Introduction to Mobile Radio Propagation and Characterization of Frequency Bands

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Course: Wireless Communication Technologies 16:332:559

Lecture #1

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I. INTRODUCTION

The term wireless communication refers to transfer of information via electromagnetic or acoustic waves over atmospheric space rather than along a cable. The apparent wrinkle between such a scheme and conventional wired systems is the presence of the wireless channel as the medium over which the communication must take place. Unfortunately, more often than not, this medium is hostile in regards to attenuating, delaying, and even completely distorting the transmitted signal. Thus when considering a general digital wireless communication system such as that in Fig. 1, the design of each building block will be dependent on the channel between transmitter and receiver. Therefore, before moving on to specific issues such as modulation, source/channel coding, synchronization, equalization, multi-access analysis, and radio resource management; it makes sense to analyze and appreciate one of the main obstacles that such techniques are trying to account for.

For the purpose of this course, we will focus our attention on the more specific digital wireless communication system shown in Fig. 2 for terrestrial communication. Thus, for the particular case at hand, we will assume that the remaining blocks in Fig. 1 have either been taken care of or are not being used.

II. ATMOSPHERIC EFFECTS ON MOBILE RADIO PROPAGATION

The wireless medium introduces difficulties for communication by its inherent nature. The atmospheric medium most relevant to terrestrial radio propagation may be specified as that of Fig. 3. The troposphere is the first layer above the surface of the earth, and contains approximately half of the earth's atmosphere. This is the layer at which weather takes place. The ionosphere is where ions and electrons exist in sufficient quantities to reflect and/or refract the electromagnetic radio waves. For our specified model, it suffices to consider two types of electromagnetic waves: *ground waves* and *sky waves*. The ground wave is the portion of the transmitted signal that propagates along the contour of the earth. Understandably, such waves are directly affected by the earth's terrain. Ground waves are the dominant mode of propagation for frequencies below 2 MHz.

As frequency increases the sky wave separates from the sky wave, enabling long distance communication. More specifically, the sky wave propagates in space and returns to the earth via reflection in either the ionosphere or the troposphere, thereby enabling beyond the horizon communication through successive reflection. It is interesting to note that above 30 MHz the sky wave propagates in a straight line, and actually propagates through the ionosphere. This property is taken advantage of for satellite communication.

Frequency Band	Frequency Range (Wavelength)	Propagation Modes
ELF (Extremely Low Frequency)	Less than 3 KHz $(\lambda > 100$ km$)$	Ground wave
VLF (Very Low Frequency)	3-30 KHz $(10$ km $\leq \lambda < 100$ km$)$	Earth-Ionosphere guided
LF (Low Frequency)	30-300 KHz $(1$ km $\leq \lambda < 10$ km$)$	Ground wave
MF (Medium Frequency)	300 KHz-3 MHz $(100$ m $\leq \lambda < 1$ km$)$	Ground/sky wave for short/long distances.
HF (High Frequency)	3-30 MHz $(10$ m $\leq \lambda < 100$ m$)$	Sky wave, but limited, short-distance ground wave also.
VHF (Very High Frequency)	30-300 MHz $(1$ m $\leq \lambda < 10$ m$)$ 30-60 MHz $(5$ m $< \lambda < 10$ m$)$	Space wave Space wave
UHF (Ultra High Frequency)	300 MHz-3 GHz $(10$ cm $\leq \lambda < 1$ m$)$	Space wave
SHF (Super High Frequency)	3 GHz-30 GHz $(1$ cm $\leq \lambda < 10$ cm$)$	Space wave
EHF (Extremely High Frequency)	30 GHz-300 GHz $(1$ mm $\leq \lambda < 10$ mm$)$	Space wave

Table 1: Radio Frequency Allocations.

III. CHARACTERIZATION OF FREQUENCY BANDS

Due to dissimilar propagation properties of different frequencies traveling over the ionosphere and troposphere, it is logical to assign separate spectrum allocations to different applications. For example, for commercial cellular systems, small antenna size is a premium. This brings about the necessity of using radio waves with small wavelengths and hence high frequencies. Table 1 gives a brief picture of frequency spectrum classifications, below the specifications and applications are discussed:

ELF (Extremely Low Frequency) :

Radio wave propagates between surface of earth and Ionosphere, also penetrating deep into water and ground. Experiences low attenuation, and high atmospheric noise level. The very large wavelength of radio waves requires implementation of large antennas.
Applications : Worldwide military and submarine communication.

VLF (Very Low Frequency) :

Similar to ELF, slightly less reliable.
Applications : Communication underwater and in mines, SONAR.

LF (Low Frequency) :

Sky wave can be separated from ground wave for frequencies above 100 KHz. Logically, the ground wave has a larger transmission loss. Absorption in daytime.
Applications : Long-range navigation and marine communication, radio beacons.

MF (Medium Frequency) :

Sky wave separates from ground wave. Ground wave gives usable signal strength up to approximately 100 km from the transmitter.

Applications : Maritime radio, direction finding, and AM radio broadcast (550-1600 KHz).

<u>*HF* (*High Frequency*) :</u>

Sky wave is the main mode of propagation. Ground wave used for communication over shorter distances.

Applications : Amature radio (HAM), international broadcasting, long distance aircraft and ship communication, citizen band (CB) radios.

<u>*VHF* (*Very High Frequency*) :</u>

Diffraction and reflection give rise to propagation beyond the horizon. Propagation at large distance, propagates well within buildings.

Applications : FM Radio (88-108 MHz), Broadcast TV, radio beacons for air traffic, AM aircraft communication.

<u>*UHF* (*Ultra High Frequency*) :</u>

Reflection atmospheric layers, losses due to obstacles larger than those encountered in VHF band. Effect of rain and moisture negligible.

Applications : GPS, microwave links, wireless personal communication systems: Cellular, PCS, 3G, unlicensed band communication: Bluetooth, 802.11b, LMDS (500 Mbps).

<u>*SHF* (*Super High Frequency*) :</u>

Propagation distances become limited due to absorption by atmosphere (i.e. rain, clouds).

Applications : Satellite services for telephony and TV, LEO and GEO satellite systems, possible future mobile communication services, MMDS (1 Gbps), UNII band (300 MHz @ 5 GHz) communication: 802.11a, Home RF.

<u>*EHF* (*Extremely High Frequency*) :</u>

Basically all particles become obstacles due to very small wavelengths. Absorption effects greatly limit range/distance. High losses due to water, vapor, oxygen in atmosphere.

Applications : Short-distance communication (LOS required), currently being proposed for HDTV, satellite communication.

Large-Scale Mobile Radio Propagation and Path Loss Models for Macrocells

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Course: Wireless Communication Technologies 16:332:559
Lecture #2
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I. INTRODUCTION TO LARGE-SCALE PROPAGATION

The general term *fading* is used to describe fluctuations in the envelope of a transmitted radio signal. However, when speaking of such fluctuations, one must consider whether a short observation interval (or small distance) has been taken, or whether a long observation interval (or large distance) has been taken. For a wireless channel, the former case will show rapid fluctuations in the signal's envelope, while the latter will give more of an slowly varying, averaged view. For this reason the first scenario is formally called *small-scale fading* (or multipath), while the second scenario is referred to as *large-scale path loss*. In this presentation we will only focus on the large-scale effect.

Received power or its reciprocal, path loss, is generally the most important parameter predicted by large-scale propagation models. It is valuable to examine the three main propagation mechanisms that determine and describe path loss:

Reflection occurs when a radio wave collides with an object which has very large dimensions compared to the wavelength of the propagating wave. Reflections are very commonly caused by the surface of the earth and from buildings, walls, and other such obstructions.

Diffraction occurs when the radio path between the transmitter/receiver pair is obstructed by a surface with sharp edges. This causes secondary waves to arise (in any conceivable direction) from the obstructing surface. There is a possibility that the secondary waves can bend around the obstacle and provide an almost artificial LOS between transmitter and receiver. Like reflection, this phenomenon is dependent on: frequency, amplitude, phase, and the angle of arrival of the incident wave.

Scattering occurs when the radio wave travels through a medium consisting of objects with dimensions that are small compared to the wave's wavelength. In such a case the number of such particles per unit volume are usually very large. Typically scattered waves arise when the radio wave meets rough surfaces or small objects in the channel.

II. FREE SPACE PATH LOSS MODEL

To obtain a more quantitative view of the effects of path loss, it is useful to consider a few examples. The simplest case of which is the path loss model for free space due to the fact that the influence of all obstacles is ignored. Further easing the analysis, consider the model to be *isotropic*, where the transmitting antenna signaling with power P_t, has its power radiate uniformly in all directions. Examining the path loss will tell us the amount of power available at the receive antenna a distance r meters away. This situation can be modeled as in Fig. 4 where the transmit antenna can be considered to be at the center of a sphere with radius r. The total power density on the sphere (also referred to as *flux density*) may be expressed as:

$$P_d = \frac{EIRP}{4\pi r^2} = \frac{P_t}{4\pi r^2} \quad Watts/m^2 \tag{1}$$

where $EIRP$ is the effective radiated power from an isotropic source and $4\pi r^2$ is the surface area of the sphere. In this model, the power at the receive antenna will be only a function of the transmitted power and the characteristics of the receive antenna:

$$P_r = P_d A_e = \frac{P_t A_e}{4\pi r^2} \quad Watts \tag{2}$$

where A_e is the effective aperture of the receive antenna. As seen from (2), the received power P_d is inversely proportional to r^2. It so happens that the inverse-square relation is the ideal case due to the combination of free space, LOS, and isotropic assumptions.

The effective aperture of an antenna (A_e) is generally related to its "Gain" G by

$$G = \frac{4\pi A_e}{\lambda^2} \tag{3}$$

$$\therefore \;\; P_r = \frac{P_t G \lambda^2}{(4\pi r)^2} = \frac{P_t G_T G_R \lambda^2}{(4\pi r)^2} \tag{4}$$

where G_T and G_R are the transmitter and receiver gains, respectively. Eq.(4) is referred to as the Friis free space equation.

In mobile systems the received power may change several orders of magnitude over a fraction of a typical coverage area. This coupled with the fact that mobile systems employ low-power devices (order of milliwatts) leads to the choice of *dBm* (*dB* normalized to 1.0 mW) as the preferred unit for measuring power. Thus the path loss for the free space model may be expressed as:

$$P_L(dBm) = 10\log_{10}\left(\frac{P_t}{0.001 P_r}\right) = -10\log_{10}\left(\frac{G_T G_R \lambda^2}{0.001(4\pi r)^2}\right) \tag{5}$$

III. PROPAGATION MODEL FOR NEAR EARTH'S SURFACE

When considering the more realistic model (compared to that of the highly ideal free space) of near Earth propagation, we must consider a direct wave, ground wave, and ground reflected wave component. This scenario is depicted in Fig. 5, along with its equivalent flat Earth model in Fig. 6. The main assumptions that lead to the flat Earth model are the absence of the ground waves due to the hight of the antenna when compared to that of the wavelength, and the lack of curvature of the Earth (very accurate for short distances). Looking at Fig. 6, the received signal $E(t)$ in this 2-ray model may be represented as:

$$E(t) = E_o \cos(\omega t) + \rho E_o \cos(\omega(t - \triangle t) + \phi) \tag{6}$$

where ρ and ϕ represent the attenuation and phase shift of the ground reflected wave, which is the second term. E_o, the signal field strength of the direct wave (assuming a free space model), exists in both the direct wave component and the reflected wave component. From (6) we can conclude that reflection upon earth brought about a phase change, an attenuation, and a time delay $\triangle t$ with respect to the direct path.

Making the additional assumption that the difference in path lengths between the two components is much less that the distance between the antennas (r), allows us to approximate $\rho \approx 1$. Furthermore, assuming $perfect\ mirror\ reflection$ via the ground, gives $\phi = \pi$. We can now state:

$$E(t) = E_o \cos(\omega t) + \rho E_o \cos(\omega(t - \triangle t) + \phi) = 2E_o \sin\left(\frac{\omega \triangle t}{2}\right)\cos(\omega t + \psi) \tag{7}$$

where ψ is the approximate phase, $sin(\cdot)$ is constant,
and the resulting amplitude is $E = 2E_o\ sin(\frac{\omega\Delta t}{2})$.

the geometry of of Fig. 6 yields:

$$d_D = \sqrt{r^2 + (h_2 - h_1)^2} \tag{8}$$

$$d_R = \sqrt{r^2 + (h_2 + h_1)^2} \tag{9}$$

another fair assumption would be: $r \gg h_1$ and $r \gg h_2$. Invoking this in (8) and (9):

$$d_D \approx r\left(1 + \frac{1}{2}\left(\frac{h_2 - h_1}{r}\right)^2\right) \tag{10}$$

$$d_R \approx r\left(1 + \frac{1}{2}\left(\frac{h_2 + h_1}{r}\right)^2\right) \tag{11}$$

using the relations:

$$\begin{gathered}\Delta\, d = d_R - d_D \approx \tfrac{2h_1 h_2}{r} \\ \Delta\, t = \tfrac{\Delta d}{c} \\ \omega = 2\pi f = \tfrac{2\pi c}{\lambda}\end{gathered}$$

the magnitude of the recieved recieved wave in (7) can be modeled as:

$$|E| = 2E_o\left|\sin\left(\frac{\omega\Delta t}{2}\right)\right| = 2E_o\left|\sin\left(\frac{2\pi h_1 h_2}{\lambda r}\right)\right| \tag{12}$$

thus the recieved power is

$$P_r = 4E_o^2 \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \tag{13}$$

where E_o^2 is the power recieved in the $free\ space$ model:

$$E_o^2 \triangleq P_r(freespace) = \frac{P_t G_t A_e}{4\pi r^2} \tag{14}$$

$$\therefore\ \ P_r = \frac{P_t G_t A_e}{\pi r^2}\sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \tag{15}$$

when antenna elevations are small compared to distance between transmitter/reciever pair, i.e. $h_1 h_2 \ll \lambda r$, we can make the small angle approximation $\sin(x) \approx x$ to get:

$$P_r = \frac{4\pi P_t A_e (h_1 h_2)^2}{\lambda^2 r^4} \tag{16}$$

the key point to be taken away from (13) is that for propagation close to the Earth's surface the recieved power of the signal is inversley proportional to r^4. Comparing this fourth order decay with the second order decay in (2) for the free space model leads us to conclude that recieved power decays more rapidly with distance once the ideal free space model is discarded in favor of the more realistic model for propagtion near the Earth's surface.

Further examining (16) we may express the path loss (in dBm) as:

$$P_L(dBm) = 10\log_{10}\left(\frac{P_t}{0.001P_r}\right) = -10\log_{10}\left(\frac{(h_1 h_2)^2}{0.001r^2}\right) \tag{17}$$

The unfortunate aspect of (17) for path loss near the Earth's surface, is that it is only a function of the antenna hights and the distance betwee transmitter and reciever. To be more explicit, the path loss obtained by (17) is independent of the carrier frequency used for the transmision. Thus, the above analysis is best charecterised as very simplistic and good enough to give a ball-park estimate.

IV. EMPIRICAL PATH LOSS MODELS FOR MACROCELLS

Macrocells are generally large, providing a coverage range on the order of kilometers, and used for outdoor communication. Several emperical path loss models have been determined for macrocells. Two such models will be outlined below, namely *Hata′s model* which was based on graphical path loss data provided by Okumura, and *Lee′s model*.

<u>*Hata′s model* :</u>

Hata's model was based on empirical data from measurements in Tokyo, Japan and has been claimed to give an accurate estimate of the path loss to within 1.0 dB when compared with the actual measurements. Unfortunately it does not apply too well to the North American suburban terrain. Regardless, the model is useful for the following scenarios:

Carrier frequency: 150 MHz $\leq f_c \leq$ 1000 MHz
Base station height: 30 m $\leq h_b \leq$ 200 m
Mobile station height: 1 m $\leq h_m \leq$ 10 m
Distance between mobile and base station: 1 Km $\leq$ d $\leq$ 20 Km

$$L_p(dB) = \begin{cases} A + B\log_{10}(d) & for\ urban\ areas \\ A + B\log_{10}(d) - C & for\ suburban\ areas \\ A + B\log_{10}(d) - D & for\ open\ areas \end{cases} \tag{18}$$

where

A = 69.55 + 26.16$\log_{10}(f_c)$ − 13.82$\log_{10}(h_b)$ − a(h_m)
B = 44.9 − 6.55$\log_{10}(h_b)$
C = 5.4 + 2 $\left[\log_{10}(\frac{f_c}{28})\right]$
D = 40.94 + 4.78 $[\log_{10}(f_c)]^2$ − 19.33$\log_{10}(f_c)$

and

$$a(h_m) = \begin{cases} [1.1\log_{10}(f_c) - 0.7]h_m - 1.56\log_{10}(f_c) - 0.8 & for\ meduim/small\ city \\ 8.28[\log_{10}(1.54h_m)]^2 - 1.1 & for\ large\ city\ and\ f_c \leq 400\ MHz \\ 3.2[\log_{10}(11.75h_m)]^2 - 4.97 & for\ large\ city\ and\ f_c \geq 400\ MHz \end{cases} \tag{19}$$

<u>*Lee′s model* :</u>

Lee's path loss model was based on empirical data chosen as to model a flat terrain. Large errors arise when the model is applied to a non-flat terrain, however, Lee's model has been know to be more of a "North American model" than that of Hata. The received signal power in dBm is expressed as

$$\mu_\Omega = 10\log_{10}\left(\mu_{\Omega o}\left(\frac{d_o}{d}\right)^\beta \left(\frac{f_c}{f}\right)^n \alpha_o\right) \tag{20}$$

Two parameters are initially required to characterize the model: $\mu_{\Omega o}$ (the power at a 1.6 Km point of interception) and the path loss exponent β. These two parameters are determined from empirical measurements and listed in tables such as that of Table 1. Subsequently the following nominal conditions are set when employing Lee's model:

f_c = 900 MHz

d_o = 1.6 Km
base station antenna hight = 30.48 m
mobile station antenna hight = 3.0 m
base station transmit power = 10 W
base station antenna gain = 6 dB above dipole gain
mobile station antenna gain = 0 dB above dipole gain

the following parameters must also be set:

- f the actual carrier frequency
- d distance between mobile station and base station antennas
- α_o correction factor

the parameter α_o is basically used to account for different BS and MS antenna heights, transmit powers, and antenna gains. For instance, if the actual conditions differ from the nominal ones, then α_o is computed via:

$$\alpha_o = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5 \tag{21}$$

where

$$\alpha_1 = \left(\frac{new\ BS\ antenna\ hight\ (m)}{30.48\ m}\right)^2 \tag{22}$$

Terrain	$\mu_{\Omega o}$	β
Free Space	-45	2
Open Area	-49	4.35
North American Suburban	-61.7	3.84
North American Urban	-70	3.68
North American Urban	-64	4.31
Japanese Urban	-84	3.05

Table 1: Parameters for Lee's path loss model.

$$\alpha_2 = \left(\frac{new\ MS\ antenna\ hight(m)}{3\ m}\right)^{\xi} \tag{23}$$

$$\alpha_3 = \left(\frac{new\ transmitter\ power}{10\ W}\right)^2 \tag{24}$$

$$\alpha_4 = \frac{new\ BS\ antenna\ gain\ with\ respect\ to\ \lambda_c/2\ dipole}{4} \tag{25}$$

$$\alpha_5 = different\ antenna\ gain\ correction\ factor\ at\ the\ MS \tag{26}$$

the values of n in (20) and ξ in (23) are also based on empirical data and recommended to take the following values:

$$n = \begin{cases} 2.0 & for\ f_c < 450\ MHz\ and\ in\ suburban/open\ area \\ 3.0 & for\ f_c > 450\ MHz\ and\ in\ urban\ area \end{cases} \tag{27}$$

$$\xi = \begin{cases} 2.0 & for\ MS\ antenna\ hight\ > 10\ m \\ 3.0 & for\ MS\ antenna\ hight\ < 3\ m \end{cases} \tag{28}$$

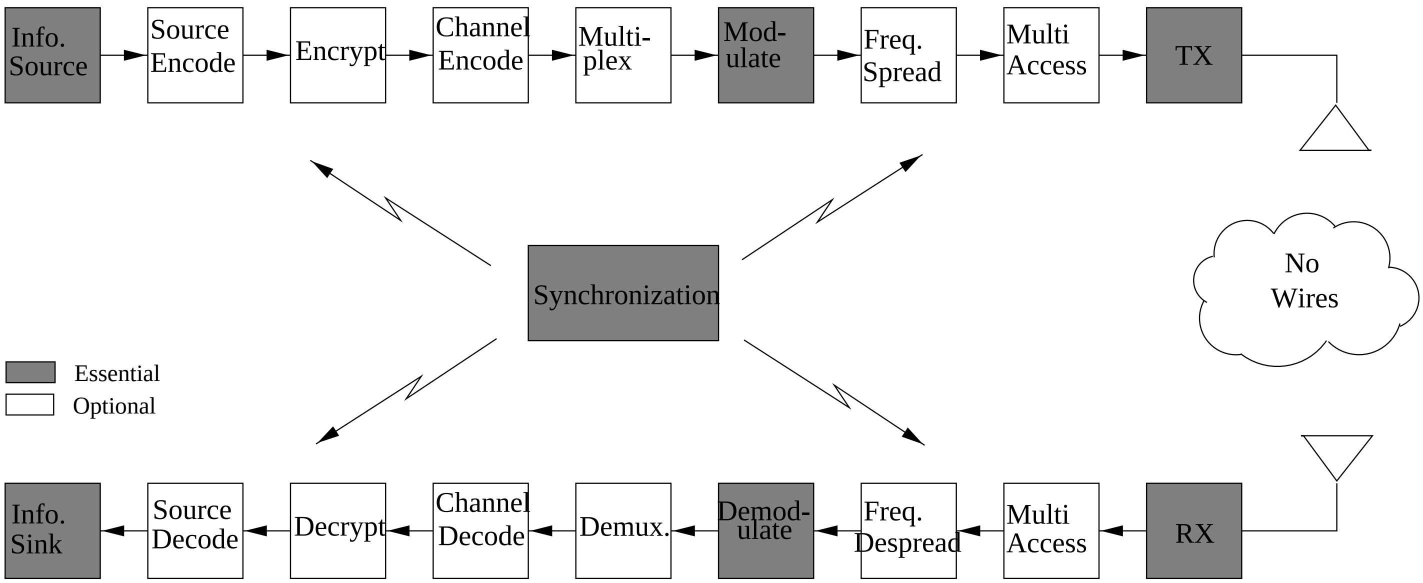

Figure 1: Block diagram of typical digital wireless communication systems as specified in [5].

Finally, the path loss L_p is defined as the difference between the transmitted and received field strengths and can be expressed as:

$$L_p = P_t - \mu_{\Omega o}\, dBm \tag{29}$$

For the scenarios listed in Table 1, the path loss obtained from Lee's model can be reduced to:

$$L_p(dBm) = \begin{cases} 85 + 20\log_{10}(\frac{r}{1.6\,Km}) + 10n\log_{10}(\frac{f}{900\,MHz}) - \alpha_o & Free\ Space \\ 89 + 43.5\log_{10}(\frac{r}{1.6\,Km}) + 10n\log_{10}(\frac{f}{900\,MHz}) - \alpha_o & Open\ Area \\ 101.7 + 38.41\log_{10}(\frac{r}{1.6\,Km}) + 10n\log_{10}(\frac{f}{900\,MHz}) - \alpha_o & Suburban \\ 110 + 36.81\log_{10}(\frac{r}{1.6\,Km}) + 10n\log_{10}(\frac{f}{900\,MHz}) - \alpha_o & Philadelphia \\ 104 + 43.1\log_{10}(\frac{r}{1.6\,Km}) + 10n\log_{10}(\frac{f}{900\,MHz}) - \alpha_o & Newark \\ 124 + 30.51\log_{10}(\frac{r}{1.6\,Km}) + 10n\log_{10}(\frac{f}{900\,MHz}) - \alpha_o & Tokyo \end{cases} \tag{30}$$

where r is in Km and f is in MHz. It should be apparent that Lee's model is more generic and flexible than that of Hata's. Several other popular path loss models for macrocells are: Longly-Rice model, Durkin's model, Okumura model, and the Walfisch and Bertoni model.

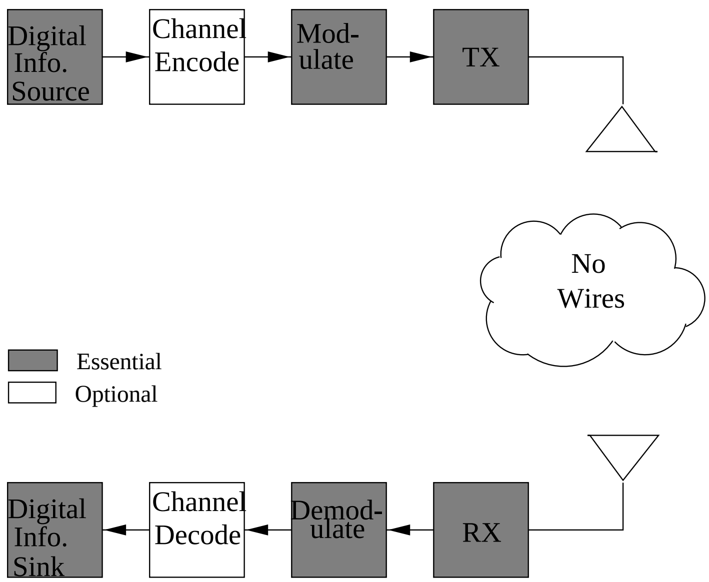

Figure 2: Block diagram of general digital wireless communication systems concentrated on in this course.

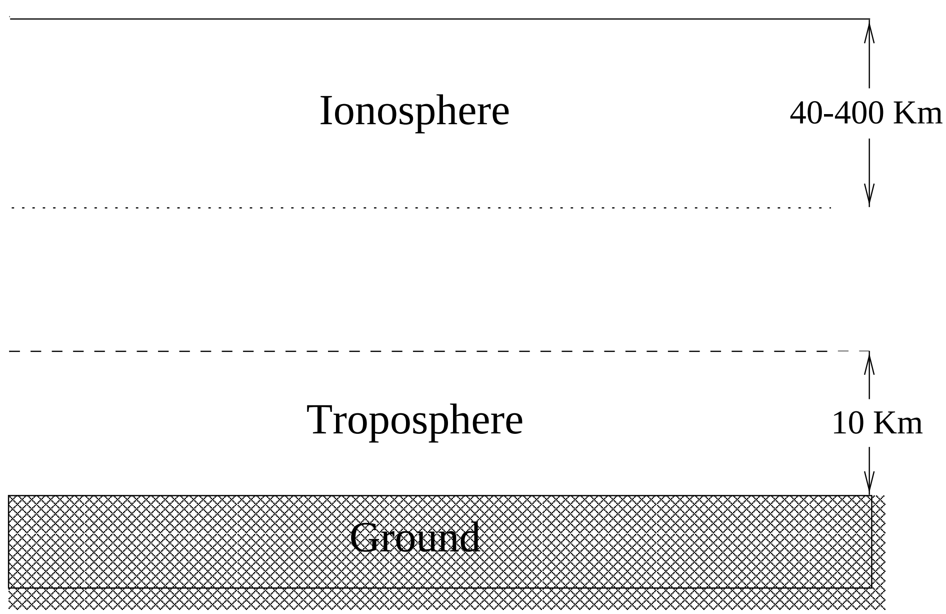

Figure 3: Layers of the Atmosphere relevant to terrestrial radio propagation.

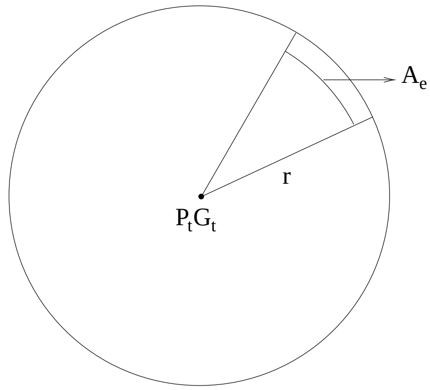

Figure 4: Propagation in free space.

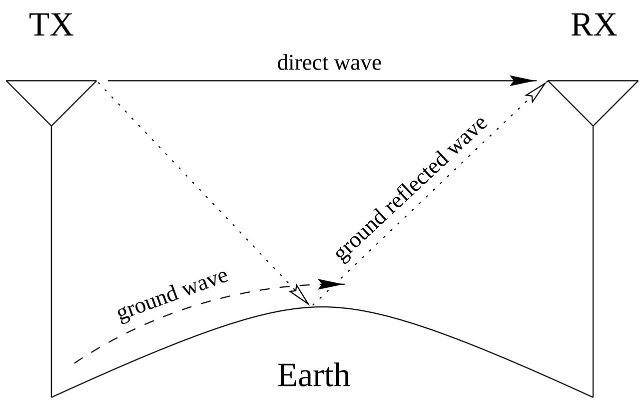

Figure 5: Propagation close to Earth's surface.

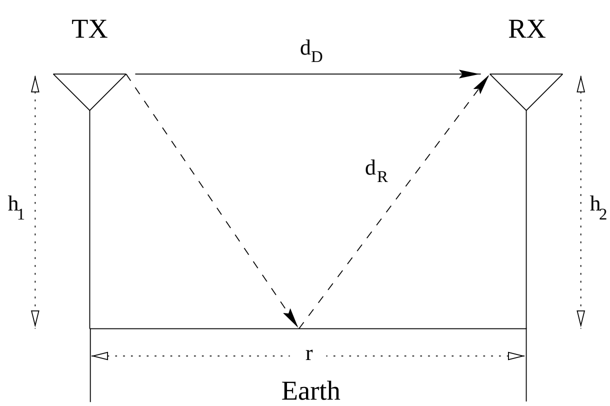

Figure 6: Equivalent model of propagation close to Earth's surface.

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