Effects of Different Parameters on Attenuation Rates in Circular and Arch Tunnels

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Abstract— Radio wave propagation in circular and arch shaped cross-section tunnels is analyzed. The electrical and mechanical parameters, such as the shape and transverse dimension of the tunnels, frequency, polarization, electrical parameters like conductivity and permittivity, which have a significant influence on the attenuation inside tunnels are determined. The impact of these parameters on the propagation is analyzed and an optimum set of values is determined. In this paper, taking circular and arch shaped tunnel as an examples, influence of various parameters on UHF radio propagation is analyzed.

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1. INTRODUCTION

UHF radio wave propagation in tunnels has been a topic of interest for a long time [1]. Tunnels exists in metropolitan cities and mountainous areas and radio coverage is needed in the tunnels for personal and emergency communications. As a result subject has been very popular, and a few investigations has been carried out in past [5]. Every new city roads includes some tunnel sections or at-least cuttings to reduce noise emission in the environment. In a modern country like Austria, 10% of high priority roads are in tunnels. Common cell planning concepts are not applicable in tunnels due to heavy waveguiding effects, so there are some simplifications introduced in theoretical studies [2].

Traditionally, leaky feeders have been proposed to supply radio services inside tunnels [3]. Leaky feeder cables are expensive, require repeaters at regular distances and maintenance at regular intervals. Their bandwidth is generally equal to one octave and by adjusting the slot configuration, it is even possible to extend this band [4]. However, the attenuation dramatically increases at high frequency, any improvement being only obtained with cables of larger diameters leading to prohibitive cost and weight [4].

Previous experimental studies of radio wave propagation characteristics in tunnel environments were almost entirely concentrated on finding the optimum frequency bands for minimum attenuation [6]. The results showed that the optimum frequency window seems to be between 1–2 GHz. The propagation attenuation in the far region of a straight tunnel is less than that in free space, thus indicating that guided wave phenomena are involved [7]. In general, tunnels may be considered as hollow waveguides surrounded by lossy materials. Radio wave impinges on a wall of the tunnel is partially refracted into the surrounding dielectric and partially reflected back into the tunnel. Characteristics of radio waves in tunnels are influenced by many factors mainly shape of the tunnel (height and width), frequency, polarization, conductivity and permittivity of surrounding material.

Impact of electrical parameters on UHF propagation in straight and circular tunnel has been analyzed in [9]. Usually, cross-section of the tunnel is arched shaped. In arched shaped tunnels, a theoretical treatment of the propagation characteristics is somehow difficult because the boundary does not coincide with a coordinate surface of an orthogonal coordinate system. For this reason, the arched shaped tunnel is modelled in [8] as a circular waveguide having the same cross sectional area. In this paper by considering circular and arched shaped tunnels as examples, we analyze influence of height and width of the tunnel, radio wave frequency, conductivity and permittivity of the tunnel boundary on the attenuation inside the tunnels.

2. ATTENUATION RATE IN TUNNELS

2.1. Circular Tunnel

The attenuation rate, in general, is a function of tunnel dimensions, radio wave frequency, dielectric constant and conductivity of the tunnel surrounding structure. For UHF waves in tunnel environment, the tunnel dimensions are always larger than the free space wavelength. The approximate equations for attenuation rate in circular tunnel for transverse electric (TE) and transverse magnetic mode (TM) is given by [10]:

$$\alpha_{0n} = 8.686 \frac{\xi_{1n}^2}{k_0^2 a^3} \begin{cases} \mathrm{Re}\frac{1}{\sqrt{\varepsilon_r'-1}} & \mathrm{TE}_{0n} \\ \mathrm{Re}\frac{\varepsilon_r'}{\sqrt{\varepsilon_r'-1}} & \mathrm{TM}_{0n} \end{cases} \tag{1}$$

where ξ_{1n} is the nth nonvanishing root of the first order Bessel function, k_0 is the free-space propagation constant, a is the circular radius in meters, $\varepsilon_r' = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}$ is the complex relative permittivity, ε_r is the relative permittivity of the tunnel wall, ω is the radio wave frequency, ε_0 is the permittivity of free space and σ is the conductivity of tunnel walls.

Approximate solution of the hybrid mode attenuation rate for circular shape tunnel is given as:

$$\alpha_{EH_{mn}} = 8.686 \frac{\xi_{m+1,n}^2}{k_0^2 a^3} \mathrm{Re}\frac{\varepsilon_r' + 1}{2\sqrt{\varepsilon_r' - 1}} \qquad \mathrm{EH_{mn}} \tag{2}$$

2.2. Arched Tunnel

Yoshio presented the approximate solution of horizontal and vertical polarized mode for an arched tunnel in [11], for the E_{11}^h and E_{11}^v mode,

$$\alpha_h = K_h \lambda^2 \mathrm{Re}\left(\frac{\varepsilon_r'}{d_1^3\sqrt{\varepsilon_r'-1}} + \frac{1}{d_2^3\sqrt{\varepsilon_r'-1}}\right) - K_h \frac{\lambda^3}{2\pi}\mathrm{Im}\left(\frac{\varepsilon_r'^2}{d_1^4(\varepsilon_r'-1)} + \frac{1}{d_2^4(\varepsilon_r'-1)}\right) \tag{3}$$

$$\alpha_v = K_v \lambda^2 \mathrm{Re}\left(\frac{1}{d_1^3\sqrt{\varepsilon_r'-1}} + \frac{\varepsilon_r'}{d_2^3\sqrt{\varepsilon_r'-1}}\right) - K_h \frac{\lambda^3}{2\pi}\mathrm{Im}\left(\frac{1}{d_1^4(\varepsilon_r'-1)} + \frac{\varepsilon_r'^2}{d_2^4(\varepsilon_r'-1)}\right) \tag{4}$$

where d_1 and d_2 are the maximum height and width respectively as shown in Figure 1. If (3) and (4) hold true in UHF band, the numerical coefficients K_h and K_v must be constant and independent

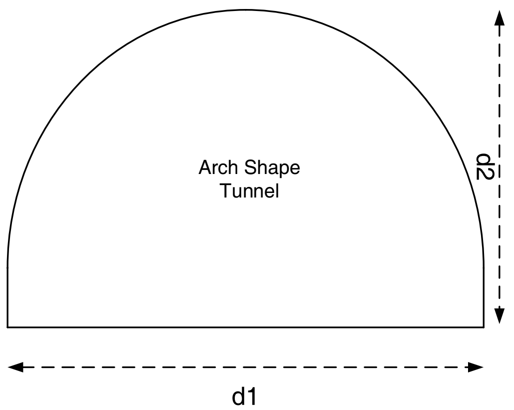

Figure 1: Tunnel dimensions: width d1, height d2.

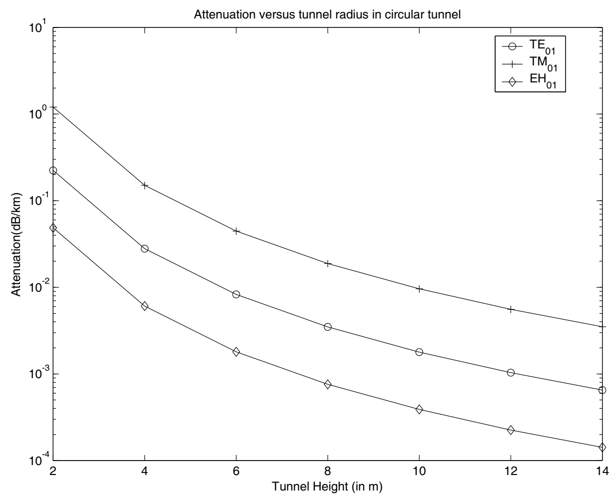

Figure 2: Attenuation versus Radius of a circular tunnel.

of d_1, d_2, λ and ε_r. Numeric values of K_h and K_v have been calculated by using point-marching method as functions of d_1/λ, d_2/λ and ε_r [11]. It has been shown that K_h and K_v approach constant values as d_1/λ and d_2/λ increases, and they are independent of ε_r [11].

3. RESULTS AND DISCUSSION

In this paper, circular and arched tunnels are considered as an example, and influence of various parameters on attenuation rate are analyzed. We consider these two types of tunnels because most practical tunnels are arch shaped tunnels and circular tunnels have close resemblance with arch tunnels. Radius of sample circular tunnel is 4 m and radio wave frequency is suppose to be 1000 MHz.

Figure 2 shows the relation between attenuation rate and radius of the tunnel. Conductivity is assumed to be 0.1 mho/m and relative permittivity is 5. Three modes (TE_{01}, TM_{01} and EH_{11}) are computed and compared. It is clear from Figure 2 that attenuation rate of all modes decreases with increase in tunnel radius, however EH_{11} mode have lowest attenuation rate. Figures 3 and 4 shows the relation between conductivity and relative permittivity of tunnel walls and attenuation in dB/km. It is clear that only in TE_{01} mode, attenuation decreases markedly with increase in conductivity and permittivity, while attenuation in TM_{01} and EH_{11} increases sharply. The certain value of conductivity or permittivity is determined by several factors, such as the radius of the tunnel, the frequency and the permittivity or conductivity etc.

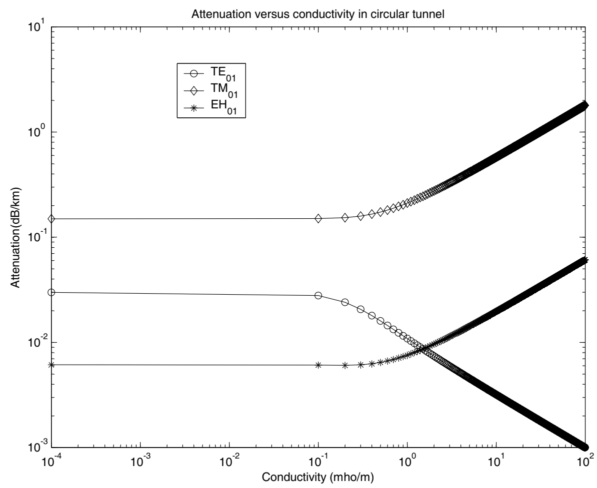

Figure 3: Attenuation versus Conductivity in a circular tunnel.

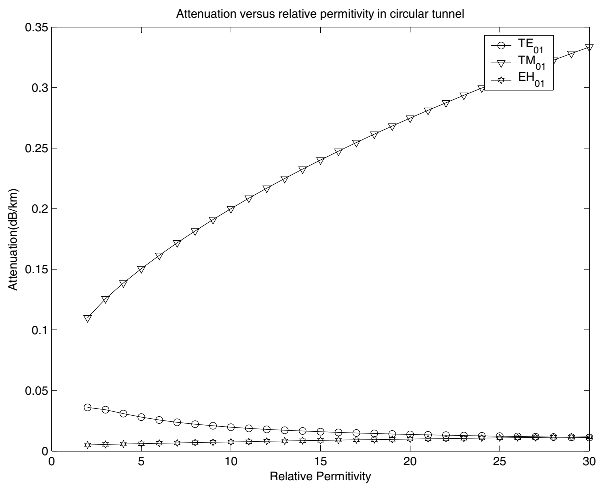

Figure 4: Attenuation versus Relative Permittivity in a circular tunnel.

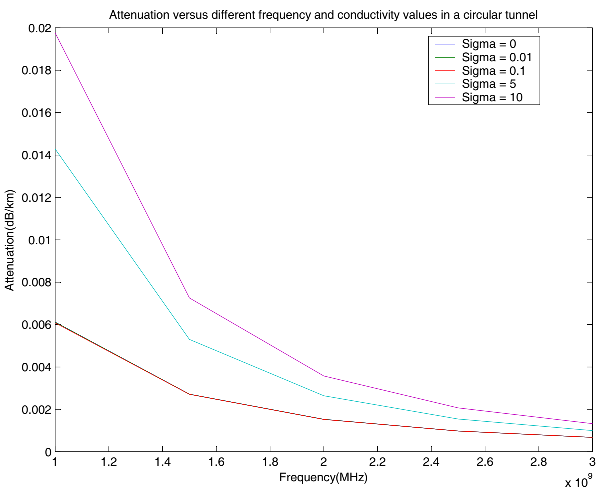

Figure 5: Attenuation versus different Frequencies and Conductivities in a circular tunnel.

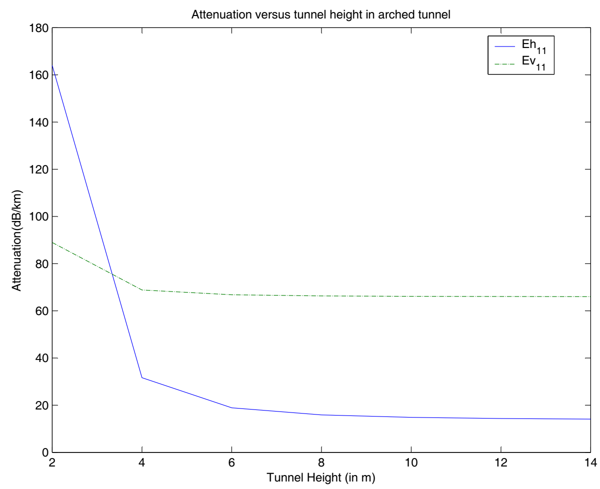

Figure 6: Attenuation versus Tunnel Height in an arched tunnel.

Figure 5 shows the attenuation of EH_{11} mode varying with different frequencies for different values of conductivity σ. We have choose different values of σ, $\sigma = 0, 0.01, 0.1, 5, 10$ mho/m for a wide range of frequencies covering from VHF to UHF. It can be seen that attenuation decreases with increase in frequency, further when $\sigma \leq 1$ mho/m, the attenuation is nearly independent of the conductivity, however its different for $\sigma \geq 5$ mho/m.

The parameters of the sample arch tunnel are choosen as follows: width 2.5 m, height 4 m, frequency 1000 MHz, conductivity 0.1 mho/m and relative permittivity is 5. Two modes (Eh_{11} and Ev_{11}) are computed and compared. Like circular tunnel, attenuation is plotted versus tunnel height and width in Figures 6 and 7 respectively. From Figure 6, with increase in tunnel height attenuation decreases in both modes, however, Eh_{11} mode decreases very sharply after a certain threshold value of tunnel height. In Ev_{11} mode, change in attenuation with tunnel height is almost constant. This situation is totally different in case of tunnel width as depicted in Figure 7. Ev_{11} mode have high attenuation for lower values of tunnel width and than decreases sharply with increase in tunnel width. For practical values of tunnel width, attenuation in Ev_{11} mode is better than Eh_{11} mode.

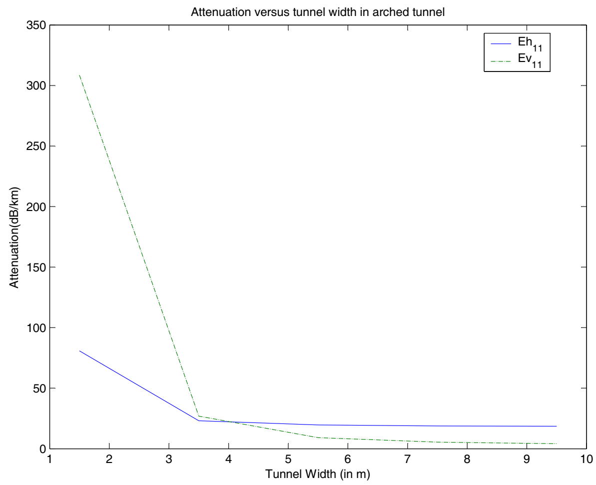

Figure 7: Attenuation versus Tunnel Width in an arched tunnel.

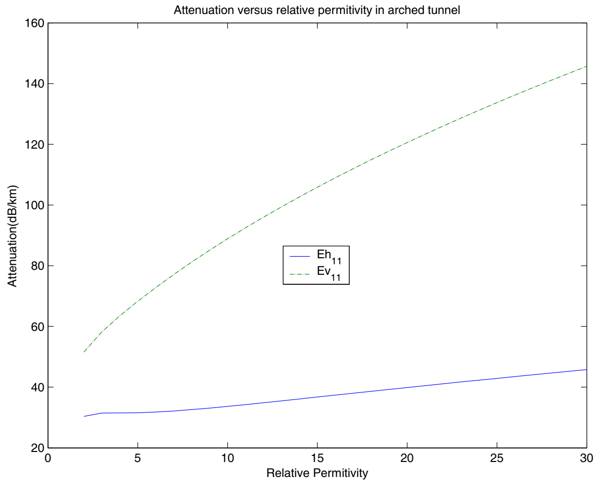

Figure 8: Attenuation versus Relative Permittivity in an arched tunnel.

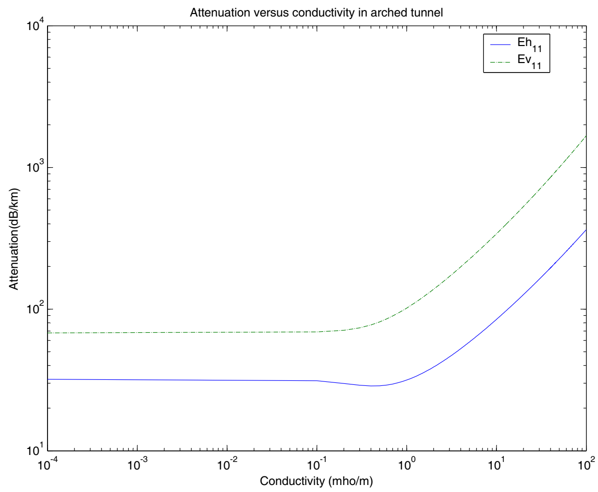

Figure 9: Attenuation versus Conductivity in an arched tunnel.

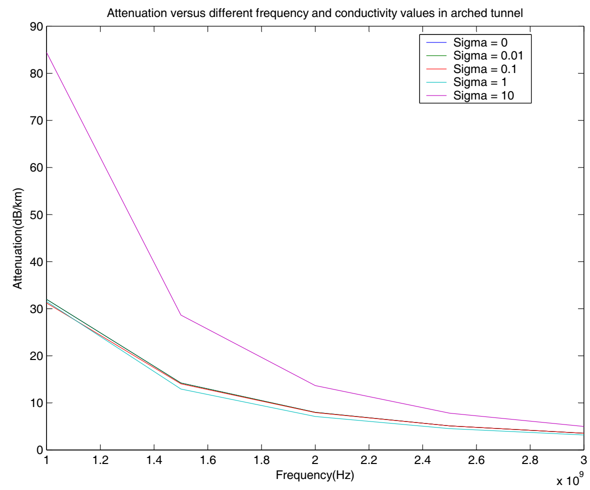

Figure 10: Attenuation versus Frequency in an arched tunnel.

Relation between the relative permittivity and conductivity of arch tunnel walls for two different kinds of mode attenuation are shown in Figure 8 and 9 respectively. Attenuation of Ev_{11} is more than Eh_{11} with relative permittivity and increases sharply. From Figure 9, it is clear that attenuation of two modes are almost constant when conductivity is less than a particular value and than increase sharply, and attenuation of Ev_{11} mode is greater clearly. Same as in circular tunnels, attenuation of Eh_{11} is plotted versus frequency for different values of conductivity in Figure 10. It is seen that like circular tunnel, attenuation is independent of conductivity for smaller values of conductivity however for larger values of conductivity attenuation increases.

4. CONCLUSION

Characteristics of radio waves in tunnels are influenced by many factors which are discussed here in this paper. Conductivity of tunnel walls is very low, so in many tunnels such as underground or mine tunnels, the influence of conductivity can be neglected. However, in some special tunnels like metallic tunnels where conductivity is high, influence of conductivity on attenuation must be considered. Tunnel dimensions also play an important role in attenuation of waves inside tunnels. Frequency, direction of polarization, permittivity etc. all have influence on the attenuation of signal inside tunnels.

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