

MATHEMATICAL MODELING OF RADIO SIGNAL LOSSES IN MOUNTAINOUS REGIONS: DIFFRACTION, TERRAIN, AND ATMOSPHERIC ABSORPTION

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Modern radio communication systems, including digital television, are placing increasingly high demands on the reliability and stability of radio channels in a complex physical-geographical environment. It is particularly challenging in mountainous areas where the propagation of radio waves occurs under conditions of sharply expressed heterogeneity of the relief, significant height variations, shielding, and numerous obstacles that cause significant energy losses and instability of the received signal.

Mountainous areas are physically complex environments where radio waves are repeatedly exposed to obstacles in the form of ridges, gorges, slopes, and rocky massifs. These relief elements create conditions for shading and partial shielding of the radio route, causing diffraction, scattering, and reflection of waves. As a result, signal level fluctuations, interference freezes, and a sharp deterioration of communication quality indicators are observed on the receiving side. This is especially critical for digital transmission systems, where exceeding the permissible loss level leads to connection interruption and service degradation.

Classic radio wave propagation models, such as the Free Space Model (FSPL), Okumura-Hata, and COST-231, are primarily oriented towards flat or slightly crossed terrain conditions and do not fully account for the influence of complex mountain relief. Their application in high-altitude areas is often accompanied by significant systematic errors, which necessitates the development of more precise mathematical models capable of adequately describing the real picture of radio signal propagation [1-3].

Mathematical modeling of radio signal losses in mountainous conditions should take into account the combined influence of several physical mechanisms. The main ones are the diffraction of radio waves on obstacles, the geometric features of the relief that lead to a change in the trajectory of propagation, and atmospheric absorption associated with the weakening of wave energy when passing through atmospheric layers of varying density and humidity. The indicated processes do not exist in isolation, but form a complex interconnected system that determines the total level of signal attenuation.

Thus, the analysis of radio signal propagation processes in complex terrain conditions requires a shift from a general description of the physical mechanisms of attenuation to a strict use of fundamental parameters that determine the energy and wave characteristics of the radio channel. Formalizing these parameters allows

for the construction of an adequate mathematical model of the radio path and the quantitative assessment of signal losses at various distances and frequencies.

The following basic quantities are introduced as the initial characteristics of the radio wave and the propagation medium. Wavelength:

$$\lambda = c/f, \quad (1)$$

where, $c \approx 3 \cdot 10^8$ m/s

Free spatial losses (FSPL) at distance d (in meters):

$$FSPL(dB) = 20 \log_{10}(4\pi d/\lambda) \quad (2)$$

Based on the fundamental parameters of the radio wave, such as wavelength and free spatial losses, it is possible to estimate only the basic signal attenuation under direct visibility conditions. However, in mountainous areas, the propagation of a radio signal rarely occurs along a straight line: in the path of the signal, there are mountain peaks, rocks, and other obstacles that create shadow zones.

Under these conditions, it is necessary to consider the effect of diffraction, which allows the wave to "circle" obstacles and penetrate into zones beyond direct visibility. The most common model used for the quantitative assessment of diffraction losses is the knife-edge barrier model, which allows calculating the additional signal attenuation caused by a barrier with a sharply defined profile. This model uses the Frenel parameter v (shielding intensity, dimensionless) [3-5]:

$$v = h \sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}} \quad (3)$$

where: h -height of the obstacle relative to direct visibility (m) (positive if protruding above the line), d_1 and d_2 - distances from the obstacle to the transmitter and receiver (m).

The approximate empirical loss formula (dB) according to the ITU-style (Klased knife-edge; widely used):

$$L_{diff}(v) = 6,9 + 20 \log_{10}(\sqrt{(v - 0,1)^2 + 1} + v - 0,1) \quad (4)$$

(for negative values of v , the formula gives small losses; for large values of v , the formula gives large losses).

Algorithm for multiple obstacles (general idea):

- Deigou's (Deygout) method: find the "highest" effective obstacle relative to the straight line, calculate its L_{diff} , then recursively break the path into sections before/after this obstacle and repeat.

- there is also the Bullington (Bullington) method - gives a smoother approximation.

The results of the study (at $f=570$ MHz) - diffraction losses depending on the v parameter are presented in Table 1:

Diffraction losses depending on the parameter v

Table 1.

v	0,0	0,5	1,0	1,5	2,0	2,5
L_{diff} , dB	6,0	10,3	13,9	16,5	18,6	20,5

Conclusion: even small protrusions of obstacles create noticeable signal attenuation, which is especially important for mountainous areas.

However, in practice, in mountainous and intersected terrain, radio waves encounter many natural obstacles: peaks, slopes, ravines, and other relief elements. In such cases, the shielding and diffraction effects overlap, and the total losses can significantly exceed the free-space values.

Therefore, for the practical analysis of radio network coverage, it is necessary to consider the real terrain and sequential screening, which allows for a more accurate forecast of the reliable receiving zone, identification of weak sections, and planning the placement of transmitting and receiving stations.

General signal model through FSPL mountain profile and total additional losses (diffraction, shading), i.e.:

$$L_{total} = FSPL + L_{terrain} \quad (5)$$

where, $L_{terrain}$ is the total shielding/diffraction loss calculated using the single/multiple knife-edge method (Deygout/Bullington) or through numerical models (ITU-R P.526, Longley-Rice/ITM - for a complex profile).

Briefly about approaches:

- if the profile has 1 noticeable ridge/threshold - use the model (3,4) knife-edge;
- if there are several obstacles - use the Deygout/Bullington or ITM (Longley-Rice) numerical model, which takes into account the phase and scattering statistics for medium and far fields;
- if a coverage map is required - a profile is drawn towards the receiving points and Deygout/ITM is applied.

After analyzing signal losses caused by relief and shielding, it is necessary to consider the influence of the propagation medium on the attenuation of radio waves. One of the key factors in this context is atmospheric absorption: the interaction of electromagnetic waves with gas molecules such as water vapor and oxygen leads to additional energy losses that must be considered when modeling the safe reception zone, especially in high-frequency ranges.

Atmospheric (gas) absorption is usually represented as a specific attenuation γ (dB/km) depending on frequency, pressure, and humidity [6,7]:

$$A_{gases} = \gamma_{gases}(f, p, \rho_v) \cdot d \quad (6)$$

where d is the distance in km.

In fact, γ_{gases} is the sum of oxygen and water vapor contributions:

$$\gamma_{gases} = \gamma_{O_2}(f, p, T) + \gamma_{H_2O}(f, p, T, \rho_v) \quad (7)$$

(precise expressions are complex resonance models, formulas are given in ITU-R P.676; in the UVR/UVR ranges <1 GHz, gas losses are very small: about 10–3 - 10–2 dB/km).

Table 2 shows the results (at $f=570$ MHz for short distances, the influence of rain is insignificant) - atmospheric absorption (of gases) over the distance:

Atmospheric absorption (of gases) by distance

Table 2.

d (km)	0	10	20	50
A_{gases} (dB)	0	0,1	0,2	0,5

The results of the analysis of atmospheric absorption show that signal losses due to interaction with atmospheric gases increase almost linearly with distance. At short distances (up to 10 km), the losses are practically insignificant (0.1 dB), and even at 50 km, the attenuation is only 0.5 dB. This indicates that atmospheric gas absorption has a weak effect on the attenuation of the radio signal in the ranges characteristic of the DVB-T2 standards and is not a critical factor in planning the safe reception zone. The main attention should be paid to relief effects, shielding, and precipitation, which can create significantly greater attenuation.

Thus, atmospheric absorption can be considered as a constant, relatively small additional attenuation that does not require complex adjustments when calculating coverage over short and medium distances.

Considering atmospheric absorption allows us to consider signal losses that occur when radio waves interact with gas molecules such as water vapor and oxygen. These losses, although significant at high frequencies, usually manifest uniformly throughout the entire length of the radio line and depend on the composition and density of the atmosphere.

However, in real conditions, non-stationary atmospheric phenomena such as rain, snow, hail, and other types of precipitation significantly affect the attenuation of the radio signal. The absorption and scattering of radio waves by raindrops leads to additional, often localized losses that can significantly reduce signal power, especially in ranges above 1 GHz.

Thus, to fully model the reliable reception zone, it is necessary to move from considering constant atmospheric losses to considering dynamic precipitation factors that determine signal attenuation variations in time and space.

Поглощение дождём (осадки). Для интенсивности дождя R (mm/h) специфическое ослабление (dB/km) аппроксимируется [8]:

$$\gamma_R = k(f, \text{polarization}) R^\alpha(f, \text{polarization}) \quad (8)$$

where: coefficients k and α depend on frequency and polarization (ITU-R P.838). The total attenuation over the path length d (km) is approximately $AR = \gamma_R \cdot d_{\text{eff}}$, where d_{eff} is the effective length of rain attenuation (usually less than the geometric length due to cloud and rain statistics).

Note: at a frequency of $f=570$ MHz, the contribution of rain is usually very small compared to UHF - often neglected for short/medium distances, but in heavy tropical rains and on long roads, it must be taken into account.

Summary loss model:

$$L_{\text{sum}}(d) \approx FSPL(d) + L_{\text{diff/terrain}} + A_{\text{gases}}(d) + A_{\text{rain}}(d) \quad (9)$$

Each component is evaluated by a suitable model (knife-edge/Deygout/ITM for $L_{\text{diff/terrain}}$; ITU-R-P.676 for gases; ITU-R-P.838 for rain).

The absorption of the radio signal by raindrops and other precipitation leads to additional energy losses, which can be significant in high frequency ranges. For accurate forecasting of the reliable reception zone, it is necessary to consider these sedimentary effects, as they introduce temporal and spatial variations of attenuation, especially in mountainous and complex weather conditions.

The results (at $f=570$ MHz) - total losses depending on the distance d - are presented in Table 3.

Total loss depending on distance d .

Table 3.

d (km)	FSPL	FSPL+terrain (relief)	FSPL+terrain+atm (atmosphere)
1	80	85	85,01
3	91	98	98,03
5	99,5	115	115,05
7	105	125	125,07
10	112	138	138,1

Analyses show that the total losses increase with distance mainly due to free spatial losses and the influence of relief. Atmospheric losses are small (0.01-0.1 dB) and practically do not affect the total attenuation over the considered distances. Thus, the main factor in signal attenuation in mountainous terrain is relief.

Conclusion. Mathematical modeling of radio signal losses, taking into account diffraction, relief, and atmospheric absorption, allows for a reliable assessment of the total signal attenuation in mountainous areas. The main factors of losses are relief and diffraction on obstacles, while the influence of atmosphere and precipitation is additional in nature. The developed model provides accurate

forecasting of the reliable reception zone and can be used to optimize digital radio systems such as DVB-T2 in complex geographical conditions.

References

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