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Re:	In response to the Call For Contributions, by IEEE 802.16.3–00/13 r1
Abstract	This document describes a set of channel models applicable to broadband fixed wireless systems.
Purpose	This contribution will be presented and discussed within the Task Group in Session #10 for possible adoption for technical assessment of broadband fixed wireless systems.
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Channel Models for Broadband Fixed Wireless Systems

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1. Introduction

Existing Broadband Wireless Access (BWA) systems cover large service areas with base station antenna heights typically more than 300 m. These are single cell ("super cell") solutions with prevailing Line-of-Sight (LOS) conditions between transmitter and receiver. We found that propagation models used for these systems are not applicable to emerging broadband fixed wireless systems. The new, cellular-like (multi-cell), fixed wireless communication systems will operate mostly over Non-Line-of-Sight (NLOS) conditions with smaller cells, shorter base station antenna heights, directive antennas, and higher frequencies.

This document summarizes the results found in recent literature that will help define fixed wireless channel characteristics for a reliable system deployment and operation. Models for path loss, gain reduction factor, rms delay spread, delay profiles, and Ricean K-factors are described in this document.

In the discussion section, we present implications of such propagation models on broadband fixed wireless system design with a high quality of service requirements.

2. Path Loss Model

The most widely used path loss model for signal strength prediction and simulation in macrocellular environments is the Hata-Okumura model [1,2]. This model is valid for the 500-1500 MHz frequency range, receiver distances greater than 1 km from the base station, and base station antenna heights greater than 30 m. There exists an elaboration on the Hata-Okumura model that extends the frequency range up to 2000 MHz [3]. We found that these models are not suitable for shorter base station antenna heights, higher receiver antenna heights, and hilly or heavily wooded terrain. To correct for these limitations, we propose a model presented in [4]. The model covers three different terrain categories. The maximum path loss category is hilly terrain with moderate-to-heavy tree densities (Category A). The minimum path loss category is mostly flat terrain with light tree densities (Category C). Intermediate path loss condition is captured in Category B. The extensive experimental data was collected by AT&T Wireless Services across the United States in 95 existing macrocells at 1.9 GHz.

Beyond close-in distance d_o = 100 m, the decibel path loss PL can be written as

$$PL = A + 10\,\gamma \log10 (d/d_o) + s; \qquad d \geq d_o \tag{1}$$

where the intercept A is given by the free-space formula

$$A = 20 \log_{10} (4 \pi d_o / \lambda) \quad (2)$$

where λ is the wavelength in meters.

The path loss exponent γ is a Gaussian random variable over the population of macrocells within each terrain category. It is expressed as

$$\gamma = (a - b h_b + c / h_b) + x \sigma_\gamma; \qquad 10 \text{ m} \leq h_b \leq 80 \text{ m} \quad (3)$$

where h_b is base station antenna height in meters. The term in between parentheses is the mean of γ; σ_γ is the standard deviation of γ; x is a zero-mean Gaussian variable of unit standard deviation; and a, b, c, and σ_γ are constants for each terrain category. The numerical values for these constants can be found in Table I in [4].

s in (1) is a lognormal shadow fading random variable whose standard deviation σ is also modeled as a Gaussian distribution. It can be written as

$$\sigma = \mu_\sigma + z \sigma_\sigma \quad (4)$$

where μ_σ is the mean of σ; σ_σ is the standard deviation of σ; z is a zero-mean Gaussian variable of unit standard deviation. The numerical values for these constants for different terrain categories can be also found in Table I.

The Hata-Okumura model predicts median path loss similar to Category C, however, it significantly underestimates the path loss in Categories A and B. The Hata-Okumura model is limited to quasi-smooth terrain [2, 8 Ch.4].

Frequency correction factor – Equation 2 accounts for the free-space frequency dependency of the path loss, but does not account for a change in diffraction loss for different frequencies. Based on results reported in [5,6], for suburban environments, a simple frequency dependent correction factor C_f due to the diffraction loss can be added to (1):

$$C_f = 6 \log_{10} (f / 1900) \quad (5)$$

where f is the frequency of interest in MHz. In [5,6] it was shown that the combined (free-space path loss and diffraction loss) frequency correction factor is valid for a wide range of frequencies (450 MHz – 11.2 GHz).

Receiver antenna height correction factor – In [7] it was reported that, for mostly NLOS conditions, doubling the receiver antenna height results in approximately 3.2 dB decrease in path loss. For LOS conditions, theoretically, doubling the receiver antenna height results in a 6 dB decrease in path loss [8, Ch.2]. It is intuitive that the decrease in path loss is less for NLOS than LOS conditions when increasing the receiver antenna height. Therefore, we propose a simple receiver antenna height correction factor that can be added to (1) (based on the results reported in [7]):

$$C_h = -10.7 \log_{10}(h/2); \qquad 2\text{ m} \le h \le 8\text{ m} \tag{6}$$

where C_h is the receiver antenna height correction factor and h is the receiver antenna height in m. In (6), number 2 represents the antenna height in m for which the path loss model was originally developed. This correction factor closely matches the Hata-Okumura mobile antenna height correction factor for a large city (doubling the receiver antenna height results in approximately 3.5 dB decrease in path loss). However, for a small or medium sized city, the Hata-Okumura model predicts approximately 12 dB decrease in path loss when the receiving antenna height is doubled (from 4 to 8 m). We find this decrease in path loss surprisingly large.

The path loss equation, PL_c, that includes both frequency and receiver antenna height correction factors can be written as follows

$$PL_c = PL + C_f + C_h \tag{7}$$

3. Gain Reduction Factor (GRF)

This is a very important factor in link budget calculations. In local scattering, the nominal gain of a directive antenna can be significantly reduced [9], depending on the receiver antenna beamwidth. This reduction in antenna gain is less pronounced for LOS systems ("supercell" systems with hundreds of meters high Base Station (BTS) antenna heights), but has to be accounted for in systems that deploy lower, cellular like, BTS and Subscriber Unit (SU) antenna heights (with prevailing NLOS conditions). For example, Fig. 1 in [9] shows a 7 dB median reduction in nominal antenna gain when a receiver antenna of 20 degree 3 dB beamwidth in azimuth is considered.

In system level simulations and link budget calculations for 90% cell coverage, the standard deviation of the GRF can also be accounted for (Fig. 2, in [9]). For a 20^o antenna, the standard deviation σ_{grf} is approximately 3 dB (lognormal random variable). It can also be argued that the variable component of the GRF is correlated with the shadow fading lognormal random variable (more scattering, i.e. larger GRF, when shadow fading is present). The combined shadow fading/GRF standard deviation σ_c can be calculated using the following formula:

$$\sigma_c^2 = \sigma^2 + \sigma_{grf}^2 + 2\rho\,\sigma\,\sigma_{grf} \tag{8}$$

where ρ is the correlation coefficient and σ is the standard deviation of the lognormal shadow fading random variable s in (1).

For σ = 8 dB and σ_{grf} = 3 dB the formula yields σ_c of 8.5 and 9.8 dB for ρ = 0 and ρ = 0.5, respectively. Larger standard deviation results in a larger path loss margin for the 90% cell coverage (approximately 0.25 dB for ρ = 0 and 1 dB for ρ = 0.5).

4. RMS Delay Spread Model

A delay spread model was proposed in [10] based on a large body of published reports. It was found that the rms delay spread follows lognormal distribution and that the median of this distribution grows as some power of distance. The model was developed for rural, suburban, urban, and mountainous environments. The model is of the following form:

$$\tau_{rms} = T_1 d^{\varepsilon} y \qquad (9)$$

Where τ_{rms} is the rms delay spread, d is the distance in km, T_1 is the median value of τ_{rms} at d = 1 km, ε is an exponent that lies between 0.5-1.0, and y is a lognormal variate. The model parameters and their values can be found in Table III of [10]. However, these results are valid only for omnidirectional antennas. To account for antenna directivity, results reported in [11] can be used. It was shown that for directive SU antennas, the delay profile can be modeled as having a so-called “spike-plus-exponential” shape. It was also shown that a 32^{o} directive antenna reduces the τ_{rms} values by a factor of 2.3 when compared to an omnidirectional antenna in suburban environments. The τ_{rms} statistics for two suburban environments were also presented.

Depending on the terrain, distances, antenna directivity and other factors, the rms delay spread values can span from very small values (tens of nanoseconds) to large values (many microseconds).

5. K-Factor Model

The received fading signal can be characterized by a Ricean distribution. The key parameter of this distribution is the K-factor, defined as the ratio of the “fixed” component power and the “scatter” component power. In [12], an empirical model was derived from a 1.9 GHz experimental data set collected in typical suburban environments for transmitter antenna heights of approximately 20 m. In [13], an excellent agreement with the model presented in [12] was reported using an independent set of experimental data collected in San Francisco Bay Area at 2.4 GHz and similar antenna heights. The K-factor distribution was found to be lognormal, with the median as a simple function of season, antenna height, antenna beamwidth, and distance. The standard deviation was found to be approximately 8 dB. The model is as follows:

$$K=F_s F_h F_b K_o d^{\gamma} u \qquad (10)$$

where:

F_s is the seasonal factor = 1 in summer and 2.5 in winter
F_h is the receiving antenna height factor = $(h/3)^{0.46}$; h in meters
F_b is the antenna beamwidth factor = $(b/17)^{-0.62}$; b in degrees
d is the distance in km
γ is the exponent = - 0.5
K_o is the 1 km intercept = 10 dB

u is the zero-mean lognormal variate with a 8.0 dB standard deviation over the cell area.

From (10) we can see that the K-factor decreases with distance ($d^{-0.5}$, i.e. 5 dB per decade). The median K-factor is 2.5 times larger in the winter (leaves-off) than in the summer time (leaves-on). K-factor is highly dependent on wind speed. The model presented here assumes variable wind conditions. Because of the large standard deviation of 8 dB, it is highly probable that K-factors are close to 0, especially with high wind conditions.

6. Discussion and Conclusions

For Broadband Wireless Access deployment in cellular like environments predominantly NLOS conditions have to be assumed. The base station antenna heights are typically 15-30 m, and the subscriber antenna heights are typically 2-3 m under the eaves location or greater for rooftop location. Low base station antenna heights yield large path loss [4] and severe signal fading because of the multipath propagation. Based on the model presented in [12], for high percentage cell coverage (90%) and 99.9% reliability, the only valid assumption for K-factor is 0.

Another important propagation channel property is the multipath dispersion which can be quantified by the rms delay spread. Large delay spread values cause inter-symbol-interference in the single-carrier modulation system. As a result, equalizers have to used. In high data rate systems and/or high delay spread environments, the complexity and cost of equalizers can pose a fundamental barrier. It was found that the delay spread values can be quite high in hilly, urban, and suburban environments close to urban centers (microseconds, [10]). Another alternative is to use Orthogonal Frequency Division Multiplexing (OFDM) systems which benefit from the delay spread (frequency diversity gain) and do not require equalizers. However, it was found that the frequency diversity gain can not be always guaranteed, especially in rural and flat suburban areas that can yield low delay spread values (tens of nanoseconds, [11]) with a high probability. Therefore, for a reliable deployment of OFDM systems, low delay spread values have to be assumed. This stresses an importance of using multiple antennas separated in space or different polarizations, together with space-time processing, to provide a reliable service.

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