to design and has the advantage of being able to be printed on a single layer, thus allowing reduced weight and cost. It is well suited to practical applications for satellite and wireless communications.

REFERENCES

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PARABOLIC-EQUATION-BASED STUDY OF DUCTING EFFECTS ON MICROWAVE PROPAGATION

I. Sirkova and M. Mikhailov
Department of Microwave Remote Sensing
Institute of Electronics
Bulgarian Academy of Sciences
1784 Sofia, Bulgaria

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ABSTRACT: This work reports a quantitative assessment of propagation loss for the frequency band 2110–2170 MHz under evaporation and surface-based ducts conditions. Flat-underlying surface and elevated-terrain cases are studied. The calculations are based on the parabolic approximation to the wave equation in conjunction with finite-element and Fourier split-step techniques. © 2004 Wiley Periodicals, Inc. Microwave Opt Technol Lett 42: 390–394, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20314

Key words: microwave propagation modeling; parabolic equation; tropospheric ducts

1. INTRODUCTION

The lower troposphere affects microwave propagation in numerous ways. Clear-air ducting, due to variations in meteorological parameters leading to vertical refractivity gradients dN/dh < −157 N-units/km, is among the most important propagation phenomena influencing various radar and communications systems [1, 2]. Ducts due to evaporation (as a result of intensive evaporation from large bodies of water and fast decrease of humidity with height) are practically almost present at lower latitudes, and their thickness increases during the summer months and during the daytime [3]. Even in moderate latitudes, evaporation ducting is not an occasional event: refractometer measurement data for the north part of the Black sea indicate super refraction and ducting conditions during 20% to 25% of the time in summer [4]. Other surface-based ducts (caused, for instance, by advection over the sea or temperature inversions over the earth surface) appear about 14% of the time worldwide [5]. Although they are stable formations, ducts suffer seasonal and diurnal variations [3], especially in coastal zones, where the sharp contrast between land and sea contributes to temporal and spatial variability of meteorological parameters. This leads to highly variable propagation conditions and thus significantly affects radio-communication links and radar performance.

The effects of ducting on meteorological, surveillance, and navigational radar have been studied for a long time and are well known [1, 6–8], while the propagation-prediction models used in mobile-communication planning tools and channel-characteristics assessment usually do not account for tropospheric super-refraction and ducting. The most common effect of ducting is long-range radio-wave propagation, leading essentially to signal enhancement near and beyond the radio horizon; this increases radar coverage [1, 6], and provokes interference between terrestrial and Earth-space communications systems [2]. Tropospheric ducting is one of the causes for multipath propagation. This multipath propagation leads to short-term fading, inter-symbol interference, and increase in signal-data bit-error rates in mobile communications [9]. The universal mobile telecommunications system (UMTS) radio network is known to be more sensitive to the propagation environment than the GSM network [10]. An accurately planned network may lead to unexpectedly lower service level and even failures for 3G-system users. This requires more precise taking into account of the influence of the propagation environment, including such effects as ducting, when assessing the network coverage, possible interference and multipath propagation.

This work studies the influence of one common cases of surface-based ducts on the downlink frequency band used by the UMTS Wideband Code Division Multiple Access-Frequency Division Duplex (WCDMA-FDD) variant. The effects of ducting are illustrated by comparing path losses calculated under ducting conditions to path losses obtained assuming standard troposphere for two carrier frequencies from the WCDMA-FDD downlink band for an open area. Flat-underlying-surface and elevated-terrain cases are studied. The “anomalous” propagation under ducting requires more sophisticated propagation prediction methods than the propagation under standard troposphere conditions [1, 6, 11]. The parabolic equation (PE) method [8, 12], is known to allow efficient and accurate field solutions for complicated propagation environment, antenna patterns, and underlying-surface characteristics and has been assumed for the calculations. The aim is to apply an accurate path loss prediction technique in order to demonstrate the need for precise accounting of the refraction and ducting when planning future radio networks.

2. MODELS AND METHOD DESCRIPTION

The tropospheric ducts are described by the corresponding refractivity profiles. In this study, all refractivity profiles are assumed to be range independent. Applying the earth-flattening concept [1], the special case of evaporation surface-based duct is modeled using the log-linear model, Eq. (1), which is known to be a reasonable approximation for this type of duct [5].

\[
M(z) = M_0 + 0.13 \left[ z - z_0 \ln \left( \frac{z + z_0}{z_0} \right) \right]
\]

where \(M(z)\) is the modified refractivity vertical profile, \(M(0) = 10^{\mu(m(z) - 1)}, m = n + za_n, \) with refractive index \(n\) and Earth radius \(a_n\); the negative gradient of \(M(z)\) indicates the presence of duct, \(z\) is the altitude in \(m, M_0 = M(0)\), and \(z_0\) is the aerodynamic roughness parameter assumed to be \(1.5 \times 10^{-3}\) \(m\) [5]. When the electromagnetic field is calculated in a single frequency, the parameter \(M_0\) can be set to
be an arbitrary constant without affecting the interference pattern in height, thus the evaporation duct model is entirely governed by $z_d$.

The modified refractivity in the case of other (non-evaporation) surface-based ducts is often modeled by bilinear or trilinear (in the presence of elevated layers leading to surface ducts) model [6, 13], which has been assumed in this study as well. This simple model is rough but allows pointing out the importance of the basic duct parameters: duct height $z_d$, and M-deficit $dM = M(z_d) - M_0$ for the bilinear model and, additionally for the trilinear model, elevated trapping layer thickness and base height. These parameters may be derived from meteorological or direct refractive-index measurements and are essential for the duct influence on radio propagation. Again, the offset of the profile is not important. The slope above the $m$ profile inversion (as well as below it, in the case of elevated trapping layer) is set to 0.118 M-units/m (the value, corresponding to standard troposphere).

Electromagnetic-field calculations have been made using the PE approximation to the wave equation. This approach is among the most widely used propagation prediction techniques for large classes of wave-propagation problems [8, 12, 14–16]. Detailed descriptions and validations of the PE application to the micro-wave propagation through the troposphere are found in [8, 12]; here, only a brief outline of this approach is given.

For the tropospheric propagation problem, the forward-scatter narrow-angle-form of the two-dimensional (2D) scalar PE is given by Eq. (2) [8, 12]:

$$\frac{\partial u(x, z)}{\partial x} + \frac{i}{2k} \frac{\partial^2 u(x, z)}{\partial z^2} + \frac{i k}{2} (m^2(z) - 1) u(x, z) = 0, \quad (2)$$

where azimuthal symmetry of the problem is assumed, $k$ is the free-space wave number, $m$ is the modified tropospheric refractive index, $u(x, z)$ is the reduced [slow-varying along the preferred propagation direction, the $x$-coordinate in Eq. (2)] function related to an electromagnetic field component $\Psi$ as: $\Psi(x, z) = i u(x, z) \exp(i k x)/(k x)^{1/2}$. In Eq. (2), horizontal homogeneity of the medium is supposed and $m(z)$ is given by Eq. (1) for the evaporation duct and by bilinear/trilinear model for surface-based duct. Eq. (2) is obtained from the scalar wave equation after applying the far-field approximation (that is, assuming $kr \gg 1$ and the paraxial approximation $[i k u(x, z)]' \ll [2 k k u(x, z)]'$). The narrow-angle approximation is very accurate at angles within $\pm 15^\circ$ of the preferred direction of propagation [16]. A more general form of the PE for the reduced function $u$ is obtained by splitting the far-field approximation of the wave equation into two equations [16]:

$$\frac{\partial}{\partial x} + i k(1 - \sqrt{1 + Z}) \left[ \frac{\partial}{\partial x} + i k(1 + \sqrt{1 + Z}) \right] u = 0, \quad (3)$$

where $Z = (1/k^2) \partial^2/\partial z^2 + m^2 - 1$ and the first and second terms in Eq. (3) describe the forward and backward propagating fields, respectively. Depending upon the approximations assumed for the square-root operator in Eq. (3) and the numerical scheme used, this form of PE provides accurate solutions in larger angular sector (up to $60^\circ$) [16]. The neglecting of the back-scattered field and the assumption of the simplest approximation $(1 + Z)^{1/2} \approx 1 + Z/2$ lead to Eq. (2).

For tropospheric radio-wave propagation prediction, one is interested in field variations over scales much larger than the wavelength and, in these cases, the forward-propagated field plays dominant role. Thus, along with the grazing angles and small heights involved in the problem, permits the use of the narrow-angle forward-scatter PE. Eq. (2) has the advantage of being easily solved numerically through marching algorithms, provided the field is known on an initial vertical and adequate boundary conditions on the scattering objects and at the outer boundaries of the integration domain are given [8]. To solve the PE, different numerical techniques are used; among the most popular are Fourier/split-step method, finite-difference, and finite-element (FE)-based schemes, each of which has its advantages and disadvantages [17].

In this paper, samples with smooth underlying surface have been studied under 2D PE in conjunction with an FE numerical scheme. To solve the 2D Eq. (2), we use the standard PE method by applying the weak Galerkin approximation [18] and the Crank-Nicholson algorithm. A detailed description of this numerical procedure application to the tropospheric ducting problem is reported in [14, 19]. When elevation terrain cases are studied, the TPEM routines of the SPAWAR Systems Center, San Diego, CA, are used. This code is based on the Terrain Parabolic Equation Model [15], and makes use of the split-step Fourier PE method [12]. The terrain effects require larger propagation angles than the flat surface. To cope with this, the TPEM uses wide-angle propagator (see a discussion on this in [15]). The initial field in both smooth and elevated terrain cases has been provided by a horizontally polarized Gaussian beam source with the following pattern factor:

$$F(\theta) = \exp \left[ \ln(0.707)(\theta - \theta_0)^2 \right] \left(\theta/2\right)^2, \quad (4)$$

where $\theta_0$ and $\theta_1$ are the half-power beamwidth and the antenna elevation angle, respectively. Perfect conductivity of the ground has been assumed for all studied cases. The results are presented in the form of path loss ($PL$, in dB):

$$PL = 20 \log\left(\frac{4\pi r}{\lambda}\right) - PF, \quad (5)$$

where $\lambda$ is the free-space wavelength, $r$ is the distance between the corresponding points, and $PF$ is the pattern propagation factor as defined in [1].

3. RESULTS AND DISCUSSION

UMTS WCDMA-FDD variant uses the frequency band of 2110–2170 MHz for downlink and 1920–1980 MHz for uplink [20]. In this work, we used two carrier frequencies, $f_{DL\min} = 2112.4$ MHz and $f_{DL\max} = 2167.4$ MHz, situated at the two ends of the downlink band. Note that frequencies about 1–3 GHz are considered to be the lowest limit at which the effect of the evaporation duct begins [1, 6]; also, signal levels on paths longer than about 5 km are significantly affected for short periods of time by multipath that results from tropospheric stratification [2].

To illustrate the evaporation duct's influence on the two carrier frequencies, we use results for $z_d$ values and variations reported in [21]; a series of evaporation-duct height measurements were made in July 1999 over a 100-min period by means of atmospheric sensors located near the Australian shore. During this short time interval, $z_d$ suffered significant changes, varying between its minimum (about 6 m) and maximum (about 24 m) values. For this 100-min period, path-loss variations due to changes in $z_d$ were computed and compared to the standard troposphere losses for the two carrier frequencies over distances of $r = 3$ km, 5 km, 10 km, and 20 km. Two links were considered. The first one has transmitter (base station) height $z_t = 30$ m ($z_t$ is always above the duct), receiver height $z_r = 1.5$ m ($z_r$ is always submerged within
the duct). The second link has $z_1 = 30$ m, $z_2 = 20$ m (for this link $z_1$ is almost always above the duct). For both links, antenna half-power beamwidth $\theta_0 = 4^\circ$, antenna tilt $\theta_t = 0^\circ$ and smooth underlying surface have been assumed.

For the abovementioned scenarios, the effect of the evaporation duct has been found negligible up to distances of about 10 km (see Figs. 1–5) where examples of path loss changes during the 100-

min period are given for the two studied links and different terminal distances. The dashed and dotted straight lines on the figures indicate standard troposphere path loss for $f = 2167.4$ MHz and $f = 2112.4$ MHz, respectively. For the first link and
distance \( r = 15 \text{ km} \) from the transmitter, Figure 2 shows significant path-loss variations with \( z_d \) changes and a maximum decrease of 6 dB of the path loss in comparison to the standard troposphere case. As shown in Figure 3, the decrease in path loss due to ducting for the maximal values of \( z_d \) (\( z_d = 24 \text{ m} \), corresponding to the 85th min) is 6.5 dB and almost 10 dB for the two studied frequencies, respectively. Path-loss decrease in longer distances due to ducting (as well as its fluctuations) may cause interference and, in the worse case, reception from an unwanted link and lack of signal from the wanted link if links are calculated for standard troposphere propagation environment. To avoid such cases, additional interference-reduction techniques can be used, or anomalous propagation conditions should be accounted for when the link budget is calculated. Figure 3 also shows, to some slight extent, the different behavior of the two carrier frequencies, regardless of the very small shift between them. That is, under anomalous tropospheric propagation, the different channels from one and same frequency band can have different performances.

During almost the whole 100-min period, the second link is above the duct (except for the three measurements for which \( z_d \) is greater than 20 m: at the 75th, 85th, and 90th min). For this link, the calculated path losses under evaporation-duct conditions were above or around those for standard troposphere for all but one case: that of the longest studied terminals distance of 20 km shown in Figure 4, where a slight decrease of losses due to ducting is seen. This coincides with the expectation that paths with terminals situated above the duct will be less affected by the guiding structure. However, Figure 5 shows significant path-loss increase and variations, not only for the cases when the receiver has been submerged within the duct. For elevated \( z_d \), surface ducts affect the propagation in relatively short distances by provoking a shift of the location of the interference maxima (in terms of path loss) and a decrease of the signal level near the interference minima [22]. These effects are illustrated in Figure 6, where path losses versus range for standard troposphere, \( z_{dmin} = 6.8 \text{ m} \) and \( z_{dmax} = 24 \text{ m} \), are compared for the second link. The 10-km terminal distance is too close to the last interference maximum (see Fig. 6); this determines the significant difference between the path loss for standard troposphere and ducting seen in Figure 5. Besides, under ducting, the depth of the interference maxima is increased (see also [7]).

Figures 7 and 8 refer to the elevated-terrain case. They show path-loss diagrams for elevated terrain under standard and surface-based duct conditions, respectively. The duct is formed by an elevated layer between \( z = 450 \text{ to } 550 \text{ m} \) with an \( M \)-deficit of 70 \( M \)-units leading to a surface-based duct. The limit values of the duct parameters have been chosen according to the ones reported in [13]. The other parameters are: \( f = 2167.4 \text{ MHz} \), \( z_i = 30 \text{ m} \), \( \theta_1 = 2^\circ \), and \( \theta_2 = 0^\circ \). As is seen from these figures, the surface-based duct provokes increase of the signal in the shadowed region between 28 and 32 km and over the slope between 32 and 40 km. Figure 9 shows the path loss for a receiver situated in the first 2 m above the surface for the ranges between 29 and 40 km: a) under ducting, b) under standard troposphere conditions. For the lowest terrain point within the studied region (at 32 km), the path-loss

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**Figure 5** Path loss vs. time for \( r = 10 \text{ km} \), link 2

**Figure 6** Path-loss comparison between standard troposphere, \( z_{dmin} = 6.8 \text{ m} \) and \( z_{dmax} = 24 \text{ m} \), link 2

**Figure 7** Path loss for standard troposphere conditions
 decrease due to ducting is 17 dB. Such a quantitative assessment of the combined effect of terrain and ducting cannot be obtained from empirical propagation models.

4. CONCLUSION
The simulation results on the influence of evaporation and surface-based ducts upon path loss for the frequency band 2110–2170 MHz have been presented. The need for accurate accounting of the ducting effects (especially in coastal regions) when planning future communications networks has been demonstrated. The simulation procedure encompasses simple duct models with statistically averaged duct parameters and sophisticated electromagnetic field-propagation predictions based on the PE method. The proposed technique, in combination with in situ refractivity data, may be used for correct preliminary assessment of the expected path loss and possible interference in order to decrease the cost of deployment and improve network performance.

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