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Radio Propagation in Curved Road Tunnels

Martin Nilsson, Jesper Slettenmark and Claes Beckman

Allgon System AB
S-183 25 Täby
Sweden
E-mail: {martin.nilsson, jesper.slettenmark, claes.beckman}@allgon.se

***Abstract*-- This report investigates radio propagation in curved road tunnels at a mobile communications frequency of 925 MHz. This is done by comparing simulations with measurements taken in Norwegian road tunnels. The simulations are based on a simple model derived from geometrical optics and hybrid waveguide modes. The simulations agree well with measurements, indicating that the proposed model is reasonably good.**

I. INTRODUCTION

THE understanding of electromagnetic wave propagation in tunnels is important for mobile communication applications. As the name "mobile communication" implies, the use of phones in cars is one of the underlying ideas of these systems. However, in some countries such as Norway and Switzerland, high mountains and deep fjords make the construction of roads and highways extremely difficult. One solution is to build long, often curved, road tunnels (through the mountains and under the fjords) into which it is hard for the radio waves to penetrate.

In order to allow for mobile communications in road tunnels repeater solutions are often provided. In the tunnel, repeaters connected to endfire antennas (such as Yagis), transmit and receive signals from the cars. The repeaters are often fed from a base station and positioned in the tunnel at distances determined by the attenuation of the radio signals. Hence, there is a need for methods that can be used to predict the attenuation accurately.

In the early seventies much work was done in order to understand the propagation loss of UHF waves in rectangular mine tunnels, using either waveguide methods [1, 2] or image techniques based on Geometrical Optics (GO) [3]. In later years, computer technology has made it possible to use "ray launching" programs based upon GO [4, 5]. These programs require powerful computers but have an advantage over the simpler methods since diffractive effects from cars and tunnel openings can be included [4-6].

With the exception of the waveguide solution [1], all methods described above suffers from great computer or theoretical complexibilities. However, the waveguide solution only provides accurate estimates of the attenuation in straight, rectangular tunnels. Unfortunately, most real tunnels are neither rectangular nor straight.

Mahmud and Wait [2] proposed that a waveguide solution could be used to solve the problem of radio propagation in curved rectangular mine tunnels. However, this method is cumbersome to implement and therefore not really useful in radio planning of mobile phone networks. A simpler but still accurate model is needed and it is the aim of this study to fill this void.

II. THEORY

A. *Waveguide solutions*

Our method is a simple Geometrical Optics (GO) extension to the standard hybrid waveguide solution [1]. The hybrid waveguide solution gives us the loss due to refraction (dB/m) of the vertical and horizontal polarizations of a wave propagating in a straight tunnel as [1]:

$$Loss_{ref,hor} = 8.686 \cdot \lambda^2 \left(\frac{m^2}{2a^3} \mathrm{Re}\left\{ \frac{\varepsilon_r^*}{\sqrt{(\varepsilon_r^* - 1)}} \right\} + \frac{n^2}{2b^3} \mathrm{Re}\left\{ \frac{1}{\sqrt{(\varepsilon_r^* - 1)}} \right\} \right) \tag{1}$$

$$Loss_{ref,ver} = 8.686 \cdot \lambda^2 \left(\frac{m^2}{2a^3} \mathrm{Re}\left\{ \frac{1}{\sqrt{(\varepsilon_r^* - 1)}} \right\} + \frac{n^2}{2b^3} \mathrm{Re}\left\{ \frac{\varepsilon_r^*}{\sqrt{(\varepsilon_r^* - 1)}} \right\} \right) \tag{2}$$

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Here, a and b are the tunnel width and height, ε_r the relative permitivity, λ the wavelength and m and n denote the mode numbers.

In a normal road tunnel $a \approx 2b$ and it can be seen from (1) and (2) that reflections against the roof will be responsible for the largest part of the loss. Further, we find that higher order modes will have a greater loss (dB/m) compared to lower. That is why in our simulations only the lowest (1,1)-modes are used.

To support the validity of only using the (1,1)-mode when calculating the attenuation in a straight tunnel we compare the loss for the (1,1)-mode given by (2) with the results from a computer simulation based upon the GO approach given in [3] (Figure 1).

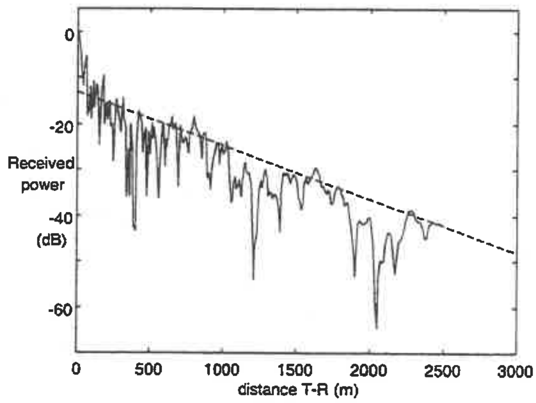

Fig. 1. GO based computer simulation of the received power, normalized to the power at a distance of 10 m from the transmitter, in a vertically polarized electric field excited by a vertically oriented dipole in a 10x5 m tunnel. Emitted frequency: 925 MHz. ε_r=8. The dotted line (12 dB/km) shows the asymptotic loss.

We find from Figure 1 that the simulated loss, using the GO method [3] at a frequency of 925 MHz and an ε_r=8 approaches the result of the (1,1)-waveguide mode (11.2 dB/km) asymptotically. Hence, the (1,1)-mode can be used as a valid approximation if the tunnel is reasonably long.

B. Ray tracing

As previously mentioned, our model is partly based upon GO where an electromagnetic wave propagating in space is looked upon as a ray. To estimate the attenuation of a ray in a curved tunnel we simply calculate the number of times the ray will be reflected in the curve and the attenuation due to each reflection.

Far away from the source, the GO rays will be almost parallel to each other and to the walls of a straight tunnel. Under these assumptions the loss in a ray traveling into a curve (Figure 2) can easily be calculated.

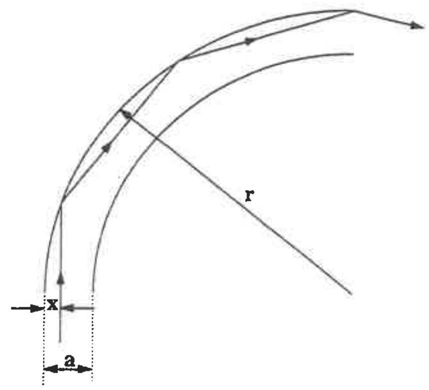

Fig. 2. A ray traveling in a tunnel of width a where the outer walls curvature has a radius of r.

Referring to Figure 3, the curve's outer wall can be expressed with the function

$$y_1(x) = \sqrt{r^2 - (x-r)^2}\ , \qquad (3)$$

where r is the radius. The ray can be expressed with the function

$$y_2(x) = x'\ , \qquad (4)$$

where x' is a constant denoting the greatest distance between the outer wall and the ray.

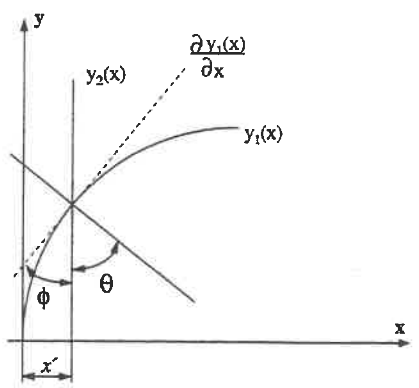

Fig. 3. The curve $y_1(x)$ represents the outer wall in the tunnel, the straight line $y_2(x)$ represents the ray and the dotted line represents the derivative of the curve $y_1(x)$. θ denotes the angle of incidence and ϕ the grazing angle.

By introducing (4) into (3) we find the intersection between the curve and the ray to be located at

$$y = \sqrt{r^2 - (x'-r)^2} \,. \tag{5}$$

Between two reflections the ray will have to travel twice this distance. It can therefore be stated that the number of reflections per meter for the ray is

$$n_{ref} = \frac{1}{2\sqrt{r^2 - (x'-r)^2}} \,. \tag{6}$$

C. Reflections

We may now estimate the number of times a ray will be reflected in a tunnel with a certain curvature. However, in order to estimate its attenuation we also need to know the loss in each reflection: For a wave reflected by the interface between air and a media with permeability $\mu = \mu_0$ (which is valid for most dielectric materials) the reflection coefficients for the perpendicular and parallel polarizations may be written as [17]:

$$\Gamma_\perp = \frac{cos(\theta) - \sqrt{\varepsilon_r}\sqrt{1 - \frac{1}{\varepsilon_r} sin^2(\theta)}}{cos(\theta) + \sqrt{\varepsilon_r}\sqrt{1 - \frac{1}{\varepsilon_r} sin^2(\theta)}} \tag{7}$$

$$\Gamma_{//} = \frac{-\cos(\theta) + \sqrt{\frac{1}{\varepsilon_r}}\sqrt{1 - \frac{1}{\varepsilon_r}\sin^2(\theta)}}{\cos(\theta) + \sqrt{\frac{1}{\varepsilon_r}}\sqrt{1 - \frac{1}{\varepsilon_r}\sin^2(\theta)}} \,. \tag{8}$$

Here ε_r denotes the relative permitivity and θ the angle of incidence.

This latter angle can be calculated by taking the derivative of equation (3):

$$\frac{dy}{dx} = -\frac{x-r}{\sqrt{r^2 - (x-r)^2}} \,. \tag{9}$$

By using this equation, the ray's grazing angle of incidence, ϕ (Figure 3), when reflecting against the outer wall can be expressed as:

$$\phi = \tan^{-1}\left\{\frac{\sqrt{r^2 - (x'-r)^2}}{r - x'}\right\} \tag{10}$$

and the angle of incidence as:

$$\theta = \frac{\pi}{2} - \phi \,. \tag{11}$$

As can be seen from (7) and (8), the reflection coefficient, Γ, will depend both on the incident angle, θ, and on the relative dielectric constant, ε_r.

We may also note that:

- When θ is approximately equal to 90 degrees $|\Gamma|$ is close to 1.
- The average reflection coefficient is smaller for the vertical than for the horizontal polarization and can even become zero at the Brewster angle.

D. Roughness

So far the roughness of the walls has been neglected. This, however, may be important to include for the frequencies considered here. The simplest way to account for the roughness is to multiply the ordinary reflection coefficients (7) and (8) with a modification coefficient ρ [8]:

$$\rho = \exp\left(-2\left(\frac{2\pi\Delta h}{\lambda}\right)^2\right), \tag{12}$$

where Δh is the standard deviation of the tunnel's roughness. The loss (dB/m) due to roughness for the waveguide modes, as given by (1) and (2), can be expressed as [1]:

$$Loss_{rough} = 8.686 \cdot \frac{\pi^2 \Delta h^2 \lambda}{4}\left(\frac{m^2}{a^4} + \frac{n^2}{b^4}\right), \tag{13}$$

independent on the polarization. For a reflection against a surface when the electromagnetic wave has a grazing angle of incidence, the effective roughness will be $\Delta h sin(\phi)$ and (12) can be rewritten as

$$\rho = \exp\left(-2\left(\frac{2\pi\sin(\phi)\Delta h}{\lambda}\right)^2\right). \tag{14}$$

The loss (dB/m) of the radio wave due to the curvature of the tunnel is calculated by averaging the loss in several different rays over the tunnels width, a, and can be expressed as

$$Loss_{curve} = \underset{a}{avg}\left\{20 \cdot n_{ref} \cdot \log\left(\Gamma(\theta)\rho(\phi)\right)\right\}. \qquad (15)$$

Here Γ is the reflection coefficient, as given by (3) or (4), depending of the polarization of the radio wave and ρ is the roughness modification coefficient, as stated in (14). In order to obtain the total loss in the tunnel the results from equations (1) and (2), depending on the polarization, should be added to (14):

$$Loss_{total} = Loss_{curve} + Loss_{rough} + Loss_{ref,hor;ref,ver}. \qquad (16)$$

In Figure 4 the loss due to curvature is plotted for some different values of Δh. We find that the loss is strongly dependent on the roughness for small radii.

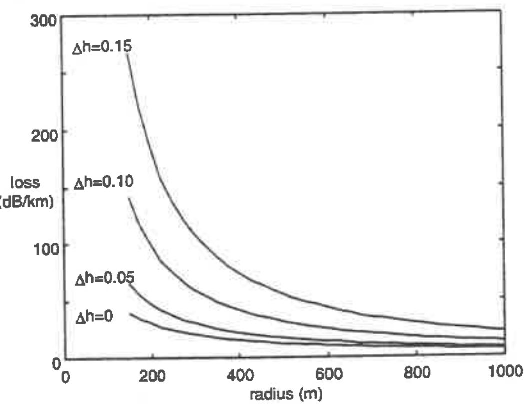

Fig. 4. The loss due to curvature, according to (15), for different values of Δh in a 10m wide tunnel with ε_r=8 and f=925 MHz.

III. MEASUREMENTS

Measurements were taken in two 3-lane 10x5 m Norwegian road tunnels (3,7 km and 4,3 km long). Both tunnels are heavily curved with somewhat well defined radii. Only limited parts of the tunnels are straight since both are situated under a fjord. As a further consequence of this, the walls and roofs of the tunnels are covered with sodium chloride which has an $\varepsilon_r \approx 5.9$ [7].

A. *Experimental set-up*

The experimental set-up consisted of one transmit and one receive part. The transmit configuration ,shown in Figure 5, transmits a 925 MHz signal with an EIRP of 46 dBm.

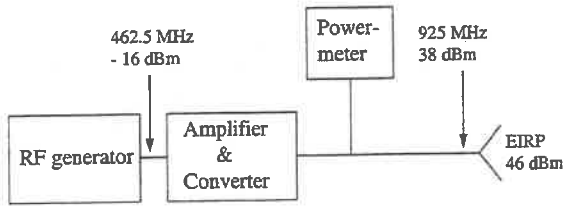

Fig. 5. Transmit configuration. The signal is generated by a RF generator. It is then amplified and frequency doubled before it is feed to a 10 dBi antenna through an cable with a 2 dB loss. This results in an EIRP of 46 dBm.

The transmitting antenna was positioned at a distance of 0.5-1 m from the roof at several positions inside the tunnels. For every antenna position, four measurement series were taken in order to achieve data enough for statistical significance.

A 1 dBi vertically oriented dipole antenna, mounted on the roof of a car, was used to measure the field strength. The receiver configuration (Figure 6) detects the received power and simultaneously correlates this with the distance from the transmitting antenna.

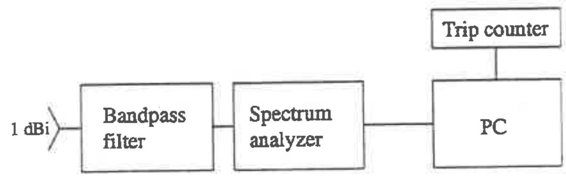

Fig. 6. The receiver configuration. After the signal is received by the antenna, it is first filtered and its power measured with a spectrum analyzer. A PC, connected to a trip counter, is used to correlate the received power with the distance from the transmitting antenna.

IV. RESULTS

From the measurements we find that the average loss per kilometer in the straight parts of the tunnels is about 15 dB/km. This is well in agreement with the 11.2 dB/km predicted by the waveguide solution (2) using ε_r=8 (as mentioned previously sodium chloride has a permitivity of $\varepsilon_r \approx 5.9$. It therefore reasonable to believe that in this case ε_r of the walls will be lower than ε_r=10, which is a common ε_r of stone and rock).

In Figure 7, the measured loss at different parts of the tunnels, of different radii, are plotted together with the results from computer simulations using (15). A roughness of Δh=0.12 m is assumed (in these tunnels a Δh of about 10-15 cm can be expected) As can be seen the curvature of the tunnel has a dramatic effect on the attenuation. Furthermore, the results from our simulations fit well to the measured data, indicating that the model is indeed reasonably good.

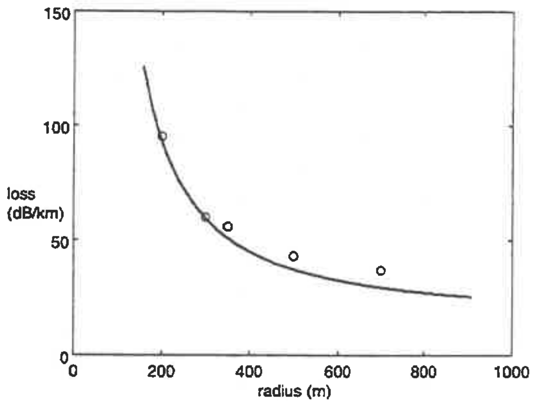

Fig. 7. Simulation of the loss per kilometer (dB/km) in a 10x5 m tunnel as a function of the radius of curvature in the tunnel. The circles are the measured average values of the loss at different radii. In the simulation ε_r=8, Δh=0.125 m and f=925 MHz.

V. DISCUSSIONS AND CONCLUSIONS

Thanks to the recent expansion of mobile communications, modeling of radio propagation in different environments have received considerable interest. The model suggested by us rest upon both waveguide methods and Geometrical Optics. Some discrepancies between measured and theoretical losses are found for both straight and curved tunnels. However, we must bare in mind that the tunnel environment is hard to model and factors like relative permittivity and roughness can not always be well estimated. Furthermore, the tunnel walls may be tilted which also effects the loss [1].

With the exception of [2], (suffering from computational difficulties), the area of attenuation due to the curvature in a tunnel has not received much attention. This is unfortunate since, as our measurements indicate, the tunnel curvature has large effects on the attenuation. Further, most long tunnels curve and it is in these long tunnel where mobile communication coverage is a problem. Accurate tools are thus needed to predict the loss. We hope that our model, that has proved to be both accurate and simple enough to be implemented in net planning tools, may help fill this gap.

VI. ACKNOWLEDGMENTS

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