PROPAGATION OF ELECTROMAGNETIC WAVES IN A RECTANGULAR TUNNEL

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ABSTRACT

A study of radio communication in the underground metro tunnel of the city of Cairo, Egypt was carried out. A part of this tunnel was selected, which has a rectangular shape. Its dimensions are 8.85 m wide, 5.9 m height and 4.5 km long. The walls are made of concrete which have conductivity between 10^{-1} - 10^{-2} mho/m. The attenuation below and above the cutoff frequency, both for the two values of σ are accounted for and graphically drawn. The results, plotted versus selected frequencies ranging between 30-300 MHz, show the attenuation for TE_{mn} and TM_{mn} (m, n = 0,1) modes. It is found that the attenuation constant for 30 MHz is smaller than that for 300 MHz.

I. INTRODUCTION

Electromagnetic wave propagation in road and mine tunnels has been a subject of interest in the last few years especially in relation to the design of mobile radio communication systems [1-2]. Communications in tunnels, undergrounds and other similar pathways are investigated both theoretically and experimentally [3-5] There are two main ways of communications in these pathways: leaky feeders and antenna systems. The latter means is preferred in light of its easier and cheaper installation and design. Besides, it grants the necessary radioelectric coverage.

Various measurements at 300 MHz carried out in different tunnels concluded that radio channels are characterized by a low multipath propagation and delay spread, wave-guiding effect caused by the environment and dominating direct path.

In order to maximize the performance attainable feeding in the interior of tunnels with antenna systems, it is important to estimate the value and the attenuation of the electromagnetic strength inside the tunnel. Investigations concerning radiowave propagation in railways tunnels have been performed [6] and the results confirm the existence of a waveguide effect strongly related to the antenna positions. Recently, Abo-Seida and Bishay [7] obtained a theoretical investigation for the transient electromagnetic field. Also, Bishay et al. [8] computed the frequency domain full wave solution for the fields due to a magnetic dipole in a two-layered medium with finite conductivity.

In this study, the attenuation was calculated above and below the cutoff frequency of the TE_{mn} and TM_{mn} modes for both values of σ ($\sigma = 10^{-1}$ and 10^{-2} mho/m) for the case of the rectangular tunnel. Numerical results and graphs were also obtained for these cases using different values of m and n (m, n=0 or 1). This study makes conspicuous the influence of the transverse dimensions of the tunnel on the attenuation of the electromagnetic waves.

II. THEORY OF PROPAGATION

From the theoretical point of view, one can generally represent the tunnel as a hollow conductor which acts as a waveguide. Such a guide makes possible propagation of transverse electric and transverse magnetic modes when the frequency is higher than a limiting value which is the cutoff frequency of a particular mode. The values of these cutoff frequencies depend on the given mode, and are also determined by the shape and the transverse dimension of the gallery.

In a rectangular waveguide of inner dimensions "a" and "b", the field components of the TE-mode is already known [9]. The analysis is carried out for the harmonic time dependence $e^{i\omega t}$. Theory resolves the electromagnetic field into a sum of solutions which are called modes. A mode is a solution with a dependence on the longitudinal coordinate z by a factor $e^{-\gamma z}$. The complex constant $\gamma = \alpha + i\beta$ is the propagation constant of the mode. Its real part α is the specific attenuation expressed in dB/m and its imaginary part β is the specific phase shift expressed in rad/m. Each mode is characterized by a cutoff frequency $f_c = \frac{\omega_c}{2\pi}$ which depends on the waveguide or tunnel shape and size. Below this frequency the mode is evanescent, i.e., it suffers only attenuation and no phase shift, which is given from

$$\alpha = \frac{2\pi f_c}{C}\left[\ 1-\left(\frac{f}{f_c}\right)^2\ \right]^{\frac{1}{2}} \tag{1}$$

where $f = \frac{\omega}{2\pi}$, f_c is the cutoff frequency, and $C = 3\times 10^8\ ms^{-1}$ is the speed of light. The modes are further labeled by two dimensional order numbers (m,n), thus the cutoff frequencies can be found as

$$f_{c,mn} = \frac{C}{2}\left[\ \left(\frac{m}{a}\right)^2 + \left(\frac{n}{b}\right)^2\ \right]^{\frac{1}{2}}\ . \tag{2}$$

The cutoff wavelengths are given for a rectangular waveguide by [9].

$$\lambda_{mn} = \frac{2\sqrt{ab}}{\sqrt{m^2\frac{b}{a}+n^2\frac{a}{b}}} \tag{3}$$

where m, n are equal to $1,2,3,\cdots$ for the TM_{mn} modes, and equal to $0,1,2,3,\cdots$ for the TE_{mn} modes.

Below the lowest cutoff frequency, propagation is not possible. The attenuation α is independent of the electrical properties of the wall. It increases towards a limiting value with decreasing frequency in accordance with equation (1).

$$\alpha = \frac{2\times 3.14\times 8.69}{\lambda_c}\sqrt{1-\left(\frac{\lambda_c}{\lambda}\right)^2}$$
$$= \frac{54.6}{\lambda_c}\sqrt{1-\left(\frac{\lambda_c}{\lambda}\right)^2}\quad dB/\text{unit length} \tag{4}$$

where λ_c is the longest cutoff wavelength of the waveguide and the value 8.69 is the decibels of attenuation per unit length.

Above its cutoff frequency, attenuation of each mode depends on the frequency, shape and transverse dimensions, and electrical properties of the waveguide.

For rectangular waveguides, this attenuation is given for TE_{mn} modes by [9].

$$\alpha = 8.69\frac{R}{\eta b}\Bigg[(\varepsilon_n m^2\frac{b}{a}+\varepsilon_m n^2)(m^2\frac{b}{a}+n^2\frac{a}{b})^{-1}\{1-(\lambda/\lambda_{mn})^2\}^{\frac{1}{2}}+(\varepsilon_n+\varepsilon_m\frac{b}{a})(\lambda/\lambda_{mn})^2\{1-(\lambda/\lambda_{mn})^2\}^{-\frac{1}{2}}\Bigg]dB/m \tag{5}$$

For TM_{mn} modes, this attenuation α is given by

$$\alpha = 8.69\frac{2R}{\eta a}\Bigg[(m^2+n^2\frac{a^3}{b^3})\,(m^2+n^2\frac{a^2}{b^2})^{-1}\{1-(\lambda/\lambda_{mn})^2\}^{-\frac{1}{2}}\ \Bigg]dB/m \tag{6}$$

where

η is the intrinsic impedance of the propagation medium and equal to $\sqrt{\mu / \varepsilon}$,

$R = 10.88 \times 10^{-3} \sqrt{(10^7 / \sigma)(1/\lambda)}$ Ohms,

σ conductivity of the guide walls in mho/m,

μ permeability of the propagation medium in Henry/m,

ε permitivity of the propagation medium in Farad/m, and $\varepsilon_m = 1$ if $m = 0$ and $\varepsilon_m = 2$ if $m \neq 0$.

The characteristic resistance R is a measure of the conductivity properties of the metal walls. The attenuation constant is minimum at the wavelength $\lambda = 0.577 \lambda_{mn}$.

III. COMMENTS ON PREVIOUS WORK

The actual tunnels differ from the waveguide model in that the conductivity of tunnels are very low. Thus, the waveguide model has two limits as shown in the following discussion. The first is that as the frequency increases. In this case, the walls of the tunnel act as a dielectric medium rather than a conducting one. The second is that at rather high frequencies at which the waves falling on the walls of the tunnel are partially refracted into the walls and partially reflected back into the tunnel.

These drawbacks were successfully overcome by using a geometrical optics method to approach this problem [10]. This method showed that in spite of the fact that the mode attenuation, which is due to wall roughness in mine tunnels, increases with increase in frequency, the overall attenuation is always decreasing. This result applies only when the wavelength is short compared to the transverse dimensions of the tunnel. Also this method showed that below the cutoff frequency of the tunnel, and when the frequency is quite low, the electromagnetic wave can propagate through the rock as if the tunnel was not there. This means that the attenuation α in the tunnel would be the same as through the rock. It is given by the equation

$$\alpha = 8.69 \sqrt{(2\pi f \mu \sigma / 2)}\ dB/m \tag{7}$$

where f is the frequency in Hertz, μ the permeability in Henry/m and σ the conductivity of the rock in mho/m [11].

This explains why in some tunnels a cutoff frequency does not appear. Indeed, attenuation, as given by equation (7), can be lower than attenuation resulting from equation (4).

Deryck [4] has carried out an experimental study of the electromagnetic wave propagation in various tunnels at frequencies between 1 MHz and 1000 MHz. He has investigated the case of rectangular waveguide with TE_{01} mode and selected a road tunnel with rectangular cross section. It was 17 m wide, 4.9 m high and about 600 m long. Its walls are made of concrete. In this tunnel, the attenuation of electromagnetic waves was measured at various frequencies for vertically and horizontally polarized antennas. The results are shown in Fig. 1, where the crosses represent vertical polarization and the circles represent horizontal polarization. Theoretical attenuation has been calculated below cutoff frequency using equation (4), and above cutoff frequency for the TE_{01} and TE_{10} modes using equation (5) assuming that the conductivity of walls was 0.1 mho/m. It is obvious that a vertical antenna excites essentially the TE_{10} mode, and a horizontal antenna excites the TE_{01} mode.

IV. NUMERICAL RESULTS

We are dealing with the propagation of electromagnetic waves in the underground tunnel of Cairo, Egypt. A certain part of the tunnel was selected, which has a rectangular shape. Its dimensions are 8.85 m wide, 5.9 m height and 4.5 Km long. The walls are made of concrete which have conductivity between 10^{-1}-10^{-2} mho/m, which is a probable value for concrete.

The information about the dimensions of the

two curves for TE_{10} and TE_{01}, shown in Figure 1 tunnel were obtained from the National Authority of Tunnels, Ministry of Transportation and Communications, Cairo, Egypt.

Theoretical attenuations are calculated above and below the cutoff frequency as show in the following figures. Figure 2 shows the attenuation below the cutoff frequency at 30.3MHz. The attenuation is also calculated above the cutoff frequency for the $TE_{mn}\ (m,n=0,1)$ modes for both values of σ. The results are plotted versus selected frequencies ranging between 30-300 MHz. Figures 3 and 4 show the attenuation for TE_{01} ,TE_{10} and TE_{11} modes. Cutoff frequencies of these modes are 25 MHz, 16.8 MHz, and 30.3 MHz, respectively. It can be seen from Fig. 3 that below 30.3 MHz polarization has practically no influence on propagation. The TE_{10} is the only mode which can propagate with low attenuation at these frequencies. Polarization can induce differences in attenuation when both modes propagate with low attenuation. However, these differences in attenuation do not appear at higher frequencies due to the high attenuation of the TE_{10} mode as shown in Fig. 3. Besides, a great number of modes appear at higher frequencies, Mahmoud and Wait [10] have also showed that attenuation decreases when frequency increases.

Above the cutoff frequency, if attenuation increases with the square root of resistivity of the tunnel walls, it is more strongly dependent on the transverse dimensions of the tunnel in accordance with equations (5) and (6). Thus the feasibility of a radio link in a tunnel is more dependent on the transverse size of the tunnel than on its wall's conductivity.

As in the case of TE_{mn} modes, we have also calculated the attenuation above the cutoff frequency in the $TM_{mn}\ (m,n=0,1)$ modes using equation (6) and the results obtained are shown in the Figs. (5) and (6).

The results of the present work, as shown in Figures 3 and 4 coincide with the corresponding in [4], at the same frequency range.

V. CONCLUSION

Investigations concerning radiowave propagation in the underground metro tunnel of the city of Cairo, Egypt have been performed and the results confirm the existence of a waveguide effect strongly related to the antennae positions.

This work enable us to distinguish three different ranges of frequency, characterized by three different propagation mechanisms. Below cutoff frequency, waves propagate through the rock in the same manner as if there were no cavity. The attenuation increases with the square root of frequency and is a function of the conductivity of the underground. In the neighborhood of cutoff, just below it, attenuation is only determined by frequency and by the shape and transverse dimensions of the tunnel. At frequencies above cutoff, at a given frequency, attenuation depends on both conductivity and transverse dimensions of the tunnel.

References

1. P. Delogne, "Leaky feeders and subsurface radio communication", Peter Peregrinus, Stevegage, U. K., 1982.
2. A. G. Emslie, R. L. Lagace, and P. F. Strong, "Theory of the propagation of UHF radio waves in cool mine tunnels", IEEE Trans. Antennas Propagat., AP-23, pp. 192-205, 1975.
3. J. Chiba, T. Inaba, Y. Kuwanoto, O. Banno, and R. Sato, "Radio communication in tunnels", IEEE Trans. Microwave Theory Tech., MTT-26, pp. 439-443, 1978.
4. L. Deryick, "Natural propagation of electromagnetic waves in tunnels", IEEE Trans. on Vehicular Technology, VT-27, pp. 145-150, 1978.
5. T. Klemenschits, "Narrow band measurements in road tunnels", COST 231 TD (92) 14, Vienna, 1992.

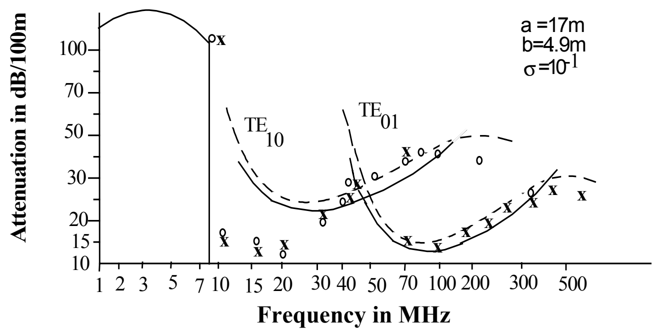

Figure 1. Attenuation versus frequency in a rectangular tunnel [4]. Crosses represent vertical polarization and circles represent horizontal polarization.

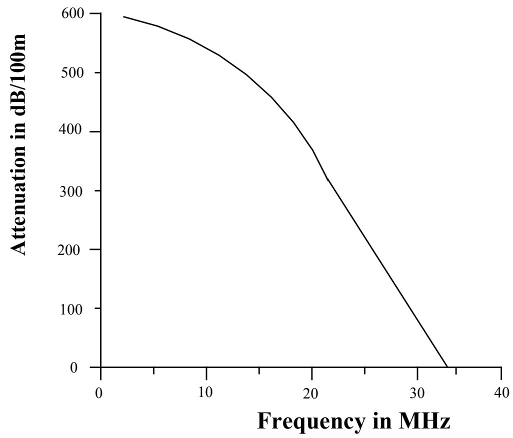

Figure 2. Attenuation versus frequency in a rectangular tunnel of Egypt below cutoff frequency.

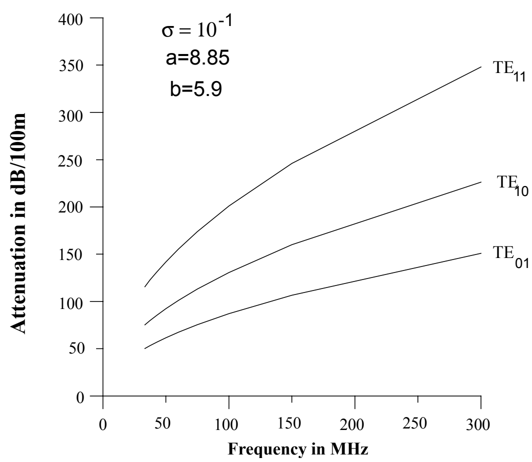

Figure 3. Theoretical attenuation above cutoff frequency of the TE_{01}, TE_{10} and TE_{11} modes in a rectangular tunnel of Egypt with $\sigma = 10^{-1}$.

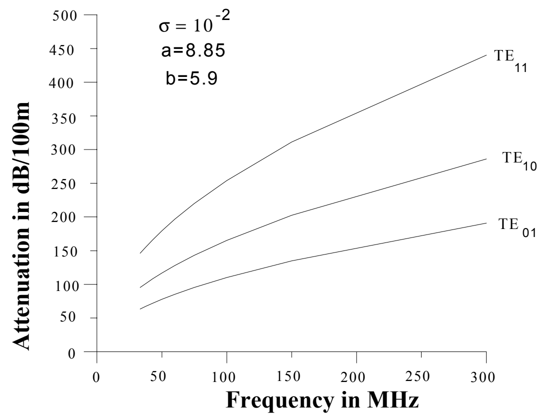

Figure 4. Theoretical attenuation above cutoff frequency of the TE_{01}, TE_{10} and TE_{11} modes in a rectangular tunnel of Egypt with $\sigma = 10^{-2}$.

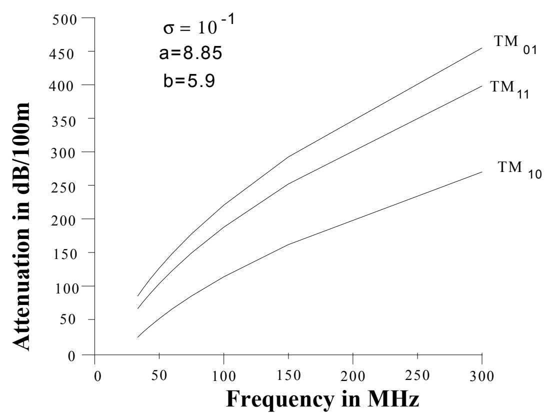

Figure 5. Attenuation versus frequency in a rectangular tunnel of Egypt of the $TM_{mn}\ (m,n = 0,1)$ modes above cutoff frequency with $\sigma = 10^{-1}$.

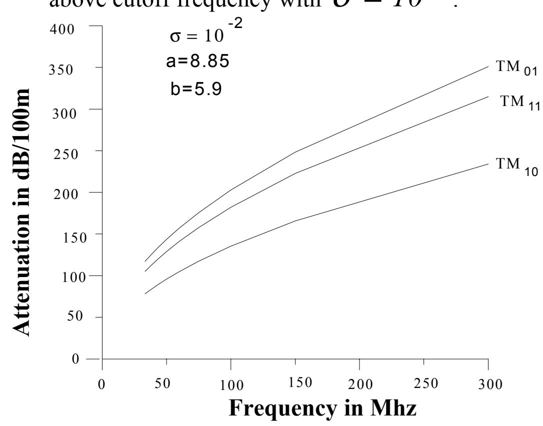

Figure 6. Attenuation versus frequency in a rectangular tunnel of Egypt of the $TM_{mn}\ (m,n = 0,1)$ modes above cutoff frequency with $\sigma = 10^{-2}$.

6. D. Mandich and E. Carpine, "An experimental study of waveguiding effect on radiowave propagation in arched railways tunnels at 450 and 900 MHz", Proceedings of the International Conference on Electromagnetics in Advanced Applications (ICEAA 95), pp. 69-72, Sept. 12-15, Politecnico di Torino, Italy, 1995.
7. O. M. Abo-Seida and S. T. Bishay "Response above a plane-conducting earth to a pulsed vertical magnetic dipole at the surface", Can. J. Phys., 78, 9, pp. 833-844, 2000.
8. S. T. Bishay , O. M. Abo-Seida and G. M. Sami, "Transient electromagnetic field of a vertical magnetic dipole on a two-layer conducting earth", IEEE Trans. on Geoscience and Remote Sensing, vol. 39, no. 4, April 2001.
9. N. Marcuvitz, "Waveguide Handbook", Mc Graw-Hill, New York and London, pp. 55-72, 1951.
10. S. F. Mahmoud and J. R. Wait, "Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels" Radio Sci, vol.9, pp. 1147-1158, 1974.
11. R. Gabillard, "Propagation des ondes electromagnetiques dans une galerie souterraine", Revue de ℓ' Industrie Minerale, vol. 52, pp. 83-108, Fevrier, 1970.

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