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Re:	Call for Contributions (posted 24 September 1999), Specific Area: Propagation Model
Abstract	Two explicit-form formulations are presented for radio propagation predictions for local multipoint distribution service. The first formulation accounts for multiple forward diffraction by rows of buildings only. The second formulation is an extension of the first one, and it accounts for multiple diffraction by rows of tree canopies and buildings, including the effects of propagation through the trees between rows of buildings. When the base transceiver station antennas are sufficiently high, the attenuation of the buildings varies around the value of free space and the building effect is negligible, because a line-of-sight (LOS) propagation path between the base transceiver station antenna and building-rooftop subscriber transceiver station antenna exists and plays a major role. The tree canopies which extend above the building rooftop heights block the LOS propagation path and cause additional signal attenuation. The attenuation effect of the buildings is significant if the base transceiver station antennas are not sufficiently high.
Purpose	To provide an input to the specific area ‘‘Propagation Model’’
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Formulations of Multiple Diffraction by Buildings and Trees for Propagation Prediction

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Introduction

In design of local multipoint distribution service (LMDS) systems in urban areas, one is often faced with radio propagation environments such as those represented by Figs. 1 and 2. Figure 1 shows radio propagation in the presence of rows of buildings and Fig. 2 shows the case where trees are present in the environment. It is appropriate to implement a high base transceiver station antenna and building rooftop subscriber transceiver station antennas, which provide line-of-sight (LOS) propagation paths between transmitter and receivers. The rows of buildings are considered to have an average separation distance d and an average height, which is used to determine the elevation angle α of a subscriber transceiver station antenna.

In the case represented in Fig. 1, where trees are absent, propagation models of multiple-building forward diffraction are available for mobile radio communications typically at UHF band (300 MHz-3 GHz). The multiple-building forward diffraction formulation [1], [2] is introduced here for the propagation prediction, since it also valid at millimeter wave and microwave frequencies being used for LMDS systems. It is a closed-form formulation and it applies to the grazing aspects of incidence and observations, i.e., the elevation angle $\alpha \rightarrow 0$. It is derived from the uniform geometrical theory of diffraction (UTD) [3] and from physical optics (PO). It is known that UTD itself may become incorrect when the rooftop of each multiple diffraction building (modeled as an edge) lies in the transition zone of rooftops of the preceding diffraction buildings, i.e., grazing aspects of incidence and observations. Consequently, PO-based results were applied [4], [5] for multiple edge diffraction near and in the transition zone. The physical optics approximation is accurate in and near the transition zone but generally involves multiple dimension integration due to multiple diffraction.

In the case where trees are present, depicted in Fig. 2, tree canopies which extend above the building rooftop heights block LOS propagation paths. For the wavelengths λ much larger than the size of tree leaves and branches, e.g., at 900 MHz, a theoretical model [6] has been proposed to compute the diffraction effects of tree canopies and buildings. At centimeter and millimeter frequencies, λ (1 centimeter at 30 GHz) may be on the order of size of tree leaves and branches and even much smaller. Therefore, the model proposed in [6] for use in mobile radio systems is not valid for LMDS propagation predictions.

An explicit-form formulation for multiple diffraction by trees and buildings is presented for the propagation prediction for the environment depicted in Fig. 2(a). It is an extension of the multiple-building diffraction formulation, but it includes the effects of propagation through the trees calculated by existing models [7], [8] for vegetation. The diffraction modeling of Fig. 2 (a) is indicated in Fig. 2 (b). A multiplication of a knife-edge diffraction and a tree attenuation and phase factor is used to account for the diffraction of a row of buildings and a tree canopy above the building rooftop height. The rows of buildings or trees are numbered from 1 to n. There is no direct ray from a base transceiver station antenna to a subscriber transceiver station antenna, because the tree canopies extend above the average building rooftop height and block the LOS propagation path. The strongest ray suffers from attenuation by the tree canopy.

Formulation for Multiple Diffraction by Buildings

The propagation loss A_{md} (attenuation relative to free space loss) in dB due to multiple diffraction by buildings is defined as

$$A_{md} = 20\log_{10}\left|\frac{E_{n+1}}{E_0}\right| \qquad (1)$$

where E_0 represents an incident plane wave, E_{n+1} represents the corresponding total field at the reference point $n+1$ (receiver), and n is the number of rows of buildings between a base transceiver station and one subscriber transceiver station.

Define a grouping parameter $g = \sin\alpha\sqrt{d/\lambda}$. In the case where trees are absent, the ratio E_{n+1}/E_0 [9], in the range $g \geq 0.1$, is written as

$$\frac{E_{n+1}}{E_0} = 1 + \frac{D_{s,h}}{\sqrt{d}}\exp[-jkd(1-\cos\alpha)]\frac{1-(D^c_{s,h}\exp[-jkd(1-\cos\alpha)]/\sqrt{d})^n}{1-D^c_{s,h}\exp[-jkd(1-\cos\alpha)]/\sqrt{d}} \qquad (2)$$

$$D_{s,h} = \frac{-\exp(-j\pi/4)}{2\sqrt{2\pi k}}\left[\frac{F(X)}{\sin(\alpha/2)} \quad \frac{1}{-\cos(\alpha/2)}\right] \qquad (3)$$

$$F(X) = \sqrt{\pi X}\exp(j\pi/4 + jX) - 2j\sqrt{X}\exp(jX)\int_0^{\sqrt{X}}\exp(-j\tau^2)d\tau \qquad (4)$$

$$\sqrt{X} = \sqrt{2kd}\,|\sin(\alpha/2)| \qquad (5)$$

$$D^c_{s,h} = \frac{-\exp(-j\pi/4)}{2\sqrt{2\pi k}}\left[-\sqrt{\pi kd}\cdot\exp(j\pi/4) \quad (-1)\right] \qquad (6)$$

where k is the wave-number, subscripts ‘‘s’’ and ‘‘h’’ of UTD diffraction coefficients $D_{s,h}$ and $D^c_{s,h}$ denote soft and hard boundaries, respectively, and they take signs ‘‘–’’ and ‘‘+’’ on the right-hand side of equations (3) and (6). The hard boundary corresponds to vertical polarization transmission and reception in the vertical plane. The transition function $F(X)$ can be approximated as $F(X) \approx \sqrt{\pi X}\exp(j\pi/4 + jX)$ for $X < 10^{-3}$ and $F(X) \approx 1$ for $X > 10$.

For $0 \leq g \approx \alpha\sqrt{d/\lambda} < 0.1$, including the grazing incidence of $\alpha \to 0$, E_{n+1}/E_0 [1], [2] is expressed as

$$\frac{E_{n+1}}{E_0} = 1 + \frac{D_{s,h}}{\sqrt{d}}\exp[-jkd(1-\cos\alpha)]\frac{1-1/\sqrt{3n+1}}{-D_{s,h}\big|_{\alpha=0}/\sqrt{d}} \qquad (7)$$

$$D_{s,h}\big|_{\alpha=0} = \frac{-\exp(-j\pi/4)}{2\sqrt{2\pi k}}\left[\sqrt{2\pi kd}\cdot\exp(j\pi/4)\quad(-1)\right]. \qquad (8)$$

The PO-based expression $1/\sqrt{3n+1}$ accounts for multiple forward diffraction by n rows of buildings for the grazing aspect of incidence and observation. It was given in [4] and it approximates $\Gamma(n+1/2)/(\sqrt{\pi}n!)$ derived in [5]. Since $kd >> 1$ and α is small, which implies that $\cos(\alpha/2)\sim 1$, the second term on the right-hand side of (3), (6), and (8) is negligibly small compared with the first term. Therefore, both (7) and (2) are dependent on but insensitive to the polarization (type of boundaries). Since d is in the range about $30-100$ m, $kd >> 1$ is naturally satisfied at microwave and millimeter frequencies being used in LMDS systems. In numerical computations, (6) and (8) can be approximated by $D_{s,h}^{c} \approx \sqrt{d}/(2\sqrt{2})$ and $D_{s,h}\big|_{\alpha=0} \approx -\sqrt{d}/2$, respectively.

When $\alpha \to 0.1$, equation (2) smoothly approaches equation (7). Both equations (7) and (2) also apply to the soft boundary that corresponds to horizontal polarization transmission and reception in the vertical plane.

Formulation in Presence of Trees

In the case where trees are present, such as that depicted in Fig. 2, extensions of equations (2) and (7) (including the effects of propagation through the trees) are expressed as

$$\frac{E_{n+1}}{E_0} = A\left(1+\frac{D_{s,h}}{\sqrt{d}}\exp[-jkd(1-\cos\alpha)]\frac{1-(A\exp(-j\Delta k\Delta d)D_{s,h}^{c}\exp[-jkd(1-\cos\alpha)]/\sqrt{d})^{n}}{1-A\exp(-j\Delta k\Delta d)D_{s,h}^{c}\exp[-jkd(1-\cos\alpha)]/\sqrt{d}}\right) \qquad (9)$$

for $g \geq 0.1$ and

$$\frac{E_{n+1}}{E_0} = A\left(1+\frac{D_{s,h}}{\sqrt{d}}\exp[-jkd(1-\cos\alpha)]\frac{1-A^{\gamma_n}/\sqrt{3n+1}}{-D_{s,h}\big|_{\alpha=0}/\sqrt{d}}\right) \qquad (10)$$

for $0 \leq g < 0.1$, where A and $\exp(-j\Delta k\Delta d)$ are the attenuation and phase factor of a tree in the canopy, respectively, Δd is the average propagation path length (depth) through a tree in the canopy, and γ_n is a function that ranges from 0 to $n-1$.

Quantities A and Δk can be expressed as

$$A = \exp(-L/8.686) \qquad (11)$$

$$\Delta k = k(n_R - 1) \qquad (12)$$

$$n_R = \sqrt{\varepsilon' + n_I^2} \qquad (13)$$

where L represents attenuation in dB (in excess of that of free space) due to vegetation, n_R and n_I are the real and imaginary parts of refractive index of leaves, respectively, and ε' is the real part of the relative permittivity of leaves. Several models for L are available [7]. For the frequency range of $10-40$ GHz, the expressions

$$L = 0.39 f^{0.39} \Delta d^{0.25} \qquad (14)$$

$$L = 0.37 f^{0.18} \Delta d^{0.59} \qquad (15)$$

may be taken for the in-leaf and out-of-leaf states, respectively, where f is the frequency in MHz and Δd is in meters. The approach to n_I can be expressed as

$$n_I = L\big|_{\Delta d = 1} / 8.686 \qquad (16)$$

where $L\big|_{\Delta d=1}$ represents L calculated at $\Delta d = 1$ meter. Using the results of [8], ε' is expressed as

$$\varepsilon' = A' - B' m_d \qquad (17)$$

with $0.1 \le m_d \le 0.5$, where coefficients A' and B' are listed over the frequency range of $1-94$ GHz. At frequencies about 35 GHz, one may take $A' \approx 8.8$ and $B' \approx 4.3$.

In the absence of trees, i.e., $A = 1$, equations (9) and (10) become equations (2) and (7), respectively. Equations (9) and (10) are derived from equations (2) and (7) by: 1) multiplying each UTD building diffraction coefficient by the factor A of a tree canopy with an appropriate phase factor $\exp(-j\Delta k \Delta d \cos\alpha)$ or $\exp(-j\Delta k \Delta d)$, instead of a UTD diffraction coefficient alone; 2) using the strongest ray as $A\exp(-j\Delta k\Delta d \cos\alpha) \times \exp(-jknd\cos\alpha)$, instead of the direct ray $\exp(-jknd\cos\alpha)$; and 3) multiplying the multiple building diffraction factor $1/\sqrt{3n+1}$ by a tree attenuation factor A^{γ_n}, instead of the building factor $1/\sqrt{3n+1}$ alone. Items 1) and 3) account for the diffraction by rows of trees and buildings. Item 2) is introduced for the absence of an LOS propagation path.

Numerical Results

Figures 3 and 4 present numerical results of the relative attenuation. At $\alpha = 0.5$, g takes values of 0.617 and 0.501 for $d = 50$ m and $d = 33$ m, respectively. In the case where trees are absent, the attenuation of buildings varies around the value of free space and the building effect is negligible, since an LOS propagation path between transmitter and receiver antennas exists and plays a major role for $g \ge 0.4$ corresponding to sufficiently high transmitter antennas [4], [10]. Parameter g depends on frequency, elevation angle, and average separation between buildings. The existence of an LOS path (a direct wave component) depends only on the elevation, i.e., if $\alpha > 0$. The LOS propagation path becomes dominant when elevation angle α is sufficiently large satisfying $g \ge 0.4$ for given λ and d. In the case where trees are present, the tree canopies that extend above the building rooftop heights block the LOS propagation path and cause the additional signal attenuation. Based on the analysis of experimental data, a recent study of the LMDS radio channel [11] concludes that a serious propagation impairment is the signal attenuation caused by tree canopies.

At an angle $\alpha > 0$, the absolute value of relative attenuation A_{md} increases as the separation d between trees or buildings decreases. At $\alpha = 0.05$, g takes values of 0.0617 and 0.0501 for $d = 50$ m and $d = 33$ m, respectively. For a fixed elevation angle α, g decreases with d. It is known that the multiple building forward diffraction loss increases as the group parameter g decreases [4], [10].

At $g = 0$, i.e., when $\alpha = 0$, equation (10) becomes $A^{1+\gamma_n} / \sqrt{3n+1}$ which is a multiplication of the attenuation factor $A^{1+\gamma_n}$ of tree canopies and the diffraction factor $1/\sqrt{3n+1}$ of buildings. Function γ_n ranges from 0 to $n-1$, resulting in variations of tree attenuation. In the computations of Figs. 3 and 4, $\gamma_n \approx 0$ was taken. This should be adequate to indicate the tree effects for LMDS systems that are supposed to use high base transceiver station antennas, providing LOS propagation conditions in the absence of trees. In the presence of trees, LOS propagation conditions no longer exist. Function γ_n appears for $0 \le g < 0.1$ (not sufficiently high transmitter antenna) with equation (10); $\gamma_n \approx 0$ corresponds to minimum tree attenuation, implying that only one tree is present and contributes to the multiple diffraction process. If $\gamma_n \approx 0$, the differences between the relative attenuation for trees and buildings and the attenuation in the case where trees are absent are insensitive to the number of edges modeling the trees and buildings. The value of $m_d = 0.4$ for the permittivity of tree leaves was used in the computation presented here.

Since the depth Δd is an input parameter, more numerical calculations for other values of Δd are available. Also, there are several models [7] of attenuation due to vegetation media at centimeter and millimeter wavelengths and these models can be taken as inputs of the formulation for the case with trees.

Summary

A closed-form formulation for over-rooftop multiple forward diffraction by rows of buildings is presented. An explicit form formulation for over-rooftop multiple forward diffraction by buildings and tree canopies is also presented. They both are for use in the propagation predictions at centimeter and millimeter wavelengths for local multipoint distribution service.

When the base transceiver station antennas are sufficiently high, the attenuation of the buildings varies around the value of free space and the building effect is negligible, because a line-of-sight propagation path between a base transceiver station antenna and a over-rooftop subscriber transceiver station antenna exists and plays a major role. When trees extend above the building rooftop heights, they block the LOS propagation path and cause additional signal attenuation.

The attenuation effect of the buildings is significant, if the base transceiver station antennas are not high enough as $g < 0.4$, especially for the case of $0 \le g < 0.1$ including elevation angle $\alpha \to 0$. The attenuation due to rows of tree canopies and buildings increases as the separation between buildings decreases.

Whenever enough measurement data is available, comparison with measurements and experimental study of γ_n would lead to refinement or development of the diffraction formulation for buildings and tree canopies.

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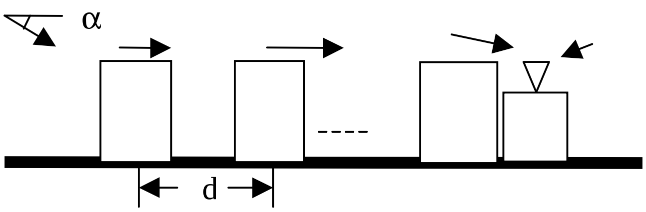
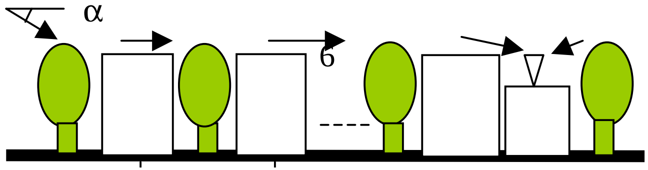


Fig. 1. Radio propagation in presence of rows buildings.



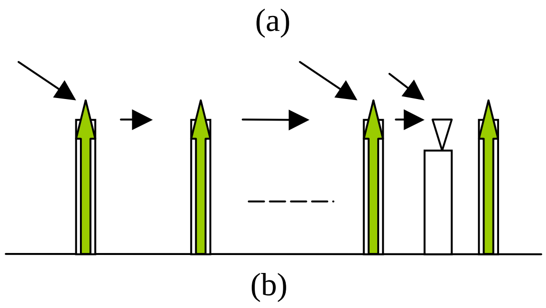


Fig. 2. Radio propagation in presence of rows of trees and buildings. (a) Diffraction by buildings and tree canopies extending above the building rooftop heights. (b) Diffraction modeling of Fig. 2 (a): a multiplication of a knife-edge diffraction and a tree attenuation and phase factor accounting for a row of buildings and tree canopies above the building rooftop height.

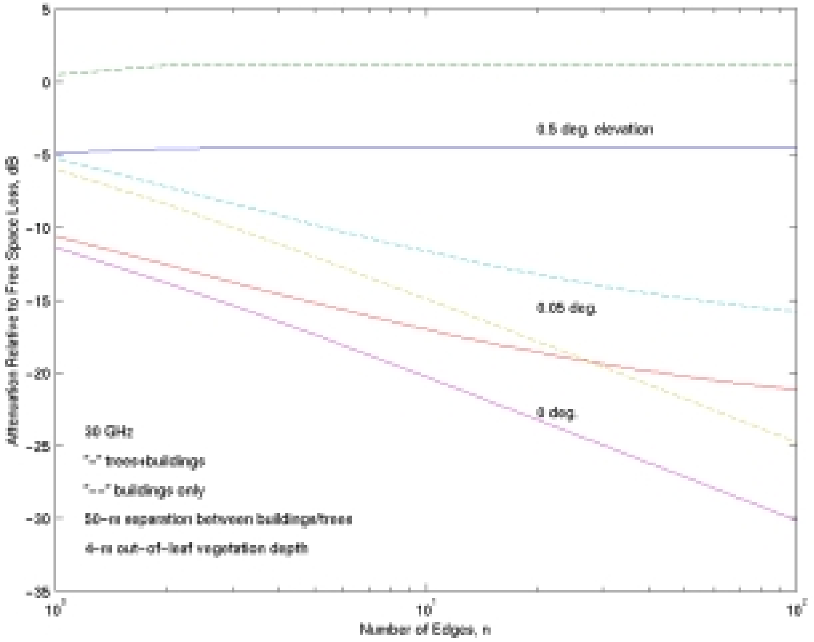


Fig. 3. Attenuation relative to free-space attenuation value for the receiver at the rooftop of a building numbering $n+1$ for a 50-m distance separation between trees/buildings.

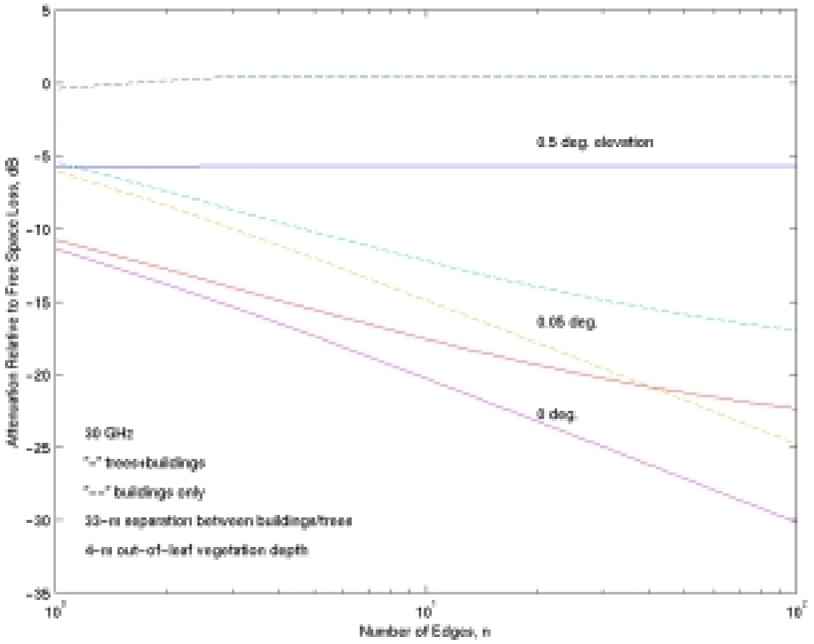


Fig. 4. Attenuation relative to free-space attenuation value for the receiver at the rooftop of a building numbering $n+1$ for a 33-m distance separation between trees/buildings.