# Basic Propagation Theory

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***Abstract*— In this paper we provide an introduction to the basics of propagation theory. The basic concepts and models for describing the propagation of electromagnetic waves in several simple scenarios are here considered. We also describe the concept of wave polarization by giving some examples. Here, we will see that the link budget may be improved by using directional instead of isotropic antennas and that by keeping the first Fresnel zone free from obstacles can give some advantages. We will also point out the differences between physical and statistical models for propagation as well as the trade-off between the accuracy and the computational complexity for propagation models.**

***Index Terms*— Isotropic and directional radiation, polarization, terrestrial propagation, diffraction, Fresnel zones.**

## I. INTRODUCTION

The study of propagation is important to wireless communication because it provides prediction models for estimating the power required to close a communication link and provide reliable communications. The study of propagation also provides clues to the receiver techniques for compensating the impairments introduced through wireless transmission.

The propagation effects and other signal impairments are often collected and referred to as the channel [6]. Channel models for wireless communications may be defined either as physical models or statistical models. In case of physical model, the basic models of propagation are the free-space or Line-of-Sight (LoS) transmission, reflection, diffraction and ducting [1].

Consequently, the RX signal is the combination of many propagation models and the transmitted signal may arrive at the receiver over many paths. The signal on these different paths can constructively or destructively interfere with each other. This is referred as multipath. If either the transmitter or the receiver is moving, then this propagation phenomena will be time varying, and fading occurs. In addition to propagation impairments, the other phenomena that limit wireless communications are noise and interference.

The wireless communication system used can be simplified into three blocks: the transmission, the propagation and the recovery. The transmission is characterized by the generation, in the transmitter (TX), of an electric signal representing the desired information. Then we have the propagation of the signal through space. Finally we consider to have a receiver (RX) that estimates the transmitted information from the recovered electrical signal.

Antennas, on both TX and RX sides, convert from electrical signals to radio waves (TX), and vice versa (RX). The transmission effects are most completely described by the Maxwell's equations. Here we assume a linear medium in which all the distortions can be characterized by attenuation or superposition of different signals.

The paper is organized as follows. First we introduce the concept of isotropic radiation. In Section III we describe directional radiation. In Section IV the link budget is introduced. This is a key idea behind wireless communications. In Section V we study the polarization of electromagnetic waves. Here we give some interesting hints on how to compute the polarization of signals. In Section VI we define the concept of physical models for propagation. In Section VII the diffraction phenomenon is described. In Section VIII we talk about statistical models. In Section II the problem of indoor propagation is considered. Finally, Section X concludes the paper.

## II. ISOTROPIC RADIATION

An antenna is isotropic if it can transmit equally in all directions, see Fig. 1. It represents an ideal antenna and it is used as reference to which other antennas are compared [1],[4].

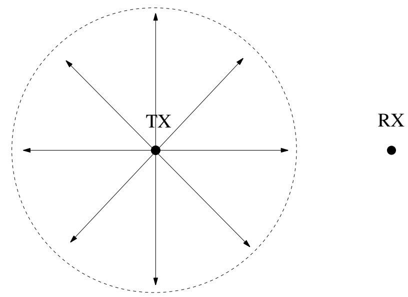


Fig. 1. Representation of an isotropic radiation. Tx and Rx refer to transmitter and receiver, respectively.

The power flux density of an isotropic source that radiates power $P_T$ watts in all directions is

$$\Phi_R = \frac{P_T}{4\pi R^2} \qquad \left[\frac{W}{m^2}\right] \tag{1}$$

where $4\pi R^2$ is the surface area of a sphere.

The power captured by the receiving antenna (RX) depends on the size and orientation of the antenna with respect to the TX

$$P_R = \Phi_R \ A_e = \frac{P_T}{4\pi R^2} \ A_e \tag{2}$$

where $A_e$ is the effective area or absorption cross section.

Notice that the effective area of an isotropic antenna in any direction can be expressed as $A_e^{iso} = \frac{\lambda^2}{4\pi}$. The antenna efficiency is defined as $\eta = \frac{A_e}{A}$ where $A$ is the physical area of the antenna.

The link between TX and RX power for isotropic antennas is

$$P_R = \left(\frac{\lambda}{4\pi R}\right)^2 P_T = \frac{P_T}{L_P} \tag{3}$$

where $L_P = \left(\frac{4\pi R}{\lambda}\right)^2$ is the free-space path loss between two isotropic antennas. Observe that the path loss depends on the wavelength of transmission.

Another interesting receiver parameter is the sensitivity. It indicates the minimum signal level required at the antenna terminals in order to provide reliable communications, see also Section IV.

## III. DIRECTIONAL RADIATION

In general, real antennas are not isotropic and they have gain and directivity $G(\phi, \theta)$ which may be functions of the azimuth $\phi$ and elevation $\theta$ angles [1],[4],[7]. In Fig. 2 we depict a Uniform Circular Array (UCA) [8]. It represents an example of directional antenna where $N$ sensors are uniformly placed along a circle. Circular arrays are of interest in a variety of applications, e.g. in multiantenna communication transceivers, navigation and electronic intelligence. Moreover, UCA's have uniform performance in azimuth regardless of the angle of arrival [8].

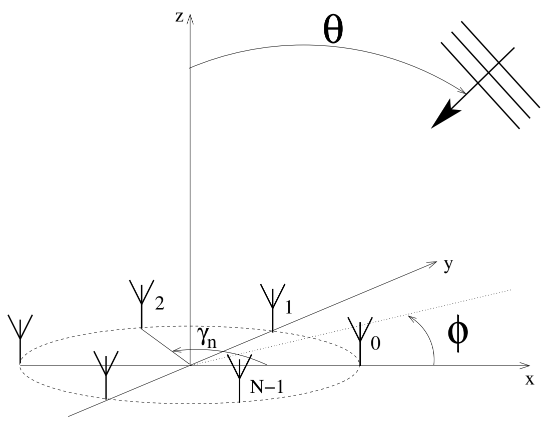


Fig. 2. Directional Antenna such as a Uniform Circular Array (UCA).

In antenna theory, the transmit and received antenna gains are defined as [1]

$$G_T(\phi,\theta) = \frac{\text{Power flux density in direction}(\phi,\theta)}{\text{Power flux density of an isotropic antenna}} \quad (4)$$

$$G_R(\phi,\theta) = \frac{\text{Effective area in direction}(\phi,\theta)}{\text{Effective area of an isotropic antenna}} \, . \quad (5)$$

The ratio between the gain $G$ and the effective aperture $Ae$ of an antenna defines the maximum transmit or receive gain [1],[4],[5]

$$\frac{G}{A_e} = \frac{4\pi}{\lambda^2} \, . \quad (6)$$

Notice that side-lode and back-lobe are not considered for using in the communications link, but they are considered when analyzing interference, see Fig.3.

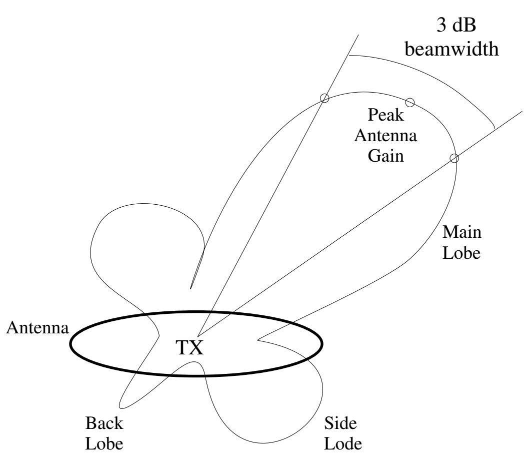


Fig. 3. Gain pattern of a general directional antenna.

An interesting concept that sometimes is useful to keep in mind is the so called principle of reciprocity. It states that signal transmission over a radio path is reciprocal in the sense that the locations of the transmitter and receiver can be interchanged without changing the transmission characteristics [1].

## IV. The Friis Equation: Link Budget

In case of non-isotropic antenna, the Free-Space loss relating the received and transmitted power is [1],[4]

$$P_R = \frac{P_T\ G_T\ G_R}{L_P} = P_T\ G_T\ G_R \left(\frac{\lambda}{4\pi R}\right)^2 \quad (7)$$

or, as a decibel relation (logarithmic scale),

$$P_R(dB) = P_T(dB) + G_T(dB) + G_R(dB) - L_P(dB) \quad (8)$$

where $X(dB) = 10\log_{10}(X)$.

When designing a wireless communication system, one of the criteria that have to be satisfied is related to the idea of closing the link. This means that the right hand side of eq.(1) provides enough power at the receiver to detect the transmitted information reliably. Notice that this concept recall the definition of sensitivity of a receiver (RX), see Section II.

Observe that the Friis equation (Link Budget), as presented so far, does not include the effect of noise, e.g. receiver noise, antenna noise, artificial noise, multiple access interference,...

Let us assume the receiver noise as dominant an let us model it by the single-sided noise spectral density $N_0$. To include the noise, the Link Budget may now be expressed as

$$\frac{P_R}{N_0} = \frac{P_T\ G_T\ G_R}{L_P\ k\ T_e} \qquad \left[\frac{\text{dB}}{\text{Hz}}\right] \quad (9)$$

where $N_0 = k\ T_e$, $k$ is the Boltzmann's constant and $T_e$ is the equivalent noise temperature of the system. Notice that in satellite application, eq.(9) is written as

$$\frac{C}{N_0} = \text{EIRP} - L_p + \frac{G}{T} - k \quad (10)$$

where $\frac{C}{N_0} = \frac{P_R}{N_0}$ stands for received carrier-to-noise density ratio [dB/Hz], EIRP $= P_T\ G_T$ is known as the TX Equivalent Isotropic Radiated Power [dBW], $\frac{G}{T} = \frac{G_R}{T_e}$ is the RX gain-to-noise temperature ratio [dB/K], $L_p$ is the Path loss [dB] and $k$ is the Boltzmann's constant.

## V. Polarization

The electric field may be expressed as [4],[6]

$$\overrightarrow{E} = E_x \overrightarrow{u}_x + E_y \overrightarrow{u}_y \quad (11)$$

where the two components alons x- and y-axes are on the plane orthogonal to the propagation direction [2],[3]. In Fig. 4 we depict the polarization of the electric and magnetic fields of an electromagnetic wave. Notice that for sake of simplicity we only consider the electric field $\overrightarrow{E}$ during the rest of the section. However, the discussion can also be extended to the magnetic field $\overrightarrow{H}$.

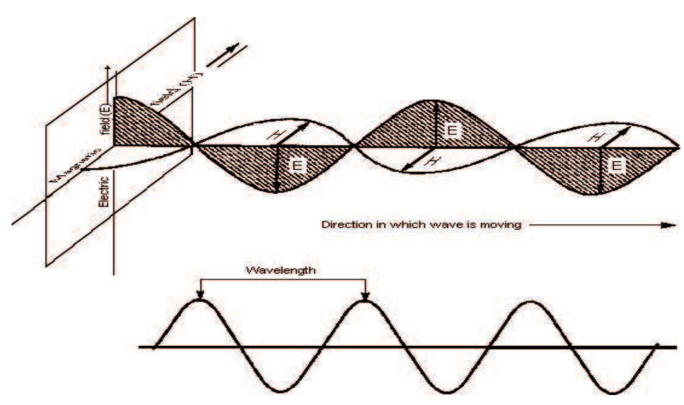


Fig. 4. Representation of a polarized wavefront. The electric and magnetic fields are here depicted.

In the phasor domain we can rewrite eq.(11) as

$$\overrightarrow{E} = \cos(\alpha)\overrightarrow{u}_x + \sin(\alpha)e^{j\phi}\overrightarrow{u}_y \tag{12}$$

where by giving different values of $\alpha$ and $\phi$ is possible to define all the different kind of polarizations. In particular, the values of the two parameters that describe the linear and circular polarizations are

- $\forall\alpha$ & $\phi = 0 \Rightarrow$ Linear polarization,
- $\alpha = \frac{\pi}{4}$ & $\phi = \pm\frac{\pi}{2} \Rightarrow$ Right-hand (-) and Left-hand (+) circular polarization.

Here we give an example where by setting the values of $\alpha$ and $\phi$ we can describe the most common signal polarizations such as Vertical Polarization (VP), Horizontal Polarization (HP), Right Hand Circular Polarization (RHCP) and Left Hand Circular polarization (LHCP):

- VP: $\alpha = \frac{\pi}{2}$ & $\phi = 0 \Rightarrow \overrightarrow{E} = \overrightarrow{u}_y$,
- HP: $\alpha = 0$ & $\phi = 0 \Rightarrow \overrightarrow{E} = \overrightarrow{u}_x$,
- RHCP: $\alpha = \frac{\pi}{4}$ & $\phi = -\frac{\pi}{2} \Rightarrow \overrightarrow{E} = \frac{1}{\sqrt{2}}\overrightarrow{u}_x - j\frac{1}{\sqrt{2}}\overrightarrow{u}_y$,
- LHCP: $\alpha = \frac{\pi}{4}$ & $\phi = \frac{\pi}{2} \Rightarrow \overrightarrow{E} = \frac{1}{\sqrt{2}}\overrightarrow{u}_x + j\frac{1}{\sqrt{2}}\overrightarrow{u}_y$ .

In Fig. 5 we show several wave polarizations depending in the phase factor $\phi$ and on the ratio $\frac{E_y}{E_x}$.

In time domain, the electric field can be expressed as

$$\overrightarrow{E}(t) = \cos(\alpha)\cos(wt)\overrightarrow{u}_x + \sin(\alpha)\cos(wt+\phi)\overrightarrow{u}_y \tag{13}$$

where $\omega = 2\pi f$ with $f$ as the signal frequency. It is important to remember that from a propagation point of view, scattering effects tend to create cross-polarization interference.

Let us define a projection matrix able to map from rectangular to circular coordinates such as [4]

$$\begin{pmatrix} E_r \\ E_l \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & j \\ 1 & -j \end{pmatrix}\begin{pmatrix} E_x \\ E_y \end{pmatrix} \tag{14}$$

where $E_r$ and $E_l$ are the right and left circular bases, respectively. In Fig. 6 we give a representation of the right and left circular bases.

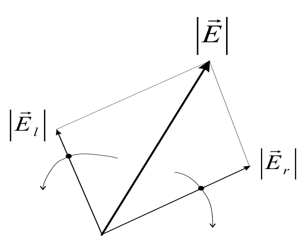


Fig. 6. Representation of the right and left circular bases.

By combining the circular bases it is possible to define a simple procedure for which we can easily compute the polarization of a signal. Hence, let us define the axial ratio as

$$R = \frac{|E_l| - |E_r|}{|E_l| + |E_r|} = \begin{cases} 1 & \text{Left-Hand Circular Pol.} \\ 0 & \text{Linear Pol.} \\ -1 & \text{Right-Hand Circular Pol.} \end{cases} \tag{15}$$

and if $R \in (0,1)$ we have a signal with Left-Hand Elliptical Polarization, if $R \in (-1,0)$ the signal is Right-Hand Elliptical Polarization. Notice that in the particular cases of $R = \{1, 0, -1\}$ we have s signal with LHCP, LP and RHCP, respectively.

Here we give an example which verifies, by using the axial ratio, that a LHCP can be identified by setting $\alpha = \frac{\pi}{4}$& $\phi = \frac{\pi}{2}$. The value if the parameters define the rectangular components of $\overrightarrow{E}$ as

$$\begin{cases} E_x = \cos(\alpha) = \frac{1}{\sqrt{2}} \\ E_y = \sin(\alpha)\ e^{j\phi} = j\frac{1}{\sqrt{2}} \end{cases}. \tag{16}$$

Therefore, by applying the transform in eq.(14), we can write

$$\begin{pmatrix} E_r \\ E_l \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & j \\ 1 & -j \end{pmatrix}\begin{pmatrix} \frac{1}{\sqrt{2}} \\ j\frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{17}$$

and defining the circular bases of the original signal. Finally, by computing the axial ration we get

$$R = \frac{|E_l| - |E_r|}{|E_l| + |E_r|} = \frac{1-0}{1+0} = 1 \tag{18}$$

which exactly identifies a Left-Hand Circular Polarization (LHCP).

## VI. Terrestrial Propagation: Physical Models

Physical models consider the exact physics of the propagation environment (site geometry). They provide reliable estimates of the propagation behavior but they are computationally expensive.

The basic models of propagation are free-space or Line-of-Sight (LoS) transmission, reflection, diffraction and ducting [1],[5]-[7]. Line-of-Sight (LoS) transmission is when there is a clear path between transmitter (TX) and receiver (RX), e.g. is case of satellite communications. Reflection represents bouncing of electromagnetic waves from surrounding objects such as buildings, mountains, vehicles,... On the other hand diffraction describes the bending of electromagnetic waves around objects such as buildings, hills, trees,... Refraction instead describes when electromagnetic waves are bent as they move from one medium to another. Finally, the ducting effect is when physical characteristics of the environment create a waveguide-like effect, e.g. urban propagation between tall buildings.

As a result the RX signal is the combination of these propagation models and the transmitted signal may arrive at the receiver over many paths. The signal on these different paths can constructively or destructively interfere with each other. This is referred as multipath. If either the transmitter or the receiver is moving, then this propagation phenomena will be time varying, and fading occurs.

In the following paragraph we describe a simple propagation model known as plane-earth model.

### A. Reflection and the Plane-Earth Model

Here we assume to neglect the effect of the earth curvature and to consider the earth as flat. This can be a reasonable assumption, especially when the distance between the Tx and Rx antennas is not too large [1]. In Fig. 7 we depict the plane-earth reflection model.

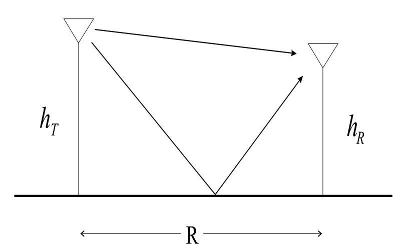


Fig. 7. Plane-Earth Reflection Model.

The Plane-Earth propagation equation can be written as

$$P_R = P_T G_T G_R \Big(\frac{h_T h_R}{R^2}\Big)^2 . \tag{19}$$

Here we can see that eq.(19) depends on both antennas distance with is inverse fourth-power law and on the antennnas height. Moreover,

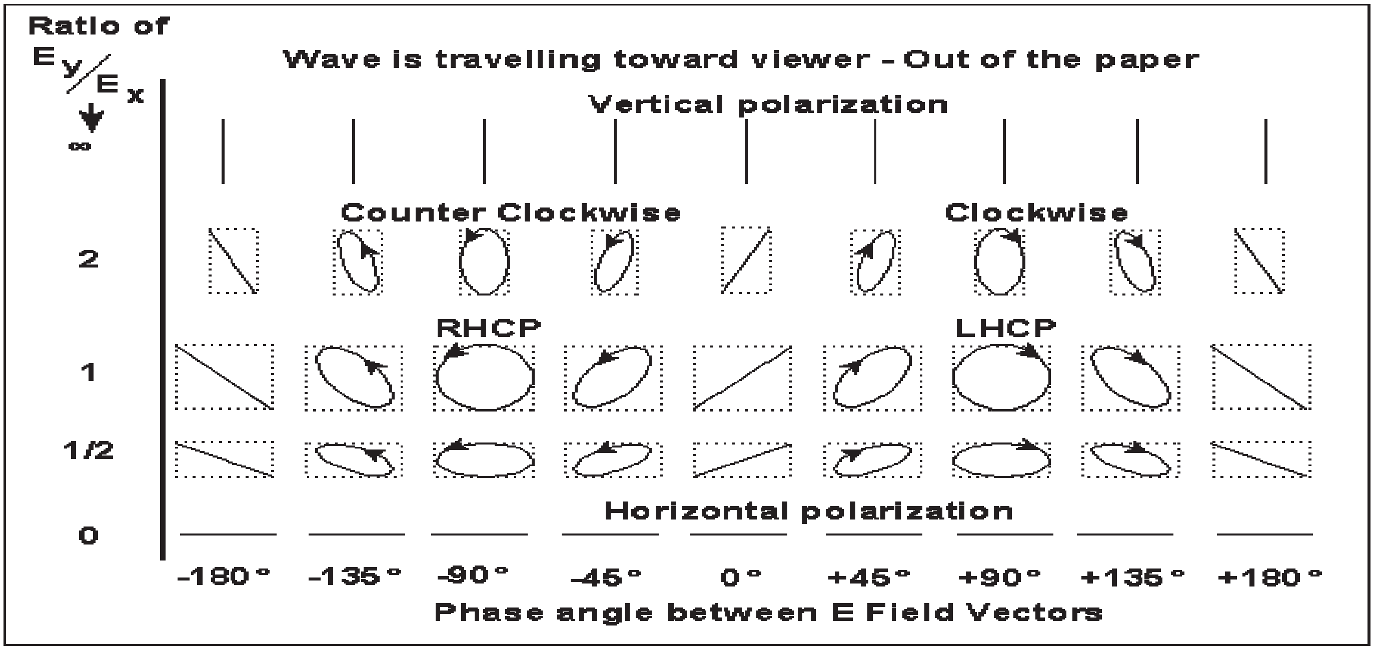


Fig. 5. Wavefront polarization as a function of the $\frac{E_y}{E_x}$ ratio and of their phase difference $\phi$.

since in eq.(19) we have assumed $R \gg h_T, h_R$, we can see that the equation is now frequency independent [1]. Notice that in eq.(7) the link budget was frequency dependent.

## VII. Diffraction

When electromagnetic waves are forced to travel through a small slit, they tend to spread out on the far end of the slit, see Fig. 8. This effect is known as Huygens's principle: each point on a wave front acts as a point source for further propagation [1],[4]. However, the point source does not radiate equally in all the directions, but favors the forward direction, of the wave front.

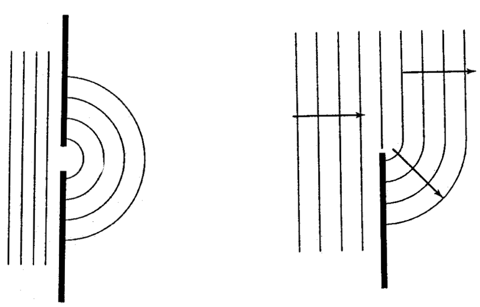

Fig. 8. On the left: behavior of plane wave passing through a slit from left opt right. On the right: illustration of knife-edge diffraction.

The diffraction effect of waves is with related to the concept of Fresnel zones and they are important in order to understand the basic propagation phenomena. In Fig. 9 we give a representation of the Fresnel zone. See [1] for a detailed derivation of them.

An interesting rule of thumb that could be useful to remember is that in order to obtain transmission under free-space condition, we have to keep the first-Fresnel zone free of obstacles.

In case a perfectly absorbing screen is placed between the TX and RX we have the phenomenon of diffraction losses. This can be studied (see [1] for details) and as a result we get that by obscuring half of the first Fresnel zone we have a loss of 6-dB. The impact of the knife-edge on the diffraction losses is represented in Fig. 10.

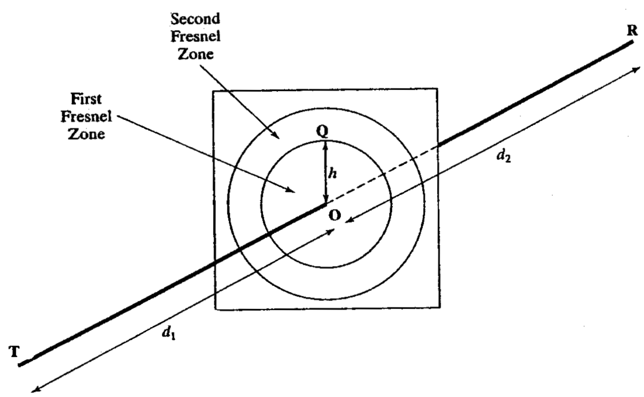


Fig. 9. Representation of the first and second Fresnel zone.

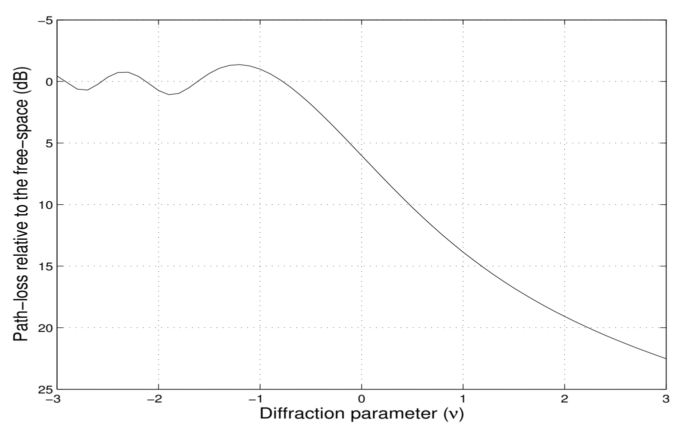


Fig. 10. Representation of the diffraction losses, when the first Fresnel zone gets obscured by a knife-edge. When the knife-edge is even with the LOS, the electric field is reduced by one-half and there is a 6-dB loss in signal power.

## VIII. Terrestrial Propagation: Statistical Models

By measuring the propagation characteristics in a variety of environments (urban, suburban, rural), researchers have developed models based on the measured statistics for a particular class of environments.

In general, they are easy to describe but they are not accurate. In fact, in contrast with the physical models (Section VI), the statistical models do not require any information concerning the propagation effects. They only study the final effects on the receive signals for a particular environment. Then, by making a large number of measurement campaigns, they build some consistent statistics about a certain class of environment, such as urban, suburban, rural and indoor [1],[5]-[7].

The statistical approach is broken down into two components which represents the statistics that we want to be able to characterize, i.e. the median path loss and the local variations.

In the case of median path loss, investigations have motivate a general propagation model such as

$$\frac{P_T}{P_R} = \frac{\beta}{r^n} \ , \tag{20}$$

where $r$ is the distance between TX and RX, $n$ is the path-loss exponent and the parameter $\beta$ represents a loss that is related to frequency , antenna heights,... See [1] for details.

In Table I we show the value of the path-loss exponent with related to a certain environment.

TABLE I
Sample Path Loss Exponents

| Environment | n |
|---|---|
| Free-Space | 2 |
| Flat Rural | 3 |
| Rolling Rural | 3.5 |
| Suburban, low rise | 4 |
| Dense Urban, Skyscrapers | 4.5 |

On the other hand the local variations, i.e. the variation about the median, can be modelled as a log-normal distribution (shadowing).

## IX. Indoor propagation

To study the effects of indoor propagations has gained more and more importance with the growth of cellular telephone. Wireless design has now to take into account the propagation characteristics in high-density location. Wireless Local Area Networks (LAN's) are being implemented to eliminate the cost of wiring of rewiring buildings.

As for the statistical models, an indoor path-loss model has been built based on measurement campaigns. The indoor path-loss model can be expressed as [1]

$$L_P(dB) = \beta(dB) + 10\log_{10}\left(\frac{r}{r_0}\right)^n + \sum_{p=1}^{P} \mathrm{WAF}(p) + \sum_{q=1}^{Q} \mathrm{FAF}(q) \tag{21}$$

where WAF and FAF stand for Wall Attenuation Factor and Floor attenuation Factor, respectively. Moreover, $r$ represents the distance between TX and RX, $r_0$ is the reference distance (1 m) and Q and P define the number of floors and walls, respectively.

## X. Conclusions

In this paper we have introduced the basics of propagation theory. The basic concepts and models for describing the propagation of an electromagnetic wave in several scenarios have been considered.

We have shown that the link budget may be improved by using directional instead of isotropic antennas and we have seen that to keep the first Fresnel zone free from obstacles can give some advantages.

We have also pointed out the differences between physical and statistical models for propagation as well as the trade-off between the accuracy and the computational complexity for propagation models.

Finally we have described the concept of polarization with simple examples. The polarization of electromagnetic waves is an important issue for wireless communication.

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