Introduction to Wireless Electromagnetic Channels & Large Scale Fading*

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Abstract- This article provides a brief introduction to wireless channels – frequency range classification of the electromagnetic spectra and large-scale propagation in such channels.

I. INTRODUCTION/MOTIVATION

The term *wireless communication* refers to the transfer of information using electromagnetic (EM) or acoustic waves over the atmosphere rather than using any propagation medium that employs wires. Not requiring an explicit network of wires and permitting communication while on the move were the main factors which motivated the study of wireless communication in the early 20th century.

Wireless communication evolved remarkably since Marconi first demonstrated radio's ability to provide continuous contact with ships sailing the English Channel in 1897. Since then, particularly during the last decade, the mobile radio communications industry has grown by orders of magnitude fueled by digital and RF circuit fabrication and miniaturization techniques that make portable radio equipment smaller, cheaper and more reliable. Digital switching techniques have facilitated large-scale deployment of networks. These trends will continue at an even greater pace.

Nature, however, exacts a price for using the wireless medium – it is susceptible to *interference* (from competing users), *noise*, *blockage* and *multi-path.* These impediments result in attenuation, delay and even complete distortion of the transmitted signal. Moreover, these channel impediments change with time in un-predictable ways due to user movement.

Thus, in order to be able to design good wireless systems, it becomes imperative, to have a good understanding of electromagnetic waves and the propagation media used in conjunction to achieve communication. This article provides an introduction to the atmospheric effects on wireless channels, characterization of the various frequency bands and an introduction to large-scale propagation. The interested reader is referred to the numerous references for details.

II. ATMOSPHERIC EFFECTS ON WIRELESS CHANNELS

The wireless medium introduces difficulties for communication by its very inherent nature. The atmosphere reflects, absorbs or scatters radio waves. The layers most relevant to terrestrial radio propagation are shown in fig 1 below.

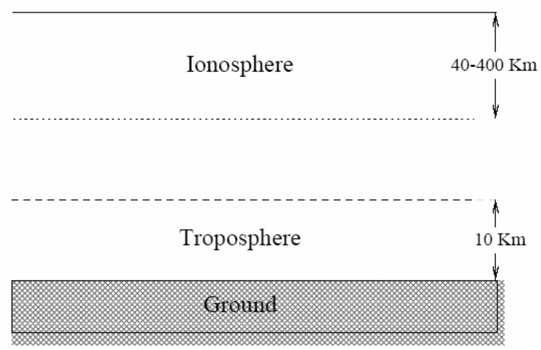

Fig 1: Atmospheric Layers relevant to terrestrial radio propagation.

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 radio waves. For our study, it has been found sufficient to consider the two components of EM waves, i.e., *sky-waves* and *ground-waves*.

Ground-wave propagation, as illustrated in fig 2 below, is the portion of the transmitted signal that propagates along the ground. Understandably, such waves are directly affected by the earth's terrain. Ground waves are the dominant mode of propagation for frequencies below 3 MHz.

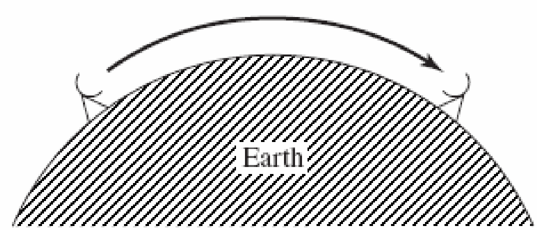

Fig 2: Illustration of ground-wave propagation.

Sky-wave propagation, results from transmitted signals being reflected (bent or refracted) from the ionosphere, which consists of several layers of charged particles ranging in altitude from 40 to 400 km above the surface of the earth. At higher frequencies, the sky-

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wave separates from the ground wave (this separation becomes more pronounced with increasing frequencies), thereby enabling long distance communication. Specifically, the sky-wave propagates in space and returns to the earth's surface due to reflections in the atmosphere, thereby enabling communication beyond the horizon through successive reflections. This is illustrated in fig 3 below.

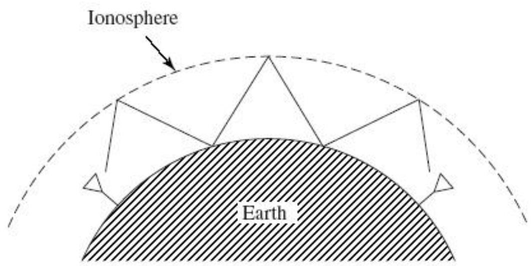

Fig 3: Illustration of ground-wave propagation.

Frequencies above 30 MHz propagate through the ionosphere with relatively little loss and make satellite and extra-terrestrial communications possible. Hence, at very high frequencies (30 MHz or higher), the dominant mode of EM propagation is *line-of-sight* (LOS). For terrestrial communication, this means that the transmitter and the receiver must be in direct LOS with relatively little or no obstruction. For this reason, television stations transmitting in this range mount their antennas on high towers to achieve a broad coverage area.

III. Characterization Of Frequency Bands

In the previous section, we discussed that sky-waves are reflected and/or refracted by the various layers of the earth's atmosphere. The key point is this: *the degree to which reflection or refraction occurs is a function of the frequency of the EM wave.* Hence due to dissimilar propagation properties of the different frequencies of EM waves traveling over the troposphere and the ionosphere, it is logical to study the behavior of the atmosphere for the entire EM spectrum. This study will help identify the proper applications that each frequency band can serve.

In wireless communication systems, EM energy is coupled to the propagation medium by an *antenna,* which serves as the *radiator*. *The physical size and configuration of the antenna depend primarily on the frequency of operation.* To obtain efficient radiation of EM energy, the antenna must be longer than $1/10^{th}$ of the wavelength. Consequently, a radio station transmitting in the *amplitude-modulated* (AM) frequency band, say at a *carrier frequency* f_c = 1 MHz [corresponding to a wavelength of $\lambda = c/f_c$ = 300 m], requires an antenna of at least 30 m. For commercial cellular systems, small antenna size is dictated by the form-factor of the device. This brings about the necessity of using radio waves with small wavelengths, i.e., high frequencies. Table 1 in the appendix provides the spectrum classification, propagation characteristics and applications for the various frequency ranges. Please note that for low frequencies (ELF – LF), ground-wave is the principle mode of communication. For medium frequencies (MF) ground-wave is used for short distances and sky-wave is used for long distances (beyond horizon). Finally, for high frequencies (HF – EHF), sky-wave is the chief mode of communication.

IV. 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 the observation has been made over short distances or long distances. For a wireless channel, the former case will show rapid fluctuations in the signal's envelope, while the latter will give a more slowly varying, averaged view. For this reason, the first scenario is formally called *small-scale fading* or *multi-path*, while the second scenario is referred to as *large-scale fading* or *path loss*.

Small scale fading is explained by the fact that, the instantaneous received signal strength is a sum of many contributions coming from different directions due to the many reflections of the transmitted signal reaching the receiver. Since the phases are random, the sum of contributions varies widely. The amplitude of the received signal obeys a *Rayleigh* fading distribution. In small-scale fading, the received signal power may very by as much as three or four orders of magnitude (30 or 40 dB) when the receiver is moved on the order of only a fraction of a wavelength.

Large scale fading is explained by the gradual loss of received signal power (since it propagates in all directions) with transmitter-receiver (T-R) separation distance.

To account for signal changes due to the peculiarities of the particular environment surrounding the transmitter or the receiver or both, a third category called *shadowing* also has been studied. Shadowing happens at a faster *time-scale* when compared to path loss, but slower compared to multi-path. Shadowing usually accounts for loss due to absorption by the *local* surrounding media such as trees, building for example. *Wave-guides* will lead to a better performance of the channel than expected. This effect also falls under shadowing. In this article, we will concern ourselves with large-scale fading, i.e., path loss only.

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 path loss:

(a) Reflection occurs when a propagating EM wave impinges upon an object, which has very large dimensions when compared to the wavelength of the propagating wave. Reflections occur from the surface of the earth and from buildings and walls.

(b) Diffraction occurs when the radio path between the transmitter and the receiver is obstructed by a surface that has sharp irregularities (edges). The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle, even when an LOS path does not exist between the transmitter and the receiver. At high frequencies, diffraction, like reflection, depends upon the geometry of the object, as well as the amplitude, phase and polarization of the incident wave at the point of diffraction.

(c) *Scattering* occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength of the propagating wave, and where the number of obstacles per unit volume is large. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel. In practice, foliage, street signs and lamp- posts induce scattering in mobile communication systems.

To obtain insight into large-scale fading, the first natural step is to consider propagation in free space, i.e., a medium that has no obstructing particles. We then refine our understanding to propagation close to the earth's surface, since the sky-wave is not the dominant mode of propagation for some part of the EM spectrum.

V. Free Space Propagation Model

The free space propagation model is used to predict received signal strength when the transmitter and receiver are separated by a medium that has absolutely no obstacles. As such, it has been found that this model also holds when the transmitter and receiver have a clear, unobstructed LOS path between them. Satellite communication systems and microwave LOS radio links typically undergo free-space propagation.

To begin the analysis, consider an isotropic radiating antenna, which communicates with a power budget P_t. (By isotropic is implied that energy flows equally in all directions). We wish to find the signal power that will reach a receiving antenna with effective aperture A_e at a distance r from the transmitter. The situation can be modeled as in fig 4 below, where the transmit antenna can be considered to be at the center of a sphere with radius r.

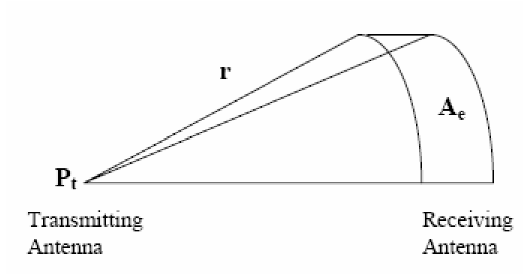

Fig 4: Propagation in free space.

Since, we are using an isotropic radiator, the power leaving the transmitter is uniformly distributed over the entire surface of the sphere of radius r.

Thus, the total power density on the sphere S_r is:

$$S_r = \frac{EIRP}{surface\_area\_of\_sphere} Watts/m^2$$

$$= \frac{P_t}{4\pi r^2} Watts/m^2 \quad (1)$$

where EIRP stands for effective radiated power from an isotropic source. The received power is a function of the transmitted power and the geometry of the receiving antenna, i.e., the effective aperture (A_e) of the receiving antenna.

Then, the received power P_r is:

$$P_r = S_r A_e = \frac{P_t A_e}{4\pi r^2} Watts \quad (2)$$

As can be seen from (2), $P_r \propto r^{-2}$. Please keep in mind that the inverse-square relation is for the ideal case of propagation in free space, under the assumption of isotropic radiator. Since this is free space, there are no obstructing particles; LOS is thus implied.

The effective aperture of an antenna is related to its *gain* by:

$$G = \frac{4\pi A_e}{\lambda^2} \quad (3)$$

$$\therefore P_r = \frac{P_t G \lambda^2}{(4\pi r)^2} = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2} \quad (4)$$

where G_t and G_r are the transmitter and the receiver gains respectively. Eqn. (4) is referred to as the *Friis Free Space Equation*.

The path loss (L_p), which represents signal attenuation as a positive quantity measured in dB, is defined as the difference (in dB) between the effective transmitted power and the received power, and may or may not include the effect of antenna gains. The path loss for the free space model when the antenna gains are included, is given by:

$$l_p(dB) = 10\log\frac{P_t}{P_r} \tag{5}$$

It is clear that Eq. (4) does not hold for r = 0, i.e., the Friis free space model is a valid predictor for P_r for values of *d*, which are in the *far-field* of the transmitting antenna. The far-field, or *Fraunhofer region*, of a transmitting antenna is defined as the distance beyond the far distance d_f, which is related to the largest linear dimension of the transmitter antenna aperture and the carrier wavelength.

$$d_f = \frac{2D^2}{\lambda} \tag{6}$$

where d_f is the Fraunhofer distance and D is the largest physical linear dimension of the antenna.

In mobile radio systems, it is not uncommon to find that P_r may change by many orders of magnitude over a typical coverage area of several square kilometers. Because of the large dynamic change of received power levels and coupled with the fact that mobile systems employ low-power devices (of the order of mW), often dBm unit is the preferred unit used to express received power levels. P_r in unit of dBm is given as:

$$P_r(dBm) = 10\log\left[\frac{P_r(inW)}{1mW}\right] \tag{7}$$

for free space propagation, we can thus write:

$$P_r(dBm) = 10\log\left[\frac{P_t G_t G_r}{1mW}\left(\frac{\lambda}{4\pi r}\right)^2\right] \tag{8}$$

Having gotten a first cut in our understanding of path loss, we now move to a model that is more realistic for everyday wireless communication – the so called *2-Ray Ground Reflection* model.

VI. 2-Ray Ground Reflection Model

For mobile communication that is close to the earth's surface, a single direct path is seldom the only physical means for propagation, and hence the free space propagation model is, in most cases inaccurate when used alone. We must now consider a direct wave, a ground wave and a ground reflected wave. At this point, we ignore the many waves that also reach the receiver due to the many atmospheric reflections. This scenario is depicted in fig 5 below.

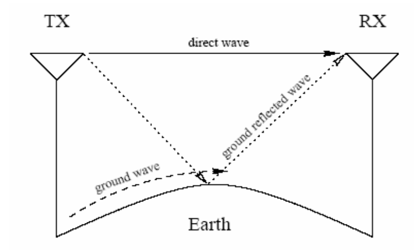

Fig 5: Propagation close to the Earth's surface.

In most mobile communication systems, the maximum T-R separation distance is at most only a few tens of kilometers, and thus, the earth may be assumed flat. Moreover, it has been found that when the antenna heights are much greater than the EM wavelength, the effect of the ground-wave can be neglected. This leads us to the *flat earth* model shown in fig 6 below.

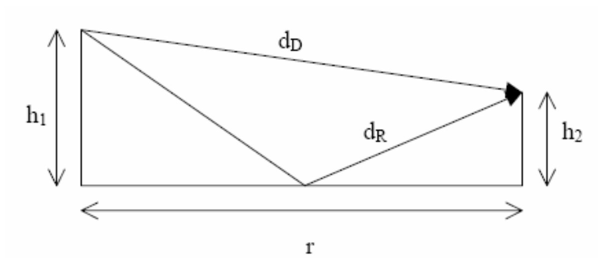

Fig 6: Equivalent model of propagation close to the Earth's surface.

Referring to the fig 6, h_1 is the height of the transmitter and h_2 is the height of the receiver. Two propagating waves arrive at the receiver: the direct wave that travels a distance d_D, and the reflected wave that travels a distance d_R. Moreover, let E_0 be the signal field strength of the direct wave (assuming a free space model). The reflected wave undergoes a change in phase ϕ and attenuation (due to loss in energy), given by the attenuation factor ρ. Let Δt be the time delay of the reflected wave relative to the direct wave.

The received signal E(t) can be written as:

$$\mathrm{E(t)} = \mathrm{E}_0\cos(\omega\, t) + \rho E_0\cos(\omega(t-\Delta t)+\phi) \tag{9}$$

At this point, two more simplifying assumptions are needed to proceed with the analysis: first – assume that the difference in path lengths between the direct and reflected wave is much smaller than the distance between the antennas 'r'. Second – assume perfect, i.e., loss free mirror reflection. This permits us to use $\rho \approx 1$ and $\phi = \pi$. So that E(t) can now be simplified to:

$$E(t) = 2E_0\sin\left(\frac{\omega\Delta t}{2}\right)\cos(\omega t + \psi) \tag{10}$$

where ψ is the appropriate phase, sin(.) is a constant. The resulting amplitude is:

$$E = 2E_0 \sin\left(\frac{\omega \Delta t}{2}\right) \quad (11)$$

The geometry of fig 6 gives:

$$d_D = \sqrt{r_2 + (h_2 - h_1)^2} \approx r\left(1 + \frac{1}{2}\left(\frac{h_2 - h_1}{r}\right)^2\right) \quad (12)$$

$$d_R = \sqrt{r_2 + (h_2 + h_1)^2} \approx r\left(1 + \frac{1}{2}\left(\frac{h_2 + h_1}{r}\right)^2\right) \quad (13)$$

where we have used h1, h2 << r (as assumed earlier) to obtain simplified versions of Eqns. (12) and (13).

$$\Delta d = d_D - d_R \approx \frac{2h_1 h_2}{r} \quad (14)$$

$$\Delta t = \frac{\Delta d}{c} \, and \omega = 2\pi f = \frac{2\pi c}{\lambda} \quad (15)$$

where Eqns. (12) and (13) were used to simplify (14). The resulting amplitude of the received signal is:

$$|E| = 2E_0 \left|\sin\left(\frac{\omega \Delta t}{2}\right)\right| = 2E_0 \left|\sin\left(\frac{2\pi h_1 h_2}{\lambda r}\right)\right| \quad (16)$$

therefore the received power is:

$$P_r = 4E_o^{\,2} \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \quad (17)$$

Since (for the free space propagation case) E_0 represents the received field strength, E_0^2 is the received power.

$$E_0^{\,2} \equiv P_r(\, freespace) = \frac{P_t G_t A_e}{4\pi r^2} \quad (18)$$

substituting (18) into (17), we get:

$$P_r = \frac{P_t G_t A_e}{\pi r^2} \sin^2\left(\frac{2\pi h_1 h_2}{\lambda r}\right) \quad (19)$$

assuming $h_1 h_2 < \lambda r$ (augmenting our earlier assumption that h_1, $h_2 < r$), we can use $\sin(x) \approx x$ to get:

$$P_r \approx \frac{4\pi P_t A_e (h_1 h_2)^2}{\lambda^2 r^4} \quad (20)$$

The key point to take away from (20) is that for propagation close to the Earth's surface, the received signal power decays inversely as the 4th power (this value is called the *path loss exponent*) of T-R distance. I.e., for propagation close to the Earth's surface, the free space model, which follows an inverse square law, is far too optimistic. Note that our result was obtained under various assumptions; actual measurements typically yield path loss exponents between 3 and 4.

The 2-Ray Ground Reflection model has been found to be reasonably accurate for predicting large-scale signal strength over distances of several kilometers for mobile radio systems that use tall towers (heights which exceed 50m), as well as for LOS microcell channels in urban environments.

VII. Path Loss In Macrocells

The propagation models that we have seen thus far attempt to predict path loss for transmission close to the Earth's surface. However, such communication often takes place over irregular terrain. The *terrain profile* of a particular area needs to be taken into account for obtaining better estimates of path loss. For example, the terrain profile may vary from a simple curved Earth profile to a highly mountainous profile. The presence of trees, buildings and other obstacles must also be taken into account. A number of propagation models are available to predict path loss over irregular terrain. While all these models attempt to predict signal strength at a particular receiving point or in a specific local area, the methods vary widely in their approach, complexity and accuracy. These models are *empirical* i.e., based on a systematic interpretation of measurement data (usually curve fitting) obtained in the service area. We now discuss the two most commonly used empirical models used in conjunction with 900 MHz (macro) cellular systems; where, by *macro-cell* we mean a cell typically on the order of tens of kilometers.

A. Hata's Model

The Hata model is an empirical formulation of the graphical path loss data provided by Okumura. Hata presented the urban propagation loss as a standard formula and supplied correction Equations for application to other situations.

The model can be described by the following Equations and parameters:

Carrier Frequency : 150 MHz $\le f_c \le$ 1500 MHz
Base Station Height : 30m $\le h_b \le$ 200m
Mobile Station Height: 1m $\le h_m \le$ 10m
T-R distance : 1km $\le d \le$ 20km

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

$A = 69.55 + 26.16 \log_{10}(f_c) – 13.82 \log_{10}(h_b) – a(h_m)$
$B = 44.9 – 6.55 \log_{10}(h_b)$
$C = 5.4 + 2[\log_{10}(f_c/28)]^2$
$D = 40.94 + 4.78 [\log_{10}(f_c)]^2 – 18.33 \log_{10}(f_c)$

$$a(h_m) = \begin{cases} [1.1\log_{10}(f_c) - 0.7]h_m - 1.56\log_{10}(f_c) - 0.8 \\ 8.28\,[\log_{10}(1.54\,h_m)]^2 - 1.1 \\ 3.2\,[\log_{10}(11.75\,h_m)]^2 - 4.97 \end{cases}$$

where the first expression for $a(h_m)$ applies to small to medium cities, the second expression applies to large cities and for $f_c \le$ 400 MHz, while the third expression applies to large cities and for $f_c \ge$ 400 MHz.

The plot below (fig 7) depicts path loss predicted by the Hata model for the following parameters: h_b = 70m, h_m = 1.5 m, f_c = 900 MHz.

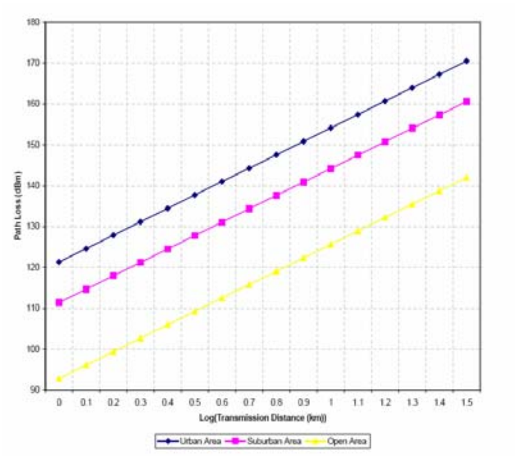

Fig 7: Example Path Loss as predicted by Hata's model.

Hata's model is based on measurements in Tokyo, Japan. It is intended for use in Japanese landscapes (urban or suburban) and performs poorly for American suburban terrain. The model has however been claimed to be detect man-made structures [7] and is accurate to within a dB as compared to actual measurements for transmission distances between 1-20 km.

B. Lee's Model

Lee's path loss model is based on empirical data chosen so as to model a flat terrain. Large errors arise when the model is applied to a non-terrain. However, Lee's model has been known to be more of a "North American model" than that of Hata.

The received signal power in dBm is given by:

$$\mu_\Omega = 10\log_{10}\left(\mu_{\Omega 0}\left(\frac{d_0}{d}\right)^\beta\left(\frac{f_c}{f}\right)^n\alpha_0\right) \qquad (21)$$

Two parameters are required to characterize the model: $\mu_{\Omega 0}$ (the power at 1 mile i.e., 1.6 km point of interception) and the path loss exponent β. These parameters are determined from empirical measurements and are listed in table 2 below.

Terrain	$\mu_{\Omega 0}$ (dBm)	β
Free Space	-45.0	2.00
Open Area	-49.0	4.35
N. American suburb	-61.7	3.84
N. American urban (Philadelphia)	-70.0	3.68
N. American urban (Newark)	-64.0	4.31
Japanese urban (Tokyo)	-84.0	3.05

Table 2: Sample values for the parameter's in Lee's path loss model.

The following nominal conditions are set when using Lee's model:

Nominal Carrier Frequency	f_c	= 900 MHz
Nominal (Calibration) Distance	d_o	= 1.6 km
Base Mobile Station Antenna	h_b	= 30.48 m
Mobile Station Antenna Height	h_m	= 3 m
Base Station Transmit Power	P_b	= 10 W
Base Station Antenna Gain	G_b	= 6 dB
Mobile Station Antenna Gain	G_m	= 0 dB

where Gb and Gm are relative to (above) the gain of a dipole radiator.

In Eqn. (21), f is the EM transmission frequency, d is the T-R distance and α_0 is a correction factor to account for BS and MS antenna heights, transmit powers and antenna gains that differ from the nominal values. As such, when the prevailing conditions differ from the nominal ones, then α_0 is given by:

$$\alpha_0 = \alpha_1\alpha_2\alpha_3\alpha_4\alpha_5$$

where:

α_1 = (new BS antenna height (m) ⁄ 30.48 m)^2

α_2 = (new MS antenna height (m) ⁄ 3 m)$^\xi$

α_3 = (new transmitter power ⁄ 10 W)^2

α_4 = (new BS antenna gain wrt λ_c/2 dipole ⁄ 4)

α5 = different antenna, use gain correction factor at MS.

The values of *n* (Eqn. (21)) and ξ are based on empirical data. The following values may be used to guide received signal strength predictions:

$$n = \begin{cases} 2 & \text{for } f_c < 450 \text{ MHz and in suburban/open area} \\ 3 & \text{for } f_c > 450 \text{ MHz and in urban area} \end{cases}$$

$$\xi = \begin{cases} 2 & \text{for MS antenna height} > 10 \text{ m} \\ 3 & \text{for MS antenna height} < 3 \text{ m} \end{cases}$$

The path loss L_p (the difference between the transmitted and received power) is: $L_p = P_b - \mu_\Omega$ dBm

For the scenarios listed in table 2, we may write the path loss expressions for the various environments as follows (where r is in km and f is in MHz):

$$L_p\,(\text{dBm}) = \begin{cases} 85 + 20\log_{10}\left(\frac{r}{1.6\,\text{km}}\right) + 10n\log_{10}\left(\frac{f}{900\,\text{MHz}}\right) - \alpha_0 & \text{Free Space} \\ 89 + 43.5\log_{10}\left(\frac{r}{1.6\,\text{km}}\right) + 10n\log_{10}\left(\frac{f}{900\,\text{MHz}}\right) - \alpha_0 & \text{Open Area} \\ 101.7 + 38.4\log_{10}\left(\frac{r}{1.6\,\text{km}}\right) + 10n\log_{10}\left(\frac{f}{900\,\text{MHz}}\right) - \alpha_0 & \text{US Suburban Area} \\ 110 + 36.8\log_{10}\left(\frac{r}{1.6\,\text{km}}\right) + 10n\log_{10}\left(\frac{f}{900\,\text{MHz}}\right) - \alpha_0 & \text{Philadelphia, PA (urban)} \\ 104 + 43.1\log_{10}\left(\frac{r}{1.6\,\text{km}}\right) + 10n\log_{10}\left(\frac{f}{900\,\text{MHz}}\right) - \alpha_0 & \text{Newark, NJ (urban)} \\ 124 + 30.5\log_{10}\left(\frac{r}{1.6\,\text{km}}\right) + 10n\log_{10}\left(\frac{f}{900\,\text{MHz}}\right) - \alpha_0 & \text{Tokyo, Japan (urban)} \end{cases}$$

For comparison with Hata's model, the path loss predicted by Lee's model is shown in the plot below (fig 8) for the following parameters: h_b = 70m, h_m = 1.5 m, f_c = 900 MHz.

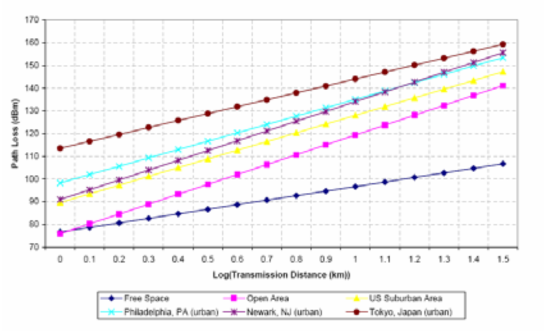

Fig 8: Example Path Loss as predicted by Lee's model.

Referring to fig 8, we draw the reader's attention to two points of interest: (1) prediction of path loss for Tokyo in Lee's model matches that of Hata's model and (2) for either model, the path loss curve is greater for urban areas than suburban areas, and is the least for open areas. This can be explained by the fact that path loss is a function of (among other things) *clutter* and *obstructions*, which are present to a higher degree in cities and to a lesser degree in open areas.

While both models are useful for 900 MHz cellular systems, it should be apparent that, Lee's model is more flexible than Hata's model in that it can accommodate more diverse landscapes (e.g. those in North America and not just those in Japan). Several other popular models that model path loss for micro-cell environments also exist. The interested reader is referred to [2] for additional reading.

VIII. PATH LOSS IN MICROCELLS

Having studied propagation in macro-cellular environments, we now turn our attention to micro-cellular environments. Micro-cellular systems are similar to cellular systems except that the base stations are placed closer to each other, thereby necessitating a greater number of base stations for proper coverage.

Micro-cells, on which Personal Communication Systems (PCS) are based, have grown in importance with the rise of PCS. Most future PCS systems are expected to operate in the 1800-2000 MHz frequency band. It has been shown that path loss can be more dramatic at these frequencies than those in the 900 MHz band. In fact, some studies have suggested that path loss experienced at 1845 MHz is approximately 10 dB larger than those experienced at 955 MHz, all other parameters being equal [8].

To that end, the European Cooperative for Scientific and Technical Research (COST) formed that COST-231 working committee, to develop an extended version of the Hata model for use at higher frequencies and in urban micro-cellular environments.

A. COST231-HATA MODEL

The COST231-Hata model extends Hata's model for use in the 1500-2000 MHz frequency range, where the original Hata model is known to underestimate path loss. The COST231 extension of the Hata model is restricted to the following range of parameters:

Carrier Frequency	f_c	= 1500 – 2000 MHz
BS antenna height	H_b	= 30 – 200 m
MS antenna height	H_m	= 1 – 10 m
T-R distance	d	= 1 – 20 km

The path loss according to the COST231-Hata model is given by:

$$L_p\,(dB) = A + B\log_{10}(d) + C \qquad (22)$$

where:

$A = 46.3 + 33.9 \log_{10}(f_c) - 13.82 \log_{10}(h_b) - a(h_m)$

$B = 44.9 - 6.55 \log_{10}(h_b)$

$$C = \begin{cases} 0 & \text{for medium sized city \& suburban areas} \\ 3 & \text{for metropolitan centers} \end{cases}$$

and $a(h_m)$ is as given by the original Hata model.

The COST231-Hata model does take into account parameters such as roof heights, street widths and building separation. While both the Hata and the COST231-Hata models are designed for use with base station antenna heights greater than 30 m, they may be used with shorter antennas provided that the surrounding buildings are well below this height. Neither model should be used to predict path loss in an *urban canyon* (e.g. city downtown with many buildings). Lastly, the model should not be used for prediction with transmission distances below 1 km as path losses become dependent on the local topography.

B. PATH LOSS IN STREET MICROCELLS – THE TWO-SLOPE MODEL

We now turn our attention to street Microcells, where transmission distances range up to 500 m and antenna heights are less than 20 m. Within these ranges, empirical measurements have shown that LOS propagation along city streets can be accurately described by the two-slope model [9].

According to this model, the received signal strength is given by:

$$\mu_\Omega = 10\log_{10}\left(\frac{A}{d^a\left(1+\frac{d}{g}\right)^b}\right) dBm \qquad (23)$$

where:
A : a constant
d : T-R distance in m.
a, b : parameters, which reflect path losses for the propagation environment. For example, at distances close to the base station, free space propagation dominates, and a = 2. At large distances, where we expect an inverse 4th power law, b ranges from 2 to 6.
g : break-point parameter (ranges from 150–300 m). This represents the distance along the LOS between antennas at which the *Fresnel Zone* first touches the ground (assuming a flat surface).

This distance is given by:

$$g = \frac{1}{\lambda_c}\sqrt{(\Sigma^2 - \Delta^2)^2 - 2(\Sigma^2 + \Delta^2)^2\left(\frac{\lambda_c}{2}\right)^2 + \left(\frac{\lambda_c}{2}\right)^4} \qquad (24)$$

$\Sigma = H_b + H_m$
$\Delta = H_b - H_m$

Note that g is frequency dependent. It may be approximated for high frequencies as:

$$g = \frac{4h_b h_m}{\lambda} \qquad (25)$$

The parameter values determined by Harley are as given in table 3 below:

H_b (meters)	a	b	g (meters)
5	2.30	-0.28	148.6
9	1.48	0.54	151.8
15	0.40	2.10	143.9
19	-0.96	4.72	158.3

Table 3: Parameter values for the Two-Slope model.

C. NLOS Propagation – Propagation Around Street Corners

As a mobile station rounds a street corner, the LOS transmission of the previous section gives way to No-Line-Of-Sight (NLOS) propagation. For such events, it is not uncommon for the average drop in the received signal to be 25 – 30 dB over distances as small as 10 m for low antenna heights in areas with multi-story buildings.

The following model, empirically derived by Grimlund and Gudmundson [10], is designed to predict the received signal power in a rounding-the-street-corner scenario. The model assumes that the mobile communicates via LOS with the base station until it reaches the street corner. After rounding the street corner, the NLOS propagation is modeled by assuming LOS propagation between the mobile station and an imaginary base station located at the street corner from the actual base station; see fig 9 below.

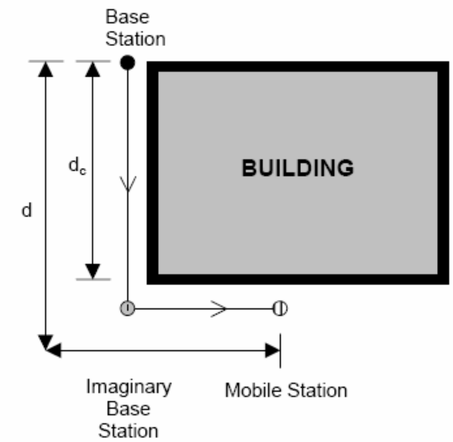

Fig 9: NLOS Propagation around a cornet in a street microcell.

The received signal strength is given by:

$$\mu_\Omega(dBm) = \begin{cases} 10\log_{10}\left(\dfrac{A}{d^a\left(1+\dfrac{d}{g}\right)^b}\right) & d \le d_c \\ 10\log_{10}\left(\dfrac{A}{d_c{}^a\left(1+\dfrac{d_c}{g}\right)^b}\dfrac{1}{(d-d_c)^a\left(1+\dfrac{d-d_c}{g}\right)^b}\right) & d > d_c \end{cases} \qquad (25)$$

where d_c (m) is the distance between the actual BS and the street corner and d is the total length of the MS to BS path, wrapping around the corner.

IX. Other Factors Contributing To Path Loss

Several other models have been developed for predicting path loss. These models emphasize the different factors that contribute to path loss – diffraction, scattering in particular. Each model is intended for a particular frequency range and may have a variety of additional parameters.

Usually transmission loss is predicted using path geometry of the terrain profile and refractivity of the troposphere. Geometric optics techniques (primarily two-ray ground reflection model) are used to predict signal strengths within the radio horizon. Diffraction losses over isolated obstacles are estimated using the *Fresnel-Kirchoff knife-edge models. Forward scatter theory* is used to make troposcatter predictions over long distances, and far-field diffraction losses in *double horizon paths* are predicted using a modified Van der Pol-Bremmer method. Advanced models (e.g. the Longley-Rice model) operate in two or more modes.

When a detailed terrain profile is available, the path specific parameters can be easily determined and the prediction is called a *point-to-point mode* prediction. On the other hand, if the terrain path profile is not available, techniques are provided to estimate the path specific parameters, and such a prediction is called an *area mode* prediction. Other enhancements to estimation techniques account for urban clutter near the transmitting antenna or receiving antenna or both. This is called the *urban factor.*

Specialized models for indoor propagation also exist. These factor losses within the same floor (partition losses due to walls and other materials, including furniture) or losses for propagation across floors. Losses due to the latter are adjusted by way of the *floor attenuation factor* (FAF). Finally sophisticated *ray-tracing and site-specific modeling* techniques also have been developed.

X. CONCLUSIONS

Different frequencies in the EM spectra undergo different fading and to varying degrees by the various atmospheric layers. Higher frequencies need smaller antennas, but also have a tendency to fade rapidly. The free space propagation model, which is a first step in understanding path loss, has a path loss exponent of 2. This is extremely optimistic for real-world-near-ground propagation. Several factors contribute to path loss for the many diverse environments that exist. A model that *"fits all"* is impossible to obtain.

XI. REFERENCES

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Name	Frequency Range	Propagation Characteristics	Applications
Extremely Low Frequency (ELF) Very Low Frequency (VLF)	300 – 3000 Hz 3 – 30 KHz	• Propagates between the Earth's surface & Ionosphere. • Can penetrate deep into the water and underground. • Large wavelength mandates the use of large antennas.	• Mining. • Underwater communication, SONAR
Low Frequency (LF)	30 – 300 KHz	• Sky wave separates from ground wave for frequencies above 100 KHz. This enables communication over large distances by reflecting the sky wave off the atmosphere. • Ground-wave has higher loss than sky-wave (naturally).	• Broadcasting. • Long range communication with ships (radio navigation).
Medium Frequency (MF)	300 – 3000 KHz	• Sky wave separates from the ground wave (in this range). • Ground wave gives usable signal strength up to 100km.	• AM radio broadcasting (550 – 1600 KHz).
High Frequency (HF)	3 – 30 MHz	• Sky wave is the main mode of propagation. • As compared to the sky wave, the Ground wave is used for communication over shorter distances. • As propagation loss increases for higher frequencies, use of repeaters may be required.	• Broadcasting over large areas. • Amateur (HAM) radio. • Citizen Band (CB) radio. • Long distance aircraft and ship communication.
Very High Frequency (VHF)	30 – 300 MHz	• Diffraction and Reflection give rise to communication beyond the horizon and also reception within buildings. • Propagation distances are thousands of Km.	• Broadcasting: TV, FM radio (88 – 108 MHz). • Radio beacons for air traffic control.
Ultra High Frequency (UHF)	300 – 3000 MHz	• Reflection due to various atmospheric layers is possible. • Effect of rain and moisture is negligible. • Losses due to obstacles larger than VHF.	• GPS, Broadcasting, Satellite TV. • PCS/Land mobile (1G to 3G) phones. • μ-wave, WiFi, Air Traffic Control.
Super High Frequency (SHF)	3 – 30 GHz	• Obstacles limit range as frequency increases. • Propagation is limited by absorption by rain and clouds.	• Future mobile services, WiFi, UNII (802.11a, Home RF). • Satellite services for telephony and TV. LEO/GEO systems.
Extremely High Frequency (EHF)	30 – 300 GHz	• Basically, all particles become obstacles due to very small wavelengths. • Absorption effects greatly limit range. • Very high losses due to water, oxygen, vapor.	• Short range communications (LOS). • Broadcast satellites for HDTV (free space, not terrestrial communication).

Table 1: The Wireless Electromagnetic Spectrum – Frequency ranges, propagation characteristics and typical applications.