# Modal Analysis of Wave Propagation in Straight and Curved Arched Tunnel Based on Equivalent Rectangular Tunnel Model

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***Abstract*** **─** In this paper, a model is presented to simulate wave propagation in straight and curved tunnels with arched cross section with imperfectly conducting walls. The model is based on treating the tunnels as a rectangular waveguide with imperfectly conducting walls, where the arched cross section of the tunnels is approximated with equivalent rectangular cross section. A scenario is considered to check the accuracy of this model. This scenario is verified by comparing experimental and numerical simulation results. Good agreement between the proposed model and the experimental results is obtained.

***Index Terms*** **─** Arched tunnels, curved waveguide, imperfect conducting walls, wave propagation.

## I. INTRODUCTION

Understanding the electromagnetic waves propagation in tunnels becomes increasingly important as a large number of communication systems, including GSM (Global System for Mobile Communications), 3G (3rd Generation), Wi-Fi systems are expected to support continuous service in subway tunnels to guarantee user experience. Since the early seventies of the last century till now, there has been a continued interest in radio communication through tunnels [1-28], since signaling within working areas in mine tunnels or road tunnels has been of prime importance [8–20]. A tunnel can act as a waveguide for radio waves of sufficiently high frequency, as the wavelength is much smaller than the tunnel linear dimensions, whence attenuation occurs only due to the surrounding rocks [8–11]. It should be noted that at frequencies of few hundred MHz, the earth rocks will act as a dielectric material with low loss tangent. In this case, the attenuation of the electromagnetic waves propagating in the tunnel occurs mainly due to leakage of waves into the rocks rather than Ohmic losses. In the presence of longitudinal conductors such as electricity cables, low frequency waves can also propagate in the form of a coaxial like mode [12–16]. Intentionally placed leaky cables have been placed inside tunnels in order to control the signal level inside the tunnel [15–19]. A typical straight tunnel with cross sectional linear dimensions of few meters can act as a waveguide to electromagnetic waves at UHF and upper VHF bands [10,15].

Modal propagation in arched tunnel has been considered by Mahmoud [3, 21], showing a considerable increase in the attenuation due to arch. Tunnels with regular cross sections such as the circular or rectangular shape are amenable to analytical analysis that lead to full characterization of their main modes of propagation [5], [27]. However, most existing tunnels do not have regular cross sections and their study may require exhaustive numerical methods [28]. In this paper we consider arched tunnels whose cross-section comprise an incomplete circle with a flat base as shown in Fig. 1. We assess previously obtained closed forms of the attenuation rates of the low order modes by Mahmoud [3]. The attenuation rate of straight arched tunnel is approximated by equivalent rectangular straight tunnel. The curved arched tunnels is approximated with an equivalent rectangular curved tunnel and attenuation rate is calculated based on the same approach proposed in [4]. Finally, experimental results are conducted in order to verify the presented theory.

## II. MODAL ANALYSIS OF STRIAGHT ARCHED TUNNEL

Most of existing tunnels do not have regular cross sections and their analysis may require numerical methods. One of the widely existing tunnels is a tunnel with cross-section that comprise a circular arch with a flat base as shown in Fig. 1.

This can be approximated as a circular tunnel whose shape is perturbed into a flat-based tunnel. So, perturbation theory can be used to predict attenuation and phase velocity of the dominant modes of arched

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tunnel from the corresponding attenuation of a circular tunnel as shown in Fig. 2. Full details about the perturbation analysis is discussed in [3, 23]. As perturbation analysis requires numerical efforts, analytical model is proposed in the next section as a fast solution which requires low computing resources.

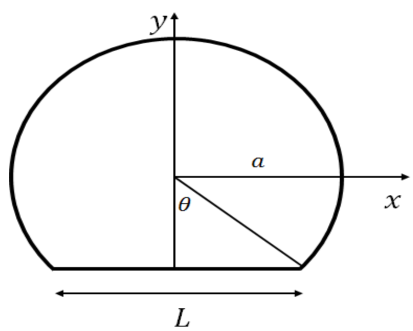



Fig. 1. Arched tunnel with radius $\boldsymbol{a}$ and flat base $\boldsymbol{L}$.

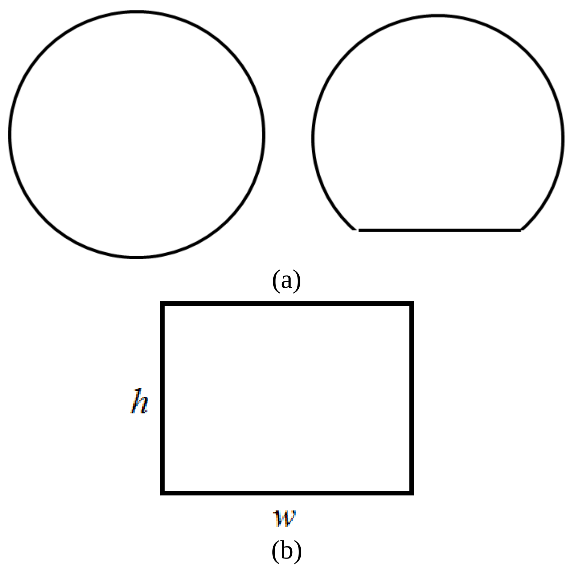



Fig. 2. (a) A circular tunnel and a perturbed circular tunnel with a flat base [3], and (b) equivalent rectangular model.

### A. An equivalent rectangular tunnel model

It is shown in [3] that we can model the arched tunnel of Fig. 2 (a) by a rectangular tunnel as shown in Fig. 2 (b). Starting with the previously proposed model in [3], the arched tunnel is simulated here by using equivalent rectangular tunnel. Then an enhancement of the model is proposed.

For the circular tunnel with radius $a$, the attenuation factor for $HE_{nm}$ is obtained as [3, 23]:

$$\alpha_{HE_{nm}} = \frac{Z_S/\eta_0 + Y_S\eta_0}{2k_0^2a^3}[x_m^{n-1}]^2, \qquad (1)$$

where $x_m^{n-1}$ is the mth zero of Bessel function $J_{n-1}(x)$ and the walls of the tunnel are characterized by constant surface impedance and admittance $Zs$ and $Ys$ where their normalized values are given by [5]:

$$Y_S = (\varepsilon_r - i\sigma/\omega\varepsilon_0)/\sqrt{\varepsilon_r - 1 - i\sigma/\omega\varepsilon_0}, \qquad (2)$$

and,

$$Z_S = 1/\sqrt{\varepsilon_r - 1 - i\sigma/\omega\varepsilon_0}, \qquad (3)$$

where $\varepsilon_r$ is the tunnel walls relative permittivity and $\sigma$ is the walls conductivity. The proposed formula (1) is based on the condition: $k_0a \gg x_m^{n-1}$[3]. For a rectangular tunnel with width $w$ and height $h$ the attenuation of $HE_{nm}$ mode with vertical polarization is obtained as [23]:

$$\alpha_{HE_{nm}} = \frac{2\pi^2}{k_0^2}\left[\frac{m^2Z_S/\eta_0}{w^3} + \frac{n^2Y_S/\eta_0}{h^3}\right]. \qquad (4)$$

Substituting in (1) and (4) for $HE_{11}$ (m = n = 1) mode in circular and square tunnel with $w = h$ and equating the attenuation rates we obtain:

$$w = h = (4\pi^2/2.4048^2)^{1/3}\text{a=1.897a}. \qquad (5)$$

This means that the area of the equivalent square tunnel is equal to 1.145 times the area of the circular tunnel [3] for same attenuation rate. It should be noted that this equivalence is valid only for the $HE_{11}$ mode in both tunnels; while for other modes the attenuation in the circular and the square tunnels are generally not equal.

Using the same approach for the case of the arched tunnel [3] by maintaining the ratio of areas as obtained from the square and circular tunnels; it can be deduced that the arched tunnel is approximated with an equivalent rectangular tunnel with area [3],

$$wh = 1.145[(\pi - \theta)a^2 + (La/2)\cos\theta]. \qquad (6)$$

The ratio $h/w$; equal to the arched tunnel height to its diameter is given by [3]:

$$\frac{h}{w} = (1 + \cos\theta)/2, \qquad (7)$$

where

$$\theta = \sin^{-1}(L/2a). \qquad (8)$$

Equations (6), (7) define a rectangular tunnel which is equivalent to the arched tunnel regarding the $HE_{11}$ mode.

The proposed analysis assumes that for all dimensions of the arched tunnels, the ratio of the equivalent rectangular area to the arched tunnel area is a fixed number which is 1.145. As an enhancement in the present paper, a new approach is proposed by introducing a more general formula which accounts for the dimensions of the arched tunnel in the equivalence ratio. The proposed modification of Eq. (6) for best ratio of the equivalent rectangular area to the arched tunnel area is obtained as:

$$Area|_{rectangular} = R \times Area|_{arched}, \qquad (9)$$

where R is the areas ratio obtained as:

$$R = 1.145C^n, \qquad (10)$$

where $C = (1 + \cos\theta)/2$ is the arched tunnel height to its diameter and $\theta$ is obtained by (8), while $n$ is the tuning factor for best fitting between arched tunnel and equivalent rectangular model. Equation (9) can be written as:

$$wh = R[(\pi - \theta)a^2 + (La/2)\cos\theta]. \qquad (11)$$

In order to check the validity of this equivalence, the proposed model is compared with the previously published results of [3]. The attenuation for $HE_{11}$ mode is calculated in an arched tunnel of radius a = 2m with a flat base of width L. The surrounding earth has a relative permittivity of $\varepsilon_r = 6$ and the operating frequency is 500 MHz. The modal attenuation factor is plotted in Fig. 3 for $HE_{11}$ mode as a function of the $L/a$. The attenuation factor is computed by using the perturbation analysis in [3] and the equivalent rectangular model for two cases. The first case: with $n = 0$ which is corresponding to the original proposed rectangular model by [3], and $n = 0.33$ which is corresponding to the best fitting of the proposed model of this work. It can be noted that the proposed modification with $n = 0.33$ has better agreement with the perturbation analysis. By changing the arched dimensions, the ratio R of equivalent rectangular area to arched tunnel area is changed according to Eq. (9), while the in old model the ratio is fixed for all cases. This will introduce a more general formula which accounts for the dimensions of the arched tunnel in the equivalence ratio.

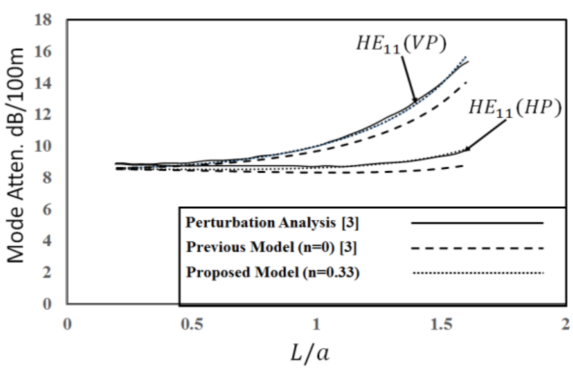



Fig. 3. Attenuation of the $HE_{11}$ mode in the arched tunnel using perturbation analysis [3], rectangular equivalent tunnel [3] and proposed rectangular equivalent tunnel for Vertical Polarization (VP) and Horizontal Polarization (HP).

Full wave numerical analysis based on FEKO Ray Launching Geometrical Optics (RL - GO) [29] simulator is used to verify the proposed equivalent rectangular model of arched tunnel. FEKO's RL - GO [29] method is a ray - based technique that models objects based on optical propagation, reflection and refraction theory [29]. GO (ray launching) is formulated for use in instances where electrically very large (>20λ) metallic or dielectric structures are modelled. Ray - interactions with metallic and dielectric structures are modelled using Huygens sources, placed at each ray, contact point on material boundaries. The ray - launching process is easily controlled, based on the angular spacing (for localized sources) or transverse spacing (for plane wave sources) of the rays and the number of multiple interactions allowed. The tunnel as shown in Fig. 1 has radius $a$ = 2m while $L = a$. Figure 4 shows the normalized electric field distribution across the center line of the tunnel for the arched and the equivalent rectangular tunnels. The width and the height of the equivalent rectangular tunnel are calculated by using (11) and (7) with $n = 0.33$ in (10). The width of the equivalent rectangular tunnel is $w = 3.52m$ while the height is $h = 3.8$. The operating frequency is assumed to be 500 MHz. The length of the tunnel is assumed to be 60m while the relative permittivity of the walls is 6 and conductivity is σ=0.01 S/m [3]. Both the emitter and receiver are kept vertically polarized. Good agreement is obtained between the electric field in arched tunnel and the one in the equivalent rectangular tunnel. The field decay rate in both tunnels is also in good agreement. The calculated mean squared error between the proposed model and the arched tunnel results is about 12.42%. Also, it can be noted that in addition to the expected decrease in the electric field strength with distance from the transmitter, the interference between the direct rays and the reflected rays from the walls creates peaks and troughs where their positions depend on the phase difference between the electric field of the direct ray and that of the rays reflected from the walls.

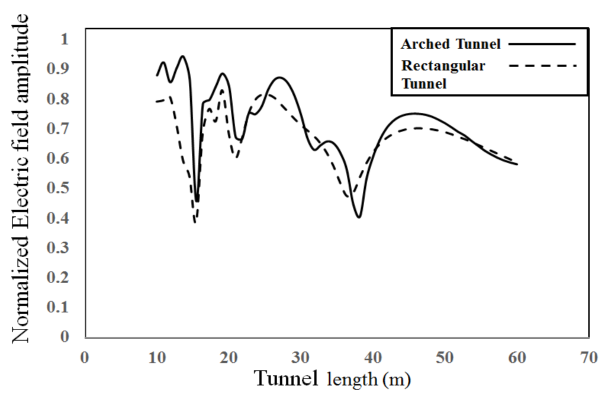



Fig. 4. Normalized electric field amplitude in arched and equivalent rectangular tunnel.

## III. MODAL ANALYSIS OF CURVED ARCHED TUNNEL

In this section, curved tunnels with arched cross section are analyzed. The approach is based on approximating the arched cross section with the proposed equivalent rectangular, then the tunnel will be analyzed as curved rectangular tunnel using the same approach as in [4,5] for curved rectangular tunnel modal analysis.

First, the equivalent rectangular dimensions $w$ and $h$ are obtained from the corresponding arch dimensions as proposed in Section II. Then following [5], let us consider a curved tunnel with rectangular cross section as in Fig. 5 (b). Using a cylindrical coordinates frame with the $z$-axis along the vertical direction, the side surfaces of the tunnel coincide with $\rho = R - w/2$ and $\rho = R + w/2$, where $R$ is the mean radius of curvature. The main assumptions in the analysis are [5]: (i) the frequency is high so that $k_0 w/2 \gg 1$ and therefore the walls can be characterized by constant surface impedance and admittance $Zs$ and $Ys$ where their normalized values are given by (2) and (3), and (ii) slow curvature such that $2R/w \gg 1$. The waveguide modes are either TM or TE to z. Considering $E_z$ for the low order TMz modes and ignoring field variation along z as the electric field is vertical, the field is almost constant in z-direction (since $k_z \ll k_0$), the electric field is given as [5]:

$$E_z = f_v(k_0\rho)exp(-jv\emptyset), \tag{12}$$

where $f_v(k_0\rho)$is a linear combination of Bessel functions of first and second kind with complex order $v$. However, with low curvature $R \gg w/2$ , and high frequency excitation, it is expected that $v$ and $k_0\rho$ are both large ($\gg 1$) while their difference is much less than $v$. Under these conditions, the modal equations for lower order $TE_z$ and $TM_z$ are derived in terms of the Airy functions instead of the Bessel function of complex order $v$ and solved numerically for the propagation constant along the $\phi$-direction [5]. Full analysis of the model is presented in [4].

The total approximate attenuation rate of wave propagating inside rectangular curved tunnel is obtained by [4] for VP modes as:

$$\alpha_{Total}^{VP} = \pi^2 Re(Y_s)/4k_0^2(h/2)^3 + (-\text{Im}\left[\frac{v}{R}\right]), \tag{13}$$

and using same analysis, the HP total attenuation rate can be obtained.

The electric field and attenuation rate inside the arched tunnel is obtained by (12) and (13) with equivalent rectangular curved tunnel of width $w$ and height $h$.

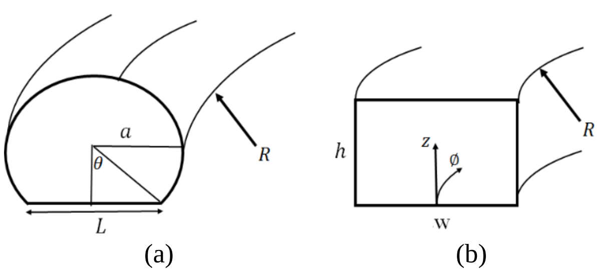



Fig. 5. Curved tunnel: (a) with arched cross section and (b) with rectangular cross section.

The electric field for arched and equivalent rectangular curved tunnels is implemented in Matlab which runs on a laptop with 8 GB of RAM, Intel 2.6 GHz processor, and operating system is Windows 8 64-bit. The tunnel has an arched cross section with radius $a = 2m$ and arch base $L = 2m$. The tunnel radius of curvature $R = 20a$ and the operating frequency is 950 MHz corresponding to GSM-900 band. The relative permittivity of the walls is considered equal to 6 and the conductivity is 0.01 S/m [3]. The equivalent rectangular tunnel has width = 3.86m and height is = 3.54m. The transmitting and receiving antennas are kept vertically polarized. The height of both transmitting and receiving antennas is kept 1.5m above the ground.

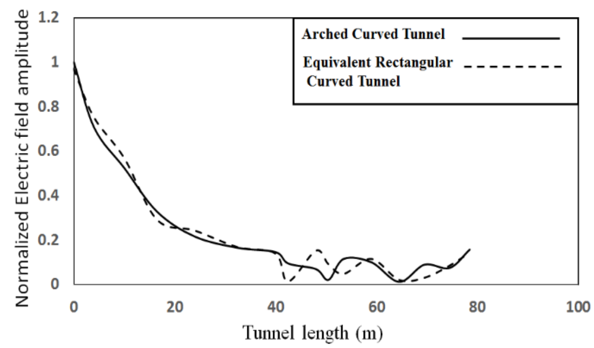



Fig. 6. Electric field in a curved arched tunnel with horizontally polarized mode. R = 20a, freq = 950 MHz, arch base L = 2.1m and arch radius = 2m, L/a = 1.05, where equivalent rectangular tunnel width dimensions are width = 3.86m, height = 3.54 m, error is 12.7%.

The total program runtime for the above example is about 12 minutes. On the other hand, the same example is simulated using FEKO version 7.0 with the same computer resources. It is found that the simulation takes about 60 minutes using FEKO RL-GO solver. So, the proposed model is faster than the simulation package and the differences will be increased by increasing the dimensions of the corridor or operating frequency. Figure 6 shows a comparison between the calculated normalized electric field along the tunnel center line using the proposed model and simulation results. It can be noted that good agreement is obtained and the calculated error between the model and simulation results is about 12.7%.

## IV. MEASUREMENTS

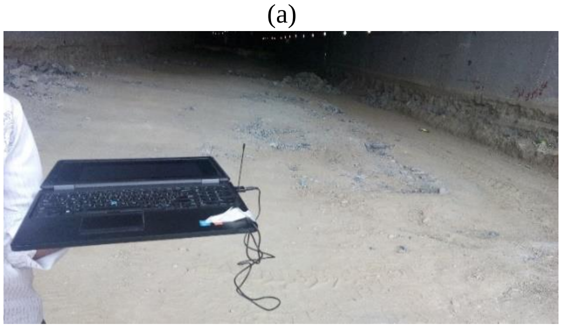
In this section, sample results are presented to verify the accuracy of the proposed model for the signal attenuation rate in arched tunnel. The proposed measurements are used to study simple wave propagating inside straight arched tunnel for cars.

This simple scenario of a curved tunnel is verified experimentally in the frequency range 450 MHz corresponding to GSM-450 band. The scenario was done in arched tunnel for cars with concrete walls as shown in Fig. 7. The experimental setup consists of Handheld RF Signal Generator (RFEGEN 1.12) with dipole antenna with gain of 2.2 dBi used as transmitter, while the receiver is RF Viewer wireless USB dongle and data is collected using computer software package RF spectrum analyzer (TOUCHSTONE PRO); as shown in Fig. 8.

The transmitting and receiving antennas are kept horizontally polarized at 1m above the ground and measurements' samples are collected every 10m for 70m across the center line of the tunnel. The tunnel consist of three plane walls with arched roof. The arched radius is 7.3m and the tunnel width is 14m. The height at the tunnel center is 10.35m. The width of the equivalent rectangular tunnel is $w = 13.2\ m$, while the height is $h = 8.4\ m$. The tunnel is approximated as two sections where the upper section represents the arched roof while the lower one represents the three plane walls. The equivalent rectangular tunnel width is calculated by the proposed model for the arched roof, while the total height is the one calculated by the proposed model for arched roof in addition to the height of the plane walls.

Fig. 7. Arched tunnel for cars, flat base (L) = 14m, radius a = 7.3m, and height at center = 10.35m.

(a)



(b)

Fig. 8. Measurement setup: (a) transmitter (RF signal generator, and (b) receiver (computer software package RF spectrum analyzer).

Figure 9 shows a comparison between measured total received power in dBm and the calculated one by using the proposed model. Good agreement between the measured and calculated results is obtained. The slight differences can be explained due to errors in the manual positioning of the receiving antenna and differences due to the boundary conditions of the actual tunnel and the existence of the small metal sheets. The calculated error between the model and measured results is about 3.9%.

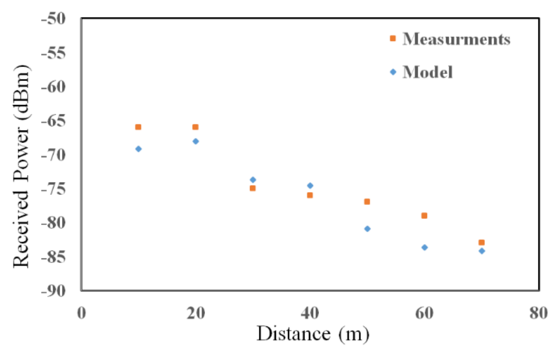



Fig. 9. Received power in arched tunnel with HP modes, tunnel dimensions are: $a = 7.3\text{m}$, $\text{L} = 14\text{m}$ and equivalent rectangular tunnel $\text{w} = 13.2\text{m}$ and $\text{h} = 8.4\text{m}$.

## V. CONCLUSION

A new approach is proposed to model the wave propagation in straight and curved arched tunnels with an equivalent rectangular tunnel. The walls of the tunnels are considered imperfectly conducting walls. The proposed model introduces a more general formula which accounts for the dimensions of the arched tunnel in the equivalence ratio. The proposed model is verified by comparison with experimental results. Good agreements are obtained from these comparisons.

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