Approximate Calculation of the Total Attenuation Rate of Propagating Wave Inside Curved Tunnel

Hany M. El-Maghrabi [1], Ahmed M. Attiya [2], Samir F. Mahmoud [3], Mostafa El-Said [3], and Essam A. Hashish [3]

[1] Department of Electromechnical
Housing and National Research Center, Cairo, Egypt
helmaghrabi@hbrc.edu.eg

[2] Department of Microwave Engineering
Electronic Research Institute, Cairo, Egypt
attiya@eri.sci.eg

[3] Department of Electronics and Electrical Communication
Cairo University, Cairo, Egypt

Abstract **─** In this paper, a model is presented to simulate wave propagation in curved rectangular tunnels with imperfectly conducting walls. The model is based on treating the tunnel as a waveguide, which is an extension of previous proposed model by Mahmoud [3]. A new approach to calculate the total attenuation rate of the propagated wave inside tunnel is proposed. The approach is considering the effect of imperfect conductivity of the upper and lower walls of the tunnel. This approach is based on assuming that the boundaries of the tunnel section are constant impedance surfaces as the surface impedance of the wall is almost independent of the angle of the wave incidence onto the wall. A simple 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 **─** Curved waveguide, imperfect conducting walls, wave propagation.

I. INTRODUCTION

Since the early seventies of the last century till now, there has been a continued interest in radio communication through tunnels [1-23], since signaling within working areas in mine tunnels or road tunnels was 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 due to the surrounding rocks [8–11]. It should be noted that at frequencies of 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 [17].

Modal propagation in curved tunnel has been considered by Mahmoud and Wait [23] and Mahmoud [3], showing a considerable increase in the attenuation due to curvature. In this paper, we review high frequency propagation in tunnels with curved rectangular cross section. We assess previously obtained closed forms of the attenuation rates of the low order modes by Mahmoud [3]. In the previous work [3], the side walls of the tunnels are considered as imperfect conducting walls, while the upper and lower walls are considered as PEC walls. So the attenuation rate is mainly due to the side walls effect. The main objective of present paper is to extend the analysis of the previous work [3] to include the effects of considering the upper and lower walls as imperfect conducting walls and to introduce the approximate total attenuation rate of the propagating signal inside tunnels due to four walls with imperfect conductivity. Also, to compare the effect of the upper and lower walls effects on the attenuation rate compared to the effects of the side walls. This approach is done by deducing the attenuation rate of the upper and lower flat walls from the analogy with rectangular waveguide analysis in [3]. Finally, experimental results are conducted

Submitted On: July 25, 2016
Accepted On: September 9, 2016

in order to verify the presented theory.

II. MODAL ANALYSIS OF CURVED TUNNEL

Following [3], let us consider a rectangular tunnel, which is curved, in the horizontal plane as shown in Fig. 1. Using a cylindrical coordinates frame with the z-axis along the vertical direction, the side surfaces of the tunnel coincide with $\rho = R - a$ and $\rho = R + a$, where R is the mean radius of curvature. The main assumptions in the analysis are [3]: (i) the frequency is high so that $k_0 a \gg 1$ and therefore the walls can be characterized by constant surface impedance and admittance Zs and Ys where their normalized values are given by [3]:

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

and

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

where ε_r is the corridor walls relative permittivity and σ is the corridor walls conductivity, and (ii) slow curvature such that $R/a \gg 1$. 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 [3]:

$$E_z = f_v(k_0\rho)exp(-jv\emptyset), \quad (3)$$

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 $R \gg a$, 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 ϕ-direction [3]:

$$f_v(k_0\rho) = C_1 A_i(t) + C_2 B_i(t), \quad (4)$$

with

$$t = (k_0\rho/2)^{2/3}(v^2/k_0^2\,\rho^2 - 1), \quad (5)$$

where $A_i(t)$ and $B_i(t)$ are the Airy functions as defined in [3] and C_1 and C_2 are two arbitrary constants. The mathematical reasoning behind the validity of the Airy function representation is found in [3]. It can be noted that $v/k_0\rho$ is close to 1, the argument $t \ll (k_0\rho)$ for $R - a \le \rho \le R + a$.

Applying the boundary conditions at the curved surfaces $\rho = R - a$ and $\rho = R + a$ require that $\eta_0 H_\phi = \pm Y_s\, E_z$. Where,

$$H_\emptyset = (-j/\omega\mu_0)\,\partial E_z/\partial\rho, \quad (6)$$

$$H_\rho = \left(-\frac{v}{\omega\mu_0\rho}\right) * E_z, \quad (7)$$

and that,

$$\partial/\partial k_0\rho \cong -(\partial/\partial t)\,(2/k_0\rho)^{1/3}. \quad (8)$$

The two boundary conditions lead to the two equations [3]:

$$C_1 A_i'(t_+) + C_2 B_i'(t_+) = \overline{Y_+}[C_1 A_i(t_+) + C_2 B_i(t_+)], \quad (9\text{-a})$$

$$C_1 A_i'(t_-) + C_2 B_i'(t_-) = \overline{Y_-}[C_1 A_i(t_-) + C_2 B_i(t_-)], \quad (9.\text{b})$$

where the prime is the differentiation with respect to the argument, $t_\pm$ are given by (5) with $\rho = R \pm a$ and,

$$\bar{Y}_\pm = jY_s[k_0(R \pm a)/2]^{1/3}, \quad (10)$$

the modal equation for v is obtained by equating the determinant of the coefficient C_1 and C_2 in (9) to zero. Once v is determined, the attenuation factor along the curved axis is given by [3]:

$$\alpha = -\text{Im}\,[v/R], \quad (11)$$

and the phase constant is:

$$\beta = \text{Re}\,[v/R]. \quad (12)$$

For TE case is treated in similar fashion with H_z the terms $\bar{Y}_\pm$ are replaced by:

$$\bar{Z}_\pm = jZ_s[k_0(R \pm a)/2]^{1/3}, \quad (13)$$

where Z_s is defined by (2).

It is noted from the proposed analysis that the previous model [3] considers the upper and lower tunnel walls as Perfect Electric Conductor (PEC) [3] and the attenuation rate in (11) is due to the side walls effects while this is not the case in real environment.

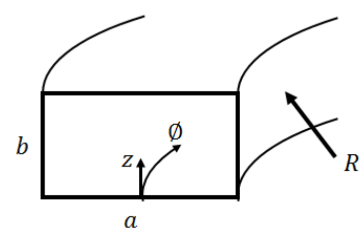


Fig. 1. Curved rectangular tunnel [3].

III. EXTRA ATTENUATION RATE DUE TO IMPERFECT CONDUCTIVITY OF THE UPPER AND LOWER

In reality, all the tunnel walls have imperfect conducting walls with low conductivity, thus for generality the attenuation rate inside the curved tunnel should be modified as to include the extra attenuation due to the imperfect conductivity of the upper and lower walls of tunnel. We can deduce the attenuation of the upper and lower flat walls of the curved tunnel with rectangular cross section from the analogy of rectangular tunnel analysis by approximating the upper and lower flat walls effect with the corresponding walls effect in the rectangular tunnel with same flat shape. We propose here, to use the attenuation of rectangular tunnel based on constant impedance walls proposed in [3]. A tunnel with rectangular cross section of dimensions *a* and *b* and the surrounding medium has a relative permittivity ε_r and conductivity σ Siemens/m. When the applied radio frequency is sufficiently high such that the tunnel dimensions are much greater than the free space wavelength λ_0, then the low order modes in the tunnel would have $k_x \ll k_0$ and $k_y \ll k_0$, where k_0 is the free space wavenumber, k_x and k_y are the wavenumbers in the x and y directions. Under these conditions, the tunnel walls are accurately modeled by normalized constant surface impedance Zs and admittance Ys, which are obtained by (2) and (1), respectively. Following the analysis in [3], the approximate attenuation rate of the dominant mode with Vertical Polarization (VP) for rectangular tunnel is:

$$\alpha^{VP}_{\text{rectangular}} = \pi^2 Re(Y_s)/4k_0^2 b^3 + \pi^2 Re(Z_s)/4k_0^2 a^3 \quad Neper/m, \quad (14)$$

while for Horizontal Polarization (HP) is obtained by duality as:

$$\alpha^{HP}_{\text{rectangular}} = \pi^2 Re(Z_s)/4k_0^2 b^3 + \pi^2 Re(Y_s)/4k_0^2 a^3 \quad Neper/m, \quad (15)$$

where the effect of the upper and lower walls with low conductivity is approximated as the first part of (14) and (15). We use the same approach to calculate the extra attenuation in curved tunnel due to imperfect conductivity of the upper and lower walls, where the walls effect is approximated with the same corresponding effect of the upper and lower rectangular tunnel walls.

Thus, the extra attenuation is approximated for VP modes as:

$$\alpha^{VP}_{extra\_atten} = \pi^2 Re(Y_s)/4k_0^2 b^3 \quad Neper/m, \quad (16)$$

where Y_s is obtaied by (1) while for HP modes is:

$$\alpha^{HP}_{extra\_atten} = \pi^2 Re(Z_s)/4k_0^2 b^3 \quad Neper/m, \quad (17)$$

where Z_s is obtaied by (2).

Thus, the total approximate attenuation rate of wave propagating inside rectangular curved tunnel is obtained by (11) for side walls and (16) for upper and lower walls for VP modes as:

$$\alpha^{VP}_{Total} = \pi^2 Re(Y_s)/4k_0^2 b^3 + \left(-\text{Im}\left[\frac{v}{R}\right]\right), \quad (18)$$

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

The percentage of the extra attenuation rate due to upper and lower walls obtained by (16) and (17) compared with the side walls attenuation rate obtained by (11) is shown in Fig. 2 for HP and VP, respectively. The tunnel width a is 4.25 m while the tunnel height is $b = a/2$.

It can be noted that the VP has more attenuation than the HP, while in general it is found that the attenuation due to the side (curved) wall is much higher than the attenuation of the upper and lower flat walls.

The proposed total attenuation rate is implemented in Matlab which runs on a laptop with 8 GB of RAM, Intel 2.6 GHz processor, and operating system is Windows 10 64-bit. The tunnel width is 4.6 m while the height is 2.6 m. The tunnel radius of curvature is 20 times the tunnel width and the simulation is done in frequency range 0.2-0.8 GHz. The total program runtime for the above example is about 12 minutes. An algorithm is applied for finding the complex root of Eq. (9), which is considered the main bottleneck in the numerical calculations and the largest influence on the program speed. 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 Physical Optics (PO) solver. It should be noted that 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 3 shows a comparison between the calculated normalized total attenuation rate 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 13.25%.

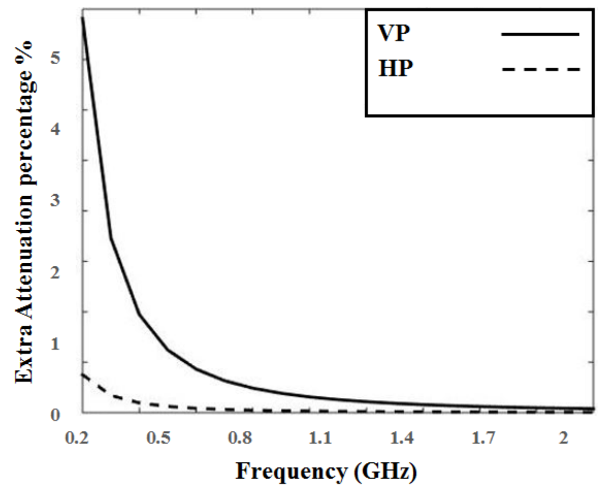


Fig. 2. Percentage of the extra attenuation due to the flat walls compared with the curved side walls attenuation.

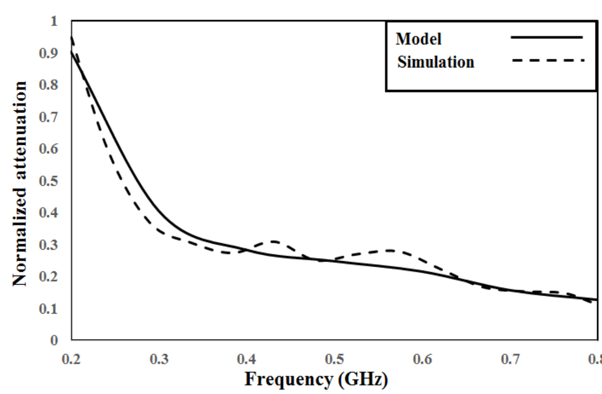


Fig. 3. Normalized attenuation in curved rectangular tunnel with VP modes, tunnel dimensions are $a = 4.6$ m, $\text{b} = 2.3$ m, and $\text{R/a} = 20$.

IV. MEASUREMENTS

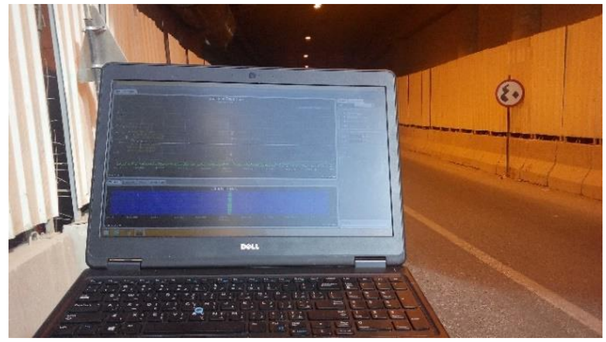
In this section sample results are presented to verify the accuracy of the proposed model for the signal attenuation rate in curved tunnel. The proposed measurements are used to study the simple wave propagating inside rectangular curved tunnel for cars.

This simple scenario of a curved tunnel is verified experimentally at frequency range 0.1-1 GHz. The scenario was done in curved tunnel for cars with concrete walls and with small metal sheets on both sides as shown in Fig. 4. The experimental setup consists of two carts. One cart is used to hold the transmitter and the other one is used to hold the receiving antenna and computer for receiving data collection and analysis as shown in Fig. 5. Handheld RF Signal Generator (RFEGEN 1.12) with dipole antenna with gain of 2.2 dBi is 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). The transmitting and receiving antennas are kept horizontally polarized and separated by a constant distance of 100 m. The tunnel width is 9.2 m and a length of 195 m. The height of the tunnel is 5.8 m. The height of both transmitting and receiving antennas is kept 1.3 m above the ground.

Figure 6 shows a comparison between measured total attenuation rate 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 12.3%.

Fig. 4. Curved rectangular tunnel for cars, width = 9.2 m, length = 195 m and height = 5.8 m.

(a)



(b)

Fig. 5. Measurement setup: (a) transmitter (RF Signal Generator, and (b) receiver (computer software package RF spectrum analyzer).

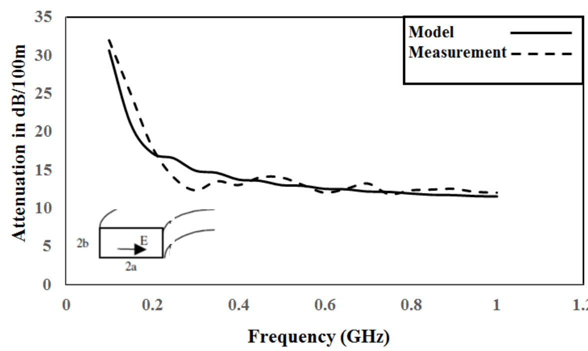


Fig. 6. Attenuation in curved rectangular tunnel with HP modes, tunnel dimensions are $a = 9.2$ m, $b = 5.8$ m, and $R/a = 56$.

V. CONCLUSION

A new approach is proposed to drive an approximate formula for the total attenuation rate in curved rectangular tunnel. The proposed model takes into consideration the attenuation effect due to imperfect conductivity of the upper and lower walls in addition to the effect of the side walls. The effect of the flat upper and lower walls are approximated by the corresponding effect of the upper and lower walls in rectangular tunnel. It is found that the attenuation due to the side (curved) wall is much higher than the attenuation of the upper and lower flat walls. The proposed total attenuation rate is verified by comparison with experimental results. Good agreements are obtained from these comparisons.

REFERENCES

[1] K. Guan, B. Ai, Z. Zhong, C. Lopez, L. Zhang, C. Briso, A. Haovat, and B. Zhang "Measurements and analysis of large-scale fading characteristics in curved subway tunnels at 920 MHz, 2400 MHz, and 5705 MHz," *IEEE Trans. on Intelligent Transportation System*, vol. 16, Oct. 2015.

[2] B. Zhang, Z. Zhong, K. Guan, R. He, and C. Briso,

"Shadow fading correlation of multi-frequencies in curved subway tunnels," *Proc. IEEE Conf. ITSC*, Qingdao, China, pp. 1111-1116, 2014.
[3] S. F. Mahmoud, "Modal propagation of high frequency electromagnetic waves in straight and curved tunnels within the earth," *J. of Electromagn. Waves and Appl.*, vol. 19, no. 12, pp. 1611-1627, 2005.
[4] M. Lienard, J. M. Molina-Garcia-Pardo, P. Laly, C. Sanchis-Borras, and P. Degauque, "Communication in tunnel: Channel characteristics and performance of diversity schemes," *General Assembly and Scientific Symposium (URSI GASS), 2014 URSI*, Aug. 2014.
[5] M. Lienard, C. Sanchis-Borras, J.-M. Molina-Garcia-Pardo, D. P. Gaillot, P. Laly, and P. Degauque, "Performance analysis of antenna arrays in tunnel environment," *IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 12-125, 2014.
[6] M. Lienard, J.-M. Molina-Garcia-Pardo, P. Laly, C. Sanchis-Borras, and P. Degauque, "MIMO and diversity techniques in tunnels," *International Conference on Computing, Management and Telecommunications (ComManTel)*, Apr. 2014.
[7] C. Garcia-Pardo, J.-M. Molina-Garcia-Pardo, M. Lienard, D. P. Gaillot, and P. Degauque, "Double directional channel measurements in an arched tunnel and interpretation using ray tracing in a rectangular tunnel," *Progress In Electromagnetics Research M*, vol. 22, pp. 91-107, 2012.
[8] A. G. Emslie and R. L. Lagace, "Theory of the propagation of UHF radio waves in coal mine tunnels," *IEEE Trans. AP*, vol. 23, no. 2, pp. 192-205, 1975.
[9] S. F. Mahmoud and J. R. Wait, "Geometrical optical approach for electromagnetic wave propagation in rectangular mine tunnels," *Radio Science*, vol. 9, no. 12, pp. 1147-1158, 1974.
[10] P. Delogne, "Basic mechanisms of tunnel propagation," *Radio Science*, vol. 11, pp. 299-303, 1976.
[11] J. R Wait and D. A. Hill, "Guided electromagnetic waves along an axial conductor in a circular tunnel," *IEEE Trans. AP*, vol. 22, pp. 627-630, 1974.
[12] S. F Mahmoud and J. R. Wait, "Theory of wave propagation along a thin wire inside a rectangular waveguide," *Radio Science*, pp. 417-420, 1974.
[13] S. F. Mahmoud, "Characteristics of electromagnetic guided waves for communication in coal mine tunnels," *IEEE Trans. COM*, vol. 22, pp. 1547-1554, 1974.
[14] J. R. Wait and D. A. Hill, "Propagation along a braided coaxial cable in a circular tunnel," *IEEE Trans. MTT*, vol. 23, pp. 401-405, May 1975.
[15] J. R.Wait, "EM theory of the loosely braided coaxial cable: Part I," *IEEE Trans. MTT*, vol. 24, pp. 262-265, 1976.
[16] D. A. Hill and J. R. Wait, "EM theory of the loosely braided coaxial cable: Part II-Numerical results," *IEEE Trans. MTT*, vol. 28, pp. 262-265, 1980.
S. F. Mahmoud and J. R. Wait, "Calculated channel characteristics of a braided coaxial cable in a mine tunnel," *IEEE Trans. COM*, vol. 24, pp. 82-87, 1976.
[17] P. Degauque, B. Demoulin, J. Fontaine, and R. Gabillard, "Theory and experiment of a mobile communication in tunnels by means of a leaky braided coaxial cable," *Radio Science*, vol. 11, pp. 305-314, 1976.
[18] P. Delogne, *Leaky Feeders and Subsurface Radio Communication*, IEE Electromagnetic Series 14, Peter Peregrinus Ltd., 1982.
[19] M. Lienard and P. Degauque, "Propagation in wide tunnels at 2 GHz: A statistical analysis," *IEEE Trans. on Vehicular Technology*, vol. 47, no. 4, pp. 1322-1328, Nov. 1998.
[20] S. F. Mahmoud, *Wireless Transmission in Tunnels, Mobile and Wireless Communications Physical Layer Development and Implementatiom*. Salma Ait Fares and Fumiyuki Adachi (Ed.), InTech.
[21] M. Lienard and P. Degauque, "Natural wave propagation in mine environment," *IEEE Trans. on AP*, vol. 48, no. 9, pp. 1326-1339, 2002.
[22] S. F. Mahmoud and J. R. Wait, "Guided electromagnetic waves in a curved rectangular mine tunnel," *Radio Science*, pp. 567-572, May 1974.

Hany M. El-Maghrabi received the B.S. degree, with Honor Degree, and M.S. degree in Electrical Engineering from the Cairo University (Egypt). El-Maghrabi has received a position of Research Assistant in Housing and Building National Research Center (HBNRC), Institute of Electromechanical, Department of Communication (Egypt) in 2005. He became Assistant Researcher at HBNRC in 2011. He has co-authored technical journal articles and conference papers. El-Maghrabi has experience in electromagnetics, antennas, microstrip structures, numerical methods, wave propgation and their applications in microwave. El-Maghrabi was awarded the best paper in NRSC 2015.

Samir F. Mahmoud graduated from the Electronic Engineering Dept., Cairo University, Egypt in 1964. He received the M.Sc. and Ph.D. degrees in the Electrical Engineering Department, Queen's University, Kingston, Ontario, Canada in 1970 and 1973. During the academic year 1973-1974, he was a Visiting Research Fellow at the Cooperative Institute for Research in Environmental Sciences (CIRES), Boulder, CO, doing research on Communication in Tunnels. He spent two sabbatical years, 1980-1982, between Queen Mary College, London and the British Aerospace, Stevenage, where he was involved in design of antennas for satellite communication. He spent several years as Professor at the EE Department, Kuwait University. Currently Mahmoud is a Full Professor at the Electronic and Telecommunication Engineering Department, Cairo University. Recently, he has visited several places including Interuniversity Micro-Electronics Centre (IMEC), Leuven, Belgium and spent a sabbatical leave at Queen's University and the Royal Military College, Kingston, Ontario, Canada in 2001-2002. His research activities have been in the areas of antennas, geophysics, tunnel communication, and EM wave interaction with composite materials. Mahmoud is a Fellow of IET and one of the recipients of the Best IEEE/MTT paper for 2003.

Ahmed M. Attiya received the M.Sc. and Ph.D. degrees in Electronics and Electrical Communications, Faculty of Engineering, Cairo University in 1996 and 2001, respectively. He joined Electronics Research Institute as a Researcher Assistant in 1991. In the period from 2002 to 2004, he was a Postdoc in Bradley Department of Electrical and Computer Engineering at Virginia Tech. In the period from 2004 to 2005, he was a Visiting Scholar in Electrical Engineering Dept. at the University of Mississippi. In the period from 2008 to 2012 he was a Visiting Teaching Member in King Saud University. He is currently Full Professor and the Head of Microwave Engineering Dept. at Electronics Research Institute.

Mostafa El-Said graduated from the Electronic Engineering Dept., Cairo University, Egypt in 1963. He received the Dipl.Ing. and Dr.Ing. degrees from Karlsruhe University, West Germany, in 1970 and 1974. Since 1992, he is Professor at the Electronic Engineering and Telecommunication Department Cairo University. His research activities have been in the areas of microstrip, wave propagation and nano technology.

Essam A. Hashish (M'96) received the B.Sc., M.Sc. and Ph.D. degrees from the Electronics and Communications Department, Faculty of Engineering, Cairo University, Giza, Egypt, in 1973, 1977, and 1985, respectively. He is currently a Professor with the Electromagnetics Group at the same department. His main interest is electromagnetic remote sensing, wave propagation, and microwave antennas.