Investigation of rough surfaces for propagation modeling in caves

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***Abstract*—Making wireless communications available in caves is important, it will benefit several activities that are caves-related such as volcanology, speleo-biology, speleo-archeology, hydrology, military reconnaissance, and cave exploration. Besides, it will also enhance the safety of the operation of show caves like the tourist caves and furthermore, may assist in the search and rescue operation in caves. In this paper, we study the behavior of radio waves on a random rough surface using ray tracing technique that incorporates a special twist to the Fresnel reflection coefficient to account for the scattering effects arising from that rough surface. The findings of our work lays a foundation for further investigation to be conducted in actual cave environment, since the ground surface inside a cave is definitely not smooth but rough.**

Keywords—ray tracing; radio propagation; caves

I. Introduction

The expeditious development of wireless communication has driven expansion for high speed and high quality data between mobile devices situated in various places or cells. The effectiveness of a wireless communication operation greatly relies on the propagation channel. For that reason, a comprehensive interpretation of the radio propagation model plays a vital role in providing a favorable design of wireless communication system. Previous research work show that it is possible to apply ray-tracing technique to model complex rough environment, including that of rough surfaces [1]-[2]. When ray-tracing technique is applied, the electromagnetic waves are treated as distinct propagation rays that endure reflection, attenuation and diffuse scattering due to the existence of obstacles, rough surface walls, and buildings. The summation of the electric fields of each multipath element defines the intercept point of receiver.

Caves are likely to have rough wall surfaces and dimensional unevenness on a number of facets [3]. Besides that, due to the geometry of intervening space, the dielectric parameters of the surroundings would act as an influential role on the propagation of electromagnetic waves in caves. In a natural cave, all rock stones contain a definite quantity of water. From our theoretical knowledge, water greatly influences the parameter of rock, which separately reflects its composition. The evaluated conductivity of this ground water in addition to its reliance on frequency was considered in [4].

In this paper, we endeavour to study the behaviour of radio waves on a random rough surface using ray tracing technique. Specifically, beyond using the conventional Fresnel reflection coefficient for simulating a flat ground surface, we have further used a modified version of the Fresnel reflection coefficient that takes into account an attenuation factor to account for the rough ground reflection. These two cases are studied and their comparison reported.

II. Ground Reflection of Random Rough Surface using Ray Tracing

We have created a random rough surface profile that resembles the natural condition of the ground in caves with indication of the position of the transmitter (Tx) and receiver (Rx). The geometry of this structure is shown in Fig. 1. The initial receiver position is placed 1 m away from the Tx, while the consecutive Rx positions dispersed 0.3 m along the simulation path of 58.78 m in total length. Both the Tx and Rx share an identical height in the simulation scheme; therefore, we solved the said geometry in a two-dimensional way.

The Rayleigh criterion is generally used to evaluate surface roughness. In [2], the critical height (h_c) of the surface protuberance is presented as

$$h_c = \frac{\lambda}{8 \cos \theta_i} \qquad (1)$$

where λ is the wavelength and Θ_i is the angle of incidence. The height (h) of a specified rough surface is distinguished between the minimum and maximum surface protuberance. Thus, if $h < h_c$ then a surface is contemplated as smooth, but rough if $h > h_c$. In our studied case, an attenuation factor (ρ_s) is being employed for minimized energy in the specular reflection direction. It is expressed as

$$\rho_S = \exp\left[-8\left(\frac{\pi \sigma_h \cos \theta_i}{\lambda}\right)^2\right] \qquad (2)$$

where Θ_i is the angle of incidence, σ_h is the standard deviation of surface heights and λ is the carrier frequency wavelength. The coarseness Fresnel reflection coefficient for parallel polarization is shown as:

$$(\Gamma_{\|})_{\text{rough}} = \rho_S \Gamma_{\|} \quad (3)$$

It was demonstrated in [5] that the attenuation factor miscounts the scattering loss for several measurements such as sharp edges impact, Gaussian distribution of surface heights, and others; therefore, a combination of smooth and rough surfaces of Fresnel reflection coefficients is introduced as the averaged reflection coefficient (Γ_{AVG}):

$$\Gamma_{AVG} = \frac{(\Gamma_{\|} + \rho_S \Gamma_{\|})}{2} \quad (4)$$

where ρ_S is the attenuation factor derived from (2). It is this averaged reflection coefficient that we use for our ray tracing simulation of the random rough surface presented in Fig. 1.

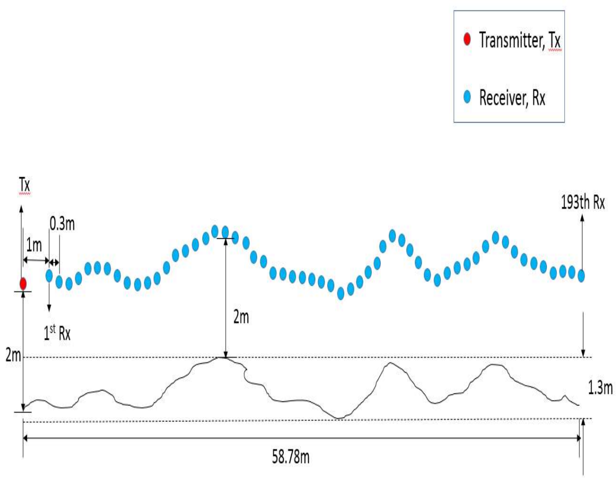

Fig. 1. Side view of the random rough ground surface in meters with indication of the Tx and Rx positions (not to scale).

III. Result And Discussion

In this section, we present the ray-tracing simulation results of the two aforementioned cases, namely, with the conventional Fresnel reflection coefficient for a smooth ground surface, and with the modified Fresnel reflection coefficient (Γ_{AVG}) for a random rough ground surface. For carrying out the simulations, a value of 7.51 is used for the relative permittivity value for the two cases, as extracted from limestones [5]. This is a close resemblance to the condition in caves [6]. Fig.2 presents the signal strength versus locations of receiver.

From Fig. 2., we may observe that the signal strength between the Tx and Rx is principally influenced by distance. This is true for the smooth ground surface as well as for the random rough ground surface. In addition, we may also observe that in these two cases, the Brewster angle phenomenon occurs at approximately 11 m away from the Tx, or, the 34th position of the Rx. This is an expected observation for ground reflection, when the reflection coefficient for parallel polarization is used. Generally, when an attenuation factor is applied for the random rough surface, it can lower the path gain by about 6 dB.

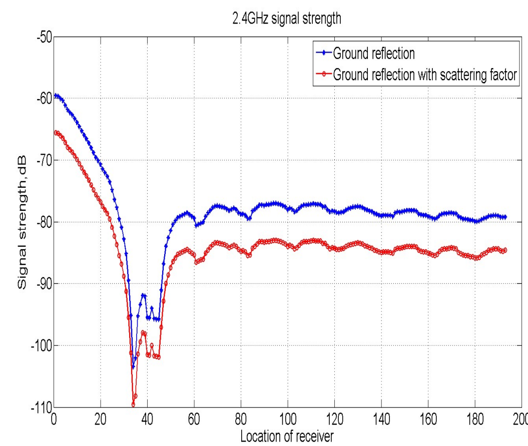

Fig. 2. Ground reflection for the two cases.

IV. Conclusion

In this paper, we have demonstrated the difference of the ground reflection from a smooth surface and a random rough surface using ray-tracing method. The trick is to use a twist to the conventional Fresnel reflection coefficient by incorporating an attenuation factor whose effect is embedded in the averaged reflection coefficient term. When this averaged reflection coefficient is applied on a random rough surface, it can lower the path gain by about 6 dB as contrast to that of a smooth ground surface. From this finding, we predict that in a cave environment when the ground surface is not smooth but rough, lower signal strength can be expected.

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