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EECS 290i
SPRING 1993

LARGE-SCALE PROPAGATION MECHANISMS

Free Space Loss

For propagation distances d much larger than the antenna size, the far field of the generated Electromagnetic wave dominates all other components. In free space, the power density w at distance d from a transmitter with power p_T and antenna gain G_T is
$w = p_T G_T / (4\pi d^2)$. The available power p_R at a receive antenna with gain G_R is

$$p_R = \frac{p_T G_T}{4\pi d^2} \cdot A = \frac{\lambda^2}{(4\pi d)^2} G_T p_T G_R$$

where A is the effective area or 'aperture' of the antenna, with $G_R = 4\pi A/\lambda^2$. The wavelength λ is c/f_c with c the velocity of light and f_c the carrier frequency. The product $G_T p_T$ is called the effectively radiated power (ERP) of the transmitter.

While cellular telephone operator mostly use received power p_R , in the planning of the coverage area of broadcast transmitters, the CCIR recommends the use of the electric field strength E at the location of the receiver, with $E = \sqrt{120\ \pi p_R}$.

Exercise: Show that for a reference transmitter with ERP of 1 kwatt in free space,

$$E_o = \sqrt{\frac{(30 p_T G_T)}{d}}$$

As the propagation distance increases, the radiated energy is spread over the surface of a sphere of radius d, so the power received decreases proportional to d^{-2}. Expressed in dB, the received power is

$$p_{dB} = p_o - 20\log\frac{d}{d_o}$$

Exercise: Show that the path loss L between two isotropic antennas ($G_R = 1$, $G_T = 1$) can be expressed as L_{dB}= -32.44 -20logf_c/1MHz -20log$d$/1km.

Plane Earth Loss

If we consider the effect of the earth surface, the expressions for the received signal become more complicated.

For (theoretical) isotropic antennas above a plane earth, the received electric field strength is

$$E = E_o\,(1 + R_c e^{j\Delta} + (1 - R_c)\,F \cdot e^{j\Delta} + \ldots)$$

with R_c the reflection coefficient and E_o the field strength for propagation in free space. This expression can be interpreted as the complex sum of a direct line-of-sight wave, a ground-reflected wave and a surface wave. The phasor sum of the first and second term is known as the 'space wave'.

For a horizontally-polarised wave incident on the surface of a perfectly smooth earth,

$$R_c = \frac{\sin\Psi - \sqrt{(\varepsilon_r - jx) - \cos^2\Psi}}{\sin\Psi + \sqrt{(\varepsilon_r - jx) - \cos^2\Psi}}$$

where ε_r is the relative dielectric constant of the earth, ψ is the angle of incidence (between the radio ray and the earth surface) and $x = \sigma/(2\pi f_c \varepsilon_o)$ with σ the conductivity of the ground and ε_o the dielectric constant of vacuum.

For vertical polarization

$$R_c = \frac{(\varepsilon_r - jx)\sin\Psi - \sqrt{(\varepsilon_r - jx) - \cos^2\Psi}}{(\varepsilon_r - jx)\sin\Psi + \sqrt{(\varepsilon_r - jx) - \cos^2\Psi}}$$

Exercise: Show that $R_c \to -1$ for $\psi \to 0$. Verify that for vertical polarization, $|R_c| > 0.9$ for $\psi < 10°$. For horizontal polarization, $|R_c| > 0.5$ for $\psi < 5°$ and $|R_c| > 0.9$ for $\psi < 1°$.

The relative amplitude $F(\cdot)$ of the surface wave is very small for most cases of mobile UHF communication ($F(\cdot) << 1$). Its contribution is relevant only a few wavelengths above the ground. The phase difference Δ between the direct and the ground-reflected wave can be found from the two-ray approximation considering only a Line-of-Sight and a Ground Reflection. Denoting the transmit and receive antenna heights as h_T and h_R, respectively, the phase difference can be expressed as

$$\Delta = \frac{2\pi}{\lambda}\left(\sqrt{d^2 + (h_T + h_R)^2} - \sqrt{d^2 + (h_T - h_R)^2}\right)$$

For $d >> 5$, one finds, using $\sqrt{1+\varepsilon} \cong 1 + \frac{\varepsilon}{2}$,

$$\Delta \cong \frac{4\pi}{\lambda}\frac{h_T h_R}{d}$$

For large d, ($d >> 5 h_T h_R$), the reflection coefficient tends to $R_c \to -1$, so the received signal power becomes

$$p_R = \frac{\lambda^2}{(4\pi d)^2}\left[2\sin\frac{2\pi}{\lambda}\frac{h_T h_R}{d}\right]^2 G_T p_T G_R$$

For propagation distances substantially beyond the turnover point $d = \frac{4}{\lambda} h_T h_R$, this tends to the fouth power distance law:

$$p_R \rightarrow \frac{(h_T h_R)^2}{d^4} p_T G_T G_R$$

Experiments confirm that in macro-cellular links over smooth, plane terrain, the received signal power (expressed in dB) decreases with "40 log$d$". Also a "6 dB/octave" height gain is experienced: doubling the height increases the received power by a factor 4.

In contrast to the theoretical plane earth loss, Egli measured a significant increase of the path loss with the carrier frequency f_c. He proposed the semi-empirical model

$$p_R = \left(\frac{40MHz}{f_c}\right)^2 \frac{(h_T h_R)^2}{d^4} p_T G_T G_R$$

i.e., he introduced a frequency dependent empirical correction for ranges $1 < d < 50$ km, and carrier frequencies 30 MHz $< f_c <$ 1 GHz.

For communication at short range, formula 2.6 looses its accuracy because the reflection coefficient is not neccessarily close to -1. For $d << h_T h_R / 4\lambda$, free space propagation is more appropriate, but a number of significant reflections must be taken into account. In streets with high buildings, guided propagation may occur.

Diffraction loss

If the direct line-of-sight is obstructed by a single knife-edge type of obstacle, with height h_m we define the following diffraction parameter v:

$$v = h_m\left(\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_T} + \frac{1}{d_R}\right)}\right)$$

where d_T and d_R are the terminal distances from the knife edge. The diffraction loss expressed in dB can be closely approximated by

$$A_d = \begin{cases} 0 & v < 0 \\ 6 + 9v - 1.27v^2 & 0 < v < 2.4 \\ 13 + \log v & v > 2.4 \end{cases}$$

The attenuation over *rounded* obstactles is usually higher than A_d in the above formula.

Approximate techniques to compute the diffraction loss over multiple knife edge have been proposed by Bullington, Epstein and Peterson, and Deygout. The method by Bullington defines a new 'effective' obstacle at the point where the line-of-sight from the two antennas cross. Deygout suggested to search the 'main' obstacle, i.e., the point with the highest value of *v* along the path. Diffraction losses over 'secondary' obstacles are added to the diffraction loss over the main obstacle. Epstein and Peterson suggested to draw lines-of-sight between relevant obstacles, and to add the diffraction losses at each obstacle.

Total Path loss

The previously presented methods for ground reflection loss and diffraction losses suggest a "Mondriaan-style" interpretation of the path profile: Obstacles occur as straight vertical lines while horizontal planes cause reflections. That is the propagation path is seen as a collection of horizonatal and vertical elements. Accurate computation of the path loss over non-line-of-sight paths with ground reflections is a complicated task and does not allow such simpliofications.

Many measurements of propagation losses for paths with combined diffraction and ground reflection losses indicate that knife edge type of obstacles significantly reduce ground wave losses. Blomquist suggested two methods to find the total loss:

$$A_{B_1} = A_{fs} + A_r + A_d$$

and the empirical formula

$$A_{B_2} = A_{fs} + \sqrt{A_r^2 + A_d^2}$$

where A_{fs} the freespace loss, A_R the ground reflection loss and A_d the multiple knife-edge diffraction loss in dB values.