, the base station and the mobile terminal are both assumed to be at elevations above the earth, which is modeled as a flat surface in between the base station and mobile terminal. Usually there is an LOS component that exists between the base station and the mobile terminal which carries the signal as in free space. There will also be another path over which the signal travels that consists of reflection off the flat surface of the earth. The two paths travel different distances based on the height of the base station antenna, h_b , and the height of the mobile terminal antenna, h_m , and result in the addition of signals either constructively or destructively at the receiver.

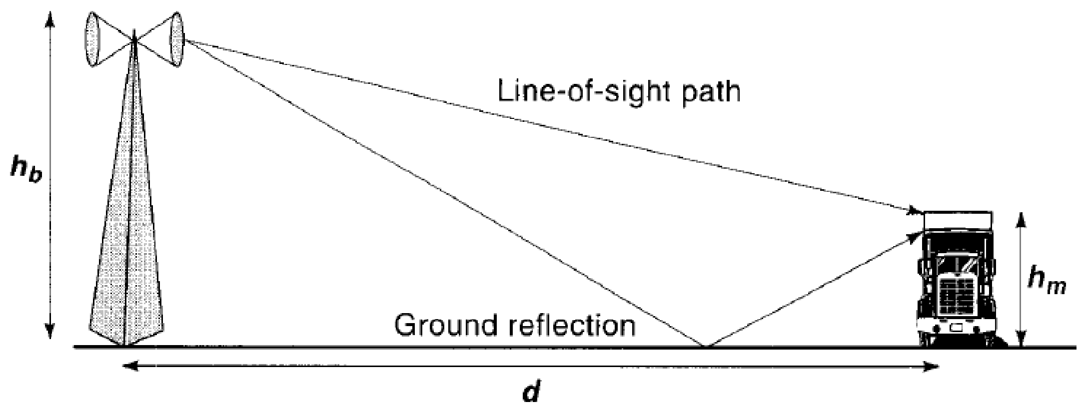


Figure 1.3. Two-ray model for mobile radio environments

It can be shown that the relationship between the transmit power and the received power for the two-ray model can be approximated as:

$$P_r = P_t G_t G_r \frac{h_b^{\,2} h_m^{\,2}}{d^4} \qquad (1.4)$$

It is interesting to see that the signal strength falls as the fourth power of the distance between the transmitter and the receiver. In other words, there is a loss of 40 dB per decade or 12 dB per octave. The other interesting observation here is that the received signal strength can be increased by raising the heights of the transmit and receive antennas.

1.4.3. Distance-Power Relationship and Shadow Fading

The simplest method of relating the received signal power to the distance is to state that the received signal power P_r is proportional to the distance between transmitter and receiver d, raised to a certain exponent α , which is referred to as the distance –power gradient, that is,

$$P_r = P_0 d^{-\alpha} \qquad (1.5)$$

where P_0 is the received power at a reference distance (usually one meter) from the transmitter. For free-space, as already discussed, $\alpha = 2$, and for simplified two-path model of an urban radio channel, $\alpha = 4$.

For indoor and urban radio channels the distance-power relationship will change with the building and street layouts, as well as with construction materials and density and height of the building in the area. Generally, variations in the value of the distance-power gradient in different outdoor areas are smaller than variations observed in indoor areas. The results of indoor radio propagation studies show values of α smaller than 2for corridors or large open indoor areas and values as high as 6 for metallic buildings.

The distance-power relationship of eq (1.5) in decibels is given by

$$10\log(P_r) = 10\log(P_0) - 10\alpha\log(d) \qquad (1.6)$$

Where P_r and P_0 are the received signal strengths at d meters and at one meter, respectively. The last term in the right-hand side of the equation represents the power loss in dB with respect to the received power at one meter, and it indicates that for a one-decade increase in distance, the power loss is $10\alpha\ dB$

and for a one-octave increase in distance, it is $3\alpha\ dB$. If we define the path loss in dB at a distance of one meter as $L_0 = 10\log_{10}(P_t) - 10\log_{10}(P_0)$ the total path loss in dB is given by:

$$L_p = L_0 + 10\alpha\log(d) \qquad (1.7)$$

This presents the total path-loss in the first meter plus the loss relative to the power received at one meter. The received power in dB is the transmitted power in dB minus the total path loss L_p. This normalized equation is occasionally used in the literature to represent the distance-power relationship.

The path loss models of this form are extensively used for deployment of cellular networks. The coverage area of a radio transmitter depends on the power of the transmitted signal and the path loss. Each radio receiver has particular power sensitivity, for example, it can only detect and decode signals with strength larger than this sensitivity. Because the signal strength falls with distance, using the transmitter power, the path-loss model, and the sensitivity of the receiver, one can calculate the coverage.

1.4.4. Path Loss Models for Megacellular Area

Megacellular areas are those where the communication is over extremely large cells spanning hundreds of kilometers. Megacells are served mostly by mobile satellites (usually low-earth orbiting-LEO). The path loss is usually the same as that of free space, but the fading characteristics are somewhat different.

Path Loss Models for Macrocellular Area

Macrocellular area span a few kilometers to tens of kilometers, depending on the location. These are the traditional "cells" corresponding to the coverage area of base station associated with traditional cellular telephony base stations. The frequency of operation is mostly around 900 MHz, though the emergence of PCS has resulted in frequencies around 1,800 to 1,900MHz, for such cells. There have been extensive measurements in a number of cities and locations of the received signal strength in macrocellular area that have been reported in the literature. The most popular of these measurements correspond to those of Okumara who determined a set of path loss curves as a function of distance in 1968 for a range of frequencies between 100MHz and 1,920 MHz. Okumara also identified the height of base station antenna h_b and the height of the mobile antenna h_m as important parameters. Masaharu Hata [HAT80] created empirical models that provide a goodfit to the measurements taken by Okumara for transmitter receiver separations d of more than 1 km. The expressions for path loss developed by Hata are called the Okumara-Hata models or simply the Hata models. Table 1.1. provides these models.

- $L_p = 69.55 + 26.16 \lg f_c - 13.82 \lg h_b - a(h_m) + [44.9 - 6.55 \lg h_b] \lg d$
  - Where f_c is in MHz, h_b and h_m are in meters, and d is in km.
- Suburban Areas Formulation:
  - Use Eq. and subtract a correction factor given by:

– $K_r(dB) = 2[lg(f_c/28)]^2 + 5.4$

Range of Values			
Center frequency f_c in MHz			150~1500MHz
h_b, h_m in meters			30~200m, 1~10m
$a(h_m)$ in dB	Large City	$f_c \leq 200$ MHz	$8.29[\lg(1.54h_m)]^2 - 1.1$
		$f_c \geq 400$ MHz	$3.2[\lg(11.75h_m)]^2 - 4.79$
	Medium-Small City	$150 \geq f_c \geq 1500$ MHz	$1.1\ [\lg f_c - 0.7]\ h_m - (1.56\lg f_c - 0.8)$

To extend the Okumara-Hata model for PCS applications operating at 1,800 to 2,000 MHz, the European Co-operative for Scientific and Technical Research (COST) came up with the COST-231model for urban radio propagation at 1.900MHz, which we provide in table 2C.1 in Appendix 2C. In this table $a(h_m)$ is chosen from Table 2.1 for large cities.

In similar way, the Joint Technical Committee (JTC) of the Telecommunications and Industry Association (TIA) has come up with the JTC models of models for PCS models applications at 1,800 MHz.