9. RADIO CHANNELS

As the telecommunication and the radio technique develop, the number of radio systems rapidly increases and newer applications are introduced. Radio systems have to meet, therefore, qualitatively new, enhanced requirements in an electromagnetic environment of growing complexity. For optimum frequency management, the estimation of the parameters of the radio links became more important. In this chapter, radio channel as the medium of the radio links is presented as well as the models of radio channels are overviewed.

9.1. Electromagnetic Spectrum, Frequency Bands

The electromagnetic spectrum used for the radio transmission is extending parallel to the progress in telecommunication. From the early days of radio the spectrum has been divided into ranges in accordance with the similar propagation characteristic and application areas. This division is permanently changed and extended towards the higher frequencies. The actual division of the electromagnetic spectrum together with typical applications is presented in Table 9.1.

Table 9.1. Frequency Ranges Used in Telecommunication

Range	Typical application
3 - 300 kHz	Navigation, beacons, LW broadcasting
300 – 3000 kHz	MW broadcasting, marine radio, navigation
3 - 30 MHz	SW broadcasting and amateur radio
30 – 300 MHz	TV and FM radio broadcasting, air navigation, mobile communication
300 - 3000 MHz	TV broadcasting, satellite communication
3 - 30 GHz	Radar, microwave link, mobile and satellite comm. and broadcasting
30 - 300 GHz	Radar and experimental communications

Models describing the various modes of wave propagation depend on the actual frequency band, the bands, therefore, will be given together with the presentation of the wave propagation modes.

9.2. The Radio Channel

To define a radio channel, the definition of the antenna has to be given first. The antenna is a device for the radiation and the reception of electromagnetic waves. From the system aspect, an antenna can be regarded as a transformer between the transmission line and the free space transforming the energy passed through the transmission line into a radiated electromagnetic wave (transmitter antenna) or transforming the incident electromagnetic wave to a guided wave (receiver antenna).

The radio channel is the medium which determines the parameters (amplitude, phase, polarization, spectrum) of the radio waves propagating between the transmitter and receiver antennas. From the system aspect, a radio channel is a four-pole, with the input of the transmitter antenna and with the output of the receiver antenna, as shown in Fig. 9.1. The attenuation of this four-pole is called *propagation attenuation* and is defined as follows:

$$a_p = 10\lg\frac{P_{in}}{P_R}, \text{ dB} \tag{9.1}$$

where P_{in} is the input power of the transmitter antenna and P_{R} is the maximum output power of the receiver antenna.

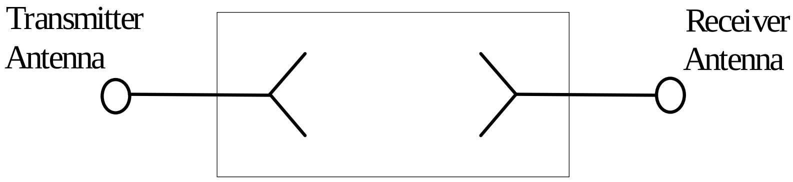

Figure 9.1. Radio Channel

Since the waves are propagating in radio channel without any man-made guide, the propagation attenuation is determined primarily by the properties of the medium between the antennas. To derive precise relations for describing the behaviour of the medium, wave propagation modes should be discussed. First, however, let us consider the properties of the antennas.

9.3. Antennas

9.3.1. Antenna as a Spatial Filter

An important feature of the antennas is their *directivity*. Since the radiation and/or the sensitivity of an antenna is not the same in all directions, this property is described by the *directional characteristic*.

Power radiated by a transmitter antenna is weighted by the directional characteristic and reversely, incident waves are also weighted by the receiver antenna. That is why the antennas are regarded as spatial filters.

9.3.2. Directional Characteristics of the Antennas

The directional characteristics of the antennas are given for the far field since antennas are usually located there. Far field strength at an $\mathbf{r} = (r, J, j)$ point of the space can be given with the linearly polarized J, j components as follows:

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}(r,\vartheta,\varphi) = E_0(\mathbf{r})\ \mathbf{p}(\mathbf{r}) = \frac{e^{-j\beta r}}{r} U_O(\vartheta,\varphi)\mathbf{p}(\vartheta,\varphi), \tag{9.2}$$

where $E_0(\mathbf{r})$ is the amplitude of the electrical field strength and $\mathbf{p} = p_J\ \mathbf{e}_J + p_j\ \mathbf{e}_j$ is the polarization vector. To introduce the *normalized power characteristics* $P(J, j)$, let us express the power density by means of equation (9.2):

$$S(r,\vartheta,\varphi) = \frac{U_0^2(J, j)}{240pr^2} = S_{\max}(r)\ P(\vartheta,\varphi) \tag{9.3}$$

where S is the maximum power density.

Taking the square root of the $P(J, j)$, a real function is obtained and it is called by definition the voltage directional characteristic or *amplitude characteristic* and is denoted as $F(J, j)$.

Instead of the three-dimensional presentation, the directional characteristics use to be given as two-dimensional cross-sections with a fixed parameter j. Cross-sections which belong to $j = 0^{\circ}$ and $j = 90^{\circ}$ are most frequently used and called *E* and *H*-plane directional diagrams (see Fig. 9.2.).

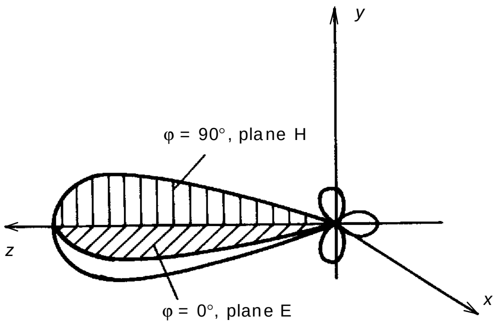

Figure 9.2. Three-Dimensional Directivity Pattern

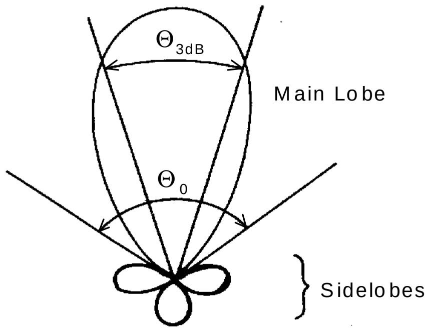

Figure 9.3 Two-Dimensional Directivity Pattern

Sometimes the directivity of an antenna is characterized simply by the 'width' of its main lobe. This is given as the conical angle determined by the zero directions encircling the main lobe and is denoted Θ_0. Usually, two narrower angles are also given: Θ_{3dB} denotes the width of the lobe, carrying half of the power (see Fig. 9.3.).

The directional characteristics of the various antennas are very different. For its importance, the *isotropic* antenna with $F(J, j) = 1$ has to be mentioned. Although such an antenna cannot be realized, it is defined and used as a reference.

9.3.3. Unidirectional Effect and the Gain

Directivity of an antenna can be characterized also by its unidirectional effect. This is the ratio of the power density radiated in main direction and the power density of the isotropic antenna radiating the same power P_t:

$$D = S_{max}/S_0 \tag{9.4}$$

where $S_0 = P_t/4\pi r^2$.

The gain of an antenna is defined by the ratio of the power density radiated by the main lobe and the power density of the izotropic antenna fed by the same input power P_{in}:

$$G = S_{max}/S_0 \tag{9.5}$$

where $S_0 = P_{in}/4\pi r^2$.

So the gain is a transfer parameter which depends on the loss of the antenna. It follows from equation (9.5) that the loss of the antenna can be characterized by the *efficiency* as follows:

$$\eta = \frac{G}{D} = \frac{P_t}{P_{in}} \qquad (9.6)$$

The terms directional gain and unidirectional effect are also used and defined as $G(\vartheta,\varphi) = GF^2(\vartheta,\varphi)$ and $D(\vartheta,\varphi) = D\,F^2(\vartheta,\varphi)$, respectively.

9.3.4. Effective Area of the Receiver Antenna

Receiver antennas can be regarded as active two-poles with inner impedance Z_{in}, open-circuit voltage U_{R} and maximum available effective power P_{R}. To characterize a receiver antenna, parameters describing the relation between the incident wave and the wave propagating on the transmission line have to be defined. One of such conversion parameters is the effective area of the antenna:

$$A_{\mathrm{R}} = P_{\mathrm{R}}/S \qquad (9.7)$$

where S is the incident power density. In equation (9.7) it is assumed that the polarization of the receiver antenna matches the polarization of the incident wave.

Using the reciprocity theorem, it can be shown that between the gain and the effective area of an antenna the following relation exists:

$$\frac{G}{A_R} = \frac{4p}{l^{\,2}} \qquad (9.8)$$

On the base of equation (9.8), the reciproque antennas can be sufficiently characterized by any one of the above parameters (usually by the gain).

9.4. Wave Propagation Modes

As it was shown in Chapter 9.2., the properties of the waves propagating between the transmitter and receiver antennas are determined by the radio channel. In the following we will examine the possible wave propagation modes which are resumed in Fig. 9.4. The main propagation modes are as follows: direct (or line-in-sight), reflected, surface, diffractive, tropospherical and ionospherical propagation.

9.4.1. Direct Wave and Free Field Attenuation

When modelling free-space wave propagation, the medium is assumed to be a homogeneous, ideal dielectric, free of charges and of current. In this case, the wave equation can be derived from the Maxwell equations, the general solution of which is a plain wave. Power density at the distance r can be determined from the input power of the transmitter antenna using equation (9.5):

$$S(J, j) = G \cdot F^2(J, j) \cdot \frac{P_{in}}{4p\ \mathrm{r}^2} \qquad (9.9)$$

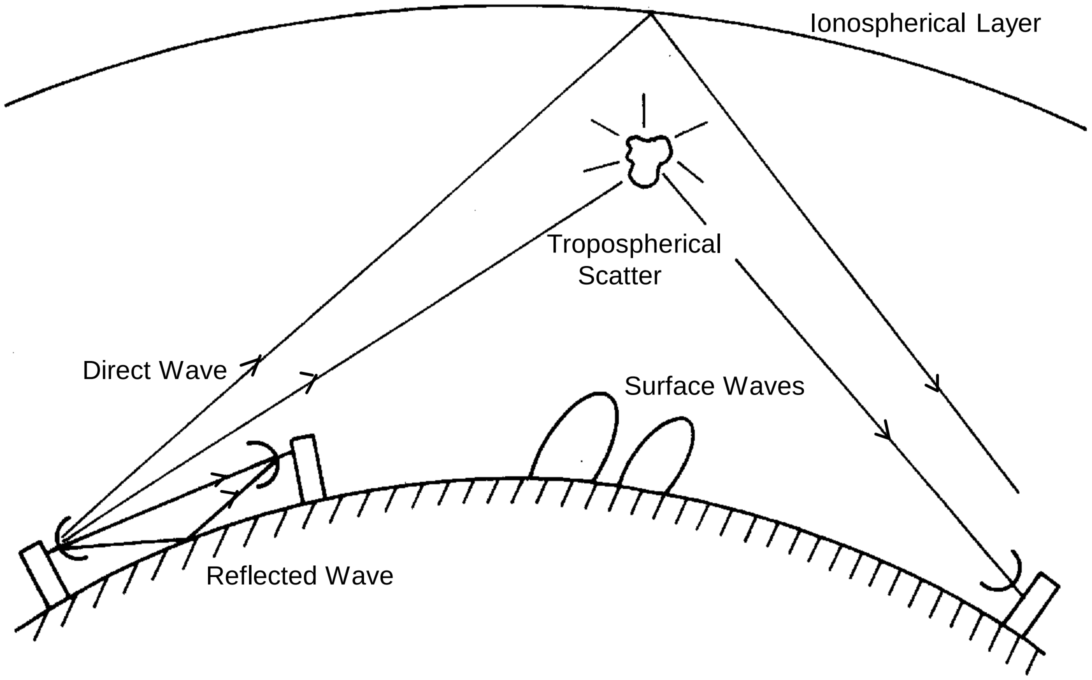

Figure 9.4. Main Wave Propagation Modes

Free-space attenuation is understood as the attenuation of the radio channel for direct wave propagation. To derive this attenuation, let us express the power density at the receiver antenna by means of equation (9.9). Suppose the distance from the transmitter antenna is r and the receiver antenna is in the main lobe of the transmitter antenna. On the basis of equation (9.2) and (9.9), the free-space field strength is

$$E_0 = \frac{\sqrt{60 P_{in} G_t}}{r} \tag{9.10}$$

According to equation (9.7), the receiver antenna transforms the power density of the incident wave to the power available at the antenna output:

$$P_R = P_{in} \frac{G_T A_R}{4p\, r^2}\,. \tag{9.11}$$

Making use of equation (9.8), the free-field attenuation can be expressed by the effective area of the transmitter and the receiver antennas

$$a_0 = \frac{(r\,l)^2}{A_T A_R} = \left(\frac{4pr}{l}\right)^2 \frac{1}{G_T G_R}$$

or it can also be given in the logarithmic form:

$$a_0 = 20\log\left(\frac{4p\, r}{l}\right) - (G_T^{dB} + G_R^{dB}) \tag{9.12}$$

9.4.2. Refraction

When speaking about direct wave propagation, *refraction* has also to be taken into consideration. While the wave propagation in vacuum is rectilinear, in the presence of the atmosphere the optical and the radio waves refract because of the varying refractive index of the air.

Air refractive index n is slightly greater than one. At the sea level, at normal climate $n = 1.0003$. This value decreases with increasing height above sea level. To be able to better distinguish the small variations of the refractive index, let us express it as $n = 1 + N\,10^{-6}$. The value of the refractivity N is given as

$$N = 77.6\,\frac{p}{T} + 3.7310^{5}\frac{e}{T^{2}} \tag{9.13}$$

where p is the air pressure [mbar], e is the partial tension of vaporized water [mbar] and T is the temperature [K]. As the result of numerous measurements, N could be approximated for the normal climate (standard atmosphere) as the function of the height above sea level h in the following form:

$$N(h) = 315 \cdot e^{-0.136h} \tag{9.14}$$

Because of refractivity changes, the waves propagating in the atmosphere refract towards the Earth as is shown (in an exaggerated form) in Fig. 9.5.

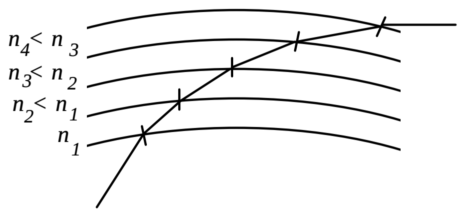

Figure 9.5. Refraction of Radio Waves

Instead of the computation of the curved propagation path, an effective radius of the Earth is defined for practical calculations: $R_{eff} = kR_o$ (R_o is the actual radius) and the path of the wave is regarded to be straight. The radius coefficient k is determined by the actual radius of the Earth (6370 km) and by the gradient of the refractive index:

$$k = \frac{1}{1 + R_0\,\dfrac{dn}{dh}} \tag{9.15}$$

From equation (9.14), $k = 4/3$ so that $R_{eff} = 8500$ km.

9.4.3. Ground Back-Scatter

To describe the reflection of the radio waves from the ground, a model of plain waves reflecting from a dissipative dielectric is used. Assuming the relative permitivity of the dielectric extended to the infinite half plane to be ε_r and its conductivity to be σ, ground reflectivity is defined as the ratio of the reflected and the incident field strengths:

$$\Gamma_g = \frac{E_r}{E_i} \tag{9.16}$$

Conditions of the ground reflectivity for the horizontal and vertical polarization are shown in Fig. 9.6. It can be seen that for small incident angles ($\vartheta < 5^\circ$) $\Gamma_g = -1$ regardless of the polarization and the frequency. Another important feature is that for vertical polarization

$|\Gamma_g^V|$ has a minimum value at the so-called Brewster-angle and $|\Gamma_g^V| = 0$ here, if the dielectric is supposed to be ideal.

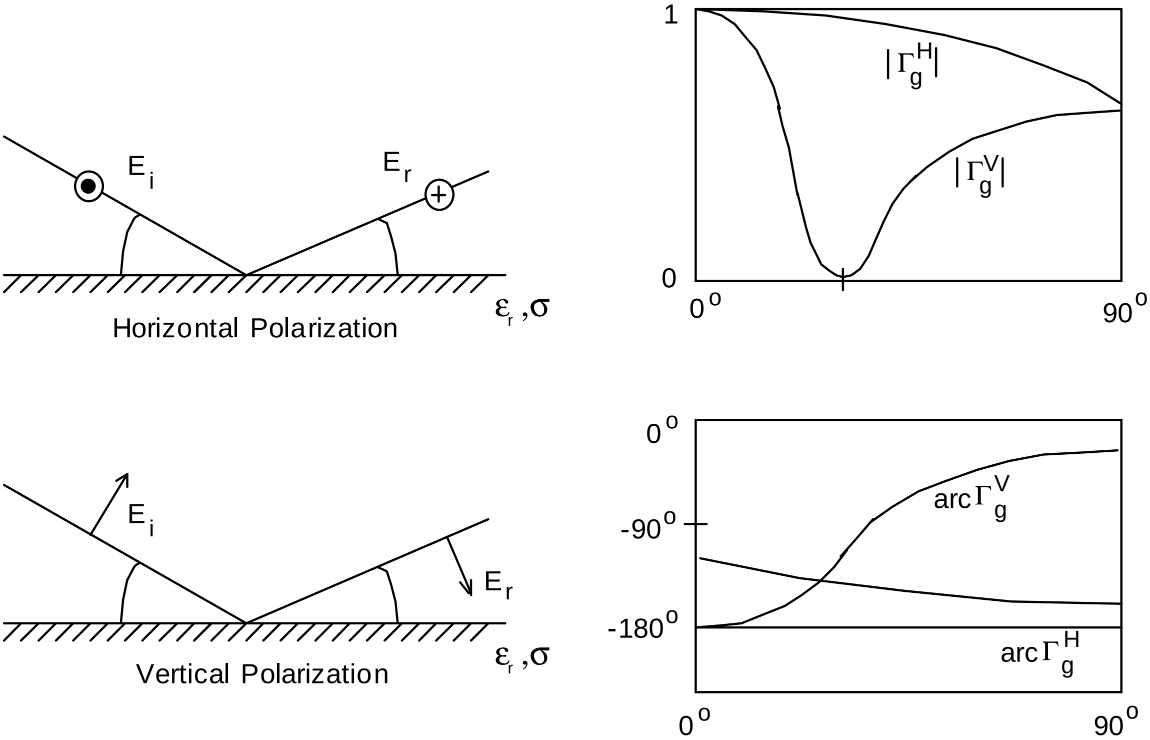

Figure 9.6. Ground Back-Scatter and the Reflection Coefficient

9.4.4. Ground Wave Multipath Propagation

Multipath propagation means that at least one reflected wave is received simultaneously with the direct wave (see Fig. 9.7.) This model is used mainly in the VHF, UHF and microwave range for mobile communications or links established within the horizon.

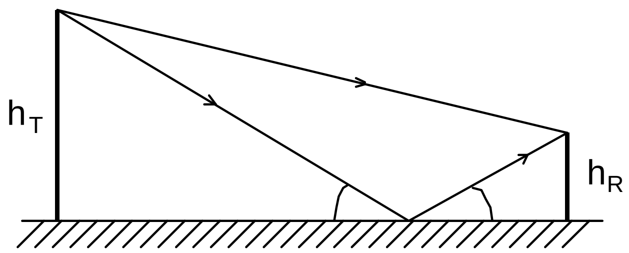

Figure 9.7. Multipath Propagation

Let us denote the length difference of the direct and the reflected path as Δ. Then the resulting field strength E_R at the receiver antenna is obtained by the summation of the direct E_0 and the reflected E_r components:

$$E_R = E_0 + E_r = E_0 + E_0 G_g\, e^{j\beta\Delta} \qquad (9.17)$$

Since for small values of ϑ $G_g \cong -1$, i.e.

$$E_R = E_0 + E_r \cong E_0\,(1 - e^{j\beta\Delta}) \qquad (9.18)$$

The length difference in the direct and the reflected paths can be expressed by the height and the distance of the two antennas:

$$\Delta = R_2 - R_1 \cong \frac{2h_T h_R}{r} \tag{9.19}$$

From equation (9.18) and (9.19) the absolute value of the field strength at the receiver antenna is

$$|E_R| = 2\,|E_0|\cdot\left|\sin\beta\frac{2h_T h_R}{r}\right| \tag{9.20}$$

thus the attenuation of the multipath propagation is

$$a_p = 20\,\lg[r^2/(h_T h_R)] - (G_T^{dB} + G_R^{dB}) \tag{9.21}$$

9.4.5. Diffraction

According to the laws of geometrical optics, obstacles standing in the path of wave propagation in the free space shadow the receiving antenna. Fortunately, this is the law of wave optics which determines the behaviour of the wave in this case, so that each point of a radiated wavefront is a secondary (Huyghens) source of elementary waves, the radiation of which is summed up (in the correct phase) with the waves of other elementary sources.

To model the obstacles of the terrain, parabolic cylinder or knife edge is used as a model. In the case of the knife edge model the field strength at the receiver depends on the relative height of the knife edge as shown in Fig. 9.8.

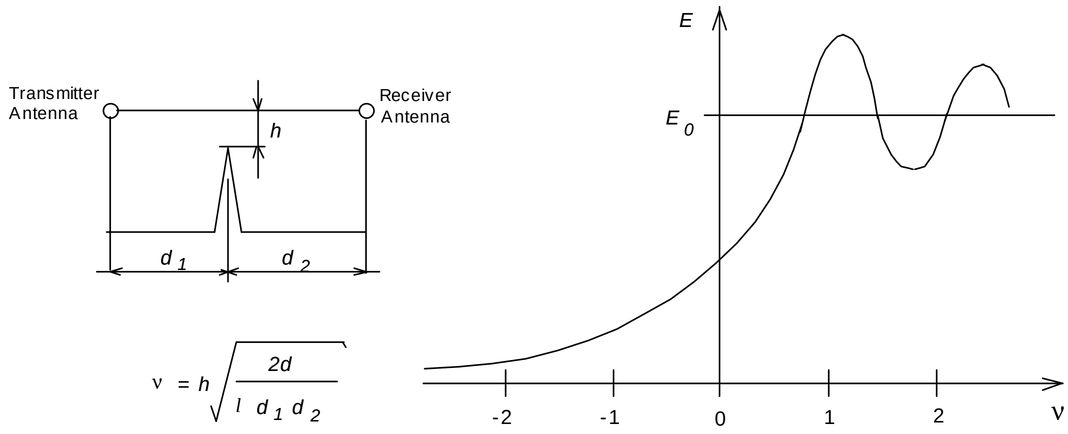

Figure 9.8. Field Strength as a Function of Diffraction

9.4.6. Surface Wave Propagation

Surface waves are generated at the boundary between the well conducting ground and the air. If the height of the antenna is low in comparison with the wavelength, wave generation is efficient since the direct and the reflected waves cancel each other in this case. The conductivity of the soil is good at frequencies from a few kHz to a few MHz so that surface wave propagation is important in this range. The channel attenuation is proportional to the fourth power of the distance. Distances used in practices span to several hundreds of km.

Field strength of vertically polarized surface waves is given by the following equation:

$$E = E_0 \cdot A(p) \tag{9.22}$$

where $A(p)=\dfrac{2+0.3p}{2+p+0.6p^2}$ is the surface wave attenuation factor, $p=\dfrac{p}{60\,l\,s}\left(\dfrac{d}{l}\right)$ is the so-called *numerical distance* and σ is the conductivity of the soil. Using equation (9.22) the section attenuation can be given as

$$a_s^{dB}=20\log\frac{d\,l}{4p\cdot A(p)}-(G_T+G_R) \qquad (9.23)$$

For long distances, $A(p)\cong 1/2p$ and the attenuation is proportional to the fourth power of the distance. For horizontal polarization the attenuation is much higher wherefore only the vertical polarization is used in practice. The greatest advantage of the surface waves is their ability to follow the curvature of the ground thus propagating to long distances, beyond the horizon.

9.4.7. Tropospherical Scatter

As it was shown, the refraction index of the atmosphere is periodically changing and the change can be described well in a long-term average. Nevertheless, because of the fast local changes of humidity, pressure and the temperature of the air, the refractive index may exhibit sudden changes. These changes are small, however, they may cause significant power-scatter if the transmitted power is large.

Tropospherical links operate in the range between 200 MHz and 10 GHz. The minimum frequency is limited by the size of the high-gain antennas while the attenuation become significant at the high frequencies. A characteristic feature of tropospherical links is the significant fluctuation of the field at the receiver. The typical distance of a tropospherical link is some hundreds of km, usually not more than 800 km. To set up a link through tropospherical scatter, lobes of the transmitting and the receiving antennas have to create a so-called *common scatter volume*. This is generated in the troposphere usually in the height within 10 km.

9.4.8. Ionospherical Propagation

The ionosphere is a layer of ionized gas particles surrounding the Earth in the height between 40 and 100 km. The ionization is caused by the solar ultraviolet and particle-radiations and by the meteorites. Since the main source of the ionization is the Sun, the state of the ionosphere depends primarily on solar activity. Ionospherical layers are characterized by the number of free electrons in the unit of volume. On the base of local maxima of electron density, D, E and F layers are distinguished. At day-time, the layer F splits into layers F_1 and F_2 while at night-time only D and F layers show up.

Since the refractive indices of these ionospherical layers are different, radio waves reflect from the layers. A maximum frequency called the *critical frequency* belongs to each layer. This is defined so that the waves with higher frequencies than the critical frequency will reflect with a probability less than 50 per cent. If the waves reach the layer askew then signals with frequency higher than the critical f_C are also reflected. The relation between the maximum usable frequency (MUF) and the critical frequency is then determined by the skew angle ψ as MUF = $f_C/\cos\psi$.

Control Questions

1. What is the radio channel?
2. Give the definition of section attenuation!
3. How does the antenna act as a spatial filter?
4. Define the normalized power directional characteristics!
5. Define the normalized voltage directional characteristic!
6. What is the directional diagram?
7. What is the definition of the gain and of the directivity?
8. How is the effective area of the antenna defined?
9. List the wave propagation modes!
10. Give the section attenuation formula for the double path propagation!

Exercises

1. Compute the free-space attenuation of the radio link operating on 450 MHz if the distance between the transmitter and the receiver is 10 km and the gain of the antennas is equally 20 dB.
2. Compute the electrical field strength at the receiver if the operating frequency is 145 MHz, the input power of the transmitter is 10 W, the gain of the transmitter antenna is 10 dB and the distance between the 10 m high transmitter and receiver antennas is 5 km. Suppose there is a double-path propagation and that the reflection coefficient of the ground is -1.

Bibliography

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[2] Stutzman W.L.-Thiele G.A.:Antenna Theory and Design. John Wiley. N.Y. 1981.

List of Notations

a_p	propagation attenuation
P_{in}	input power of the transmitting antenna
P_R	max. output power of the receiving antenna
$P(J, j)$	normalized power characteristics
$F(J, j)$	normalized amplitude characteristics
D	unidirectional effect
$D(J, j)$	directivity of the unidirectional effect
G	gain
$G(J, j)$	directivity of the gain
λ	wavelength
p	polarization vector
β	phase coefficient
S	power density
S_0	free-space power density of the izotropic antenna
P_t	power radiated by the antenna

Z_{in}	input impedance of the antenna
U_R	open circiut output voltage of the receiver antenna
A_R, A_T	effective area of the antenna
E_0	free-space field of the antenna
a	free-space attenuation
p	air pressure
e	partial tension of the steam
T	air temperature
n, N	refractive index, refractivity
R_0	radius of the Earth (6370 km)
R_{eff}	effective radius of the Earth
k	radius coefficient
Γ	groung-reflecivity ratio
Γ_g^H, Γ_g^V	ground-reflectivity ratios for horizontal and vertical polarization