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Re:	Call for Contributions: Session #10 Topic: Traffic, Deployment, and Channel Models, dated September 15, 2000 (IEEE 802163-00/13) This responds to the second item: Channel propagation model
Abstract	This document provides a joint submission that describes a set of channel models suitable for fixed wireless applications.
Purpose	This is for use by the Task Group to evaluate air interface performance
Notice	
Release	
Patent Policy and Procedures	

Channel Models for Fixed Wireless Applications

Background

An important requirement for assessing technology for Broadband Fixed Wireless Applications is to have an accurate description of the wireless channel. Channel models are heavily dependent upon the radio architecture. For example, in first generation systems, a super-cell or "single-stick" architecture is used where the Base Station (BTS) and the subscriber station are in Line-of-Sight (LOS) condition and the system uses a single cell with no co-channel interference. For second generation systems a scalable multi-cell architecture with Non-Line-of-Sight (NLOS) conditions becomes necessary. In this document a set of propagation models applicable to the multi-cell architecture is presented. Typically, the scenario is as follows:

- Cells are < 10 km in radius, variety of terrain and tree density types
- Under-the-eave/window or rooftop installed directional antennas (2 – 10 m) at the receiver
- 15 - 40 m BTS antennas
- High cell coverage requirement (80-90%)

The wireless channel is characterized by:

- Path loss (including shadowing)
- Multipath delay spread
- Fading characteristics
- Doppler spread
- Co-channel and adjacent channel interference

*It is to be noted that these parameters are random and only a statistical characterization is possible. Typically, the mean and variance of parameters are specified***.**

The above propagation model parameters depend upon terrain, tree density, antenna height and beamwidth, wind speed, and season (time of the year).

This submission combines and elaborates on contributions [7], [8], and [16] which were presented at the IEEE 802.16.3 meeting in Tampa, FL, on November 7, 2000.

Suburban 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]. It was found that these models are not suitable for lower base station antenna heights, and hilly or moderate-to-heavy wooded terrain. To correct for these limitations, we propose a model presented in [4]. The model covers three most common terrain categories found across the United States. However, other sub-categories and different terrain types can be found around the world.

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. For a given close-in distance d_0, the median path loss (PL in dB) is given by

$$PL = A + 10\,\gamma \log_{10}(d/d_0) + s \quad \text{for } d > d_0,$$

where $A = 20 \log_{10}(4\,\pi\, d_0 / \lambda)$ (λ being the wavelength in m), γ is the path-loss exponent with $\gamma = (a - b\, h_b + c / h_b)$ for h_b between 10 m and 80 m (h_b is the height of the base station in m), d_0 = 100m and a, b, c are constants dependent on the terrain category given in [4] and reproduced below.

Model parameter	Terrain Type A	Terrain Type B	Terrain Type C
A	4.6	4	3.6
B	0.0075	0.0065	0.005
C	12.6	17.1	20

The shadowing effect is represented by s, which follows lognormal distribution. The typical value of the standard deviation for s is between 8.2 and 10.6 dB, depending on the terrain/tree density type [4].

Receive Antenna Height and Frequency Correction Terms

The above path loss model is based on published literature for frequencies close to 2 GHz and for receive antenna heights close to 2 m. In order to use the model for other frequencies and for receive antenna heights between 2 m and 10 m, correction terms have to be included. The path loss model (in dB) with the correction terms would be

$$PL_{modified} = PL + \Delta PL_f + \Delta PL_h$$

where PL is the path loss given in [4], ΔPL_f (in dB) is the frequency correction term [5,6] given by

$$\Delta PL_f = 6 \log (f / 2000)$$

where f is the frequency in MHz, and ΔPL_h (in dB) is the receive antenna height correction term given by

$$\Delta PL_h = - 10.8 \log (h / 2); \quad \text{for Categories A and B [7]}$$

$$\Delta PL_h = - 20 \log (h / 2); \quad \text{for Category C [1]}$$

where h is the receive antenna height between 2 m and 10 m.

Urban (Alternative Flat Suburban) Path Loss Model

In [8], it was shown that the Cost 231 Walfish-Ikegami (W-I) model [9] matches extensive experimental data for flat suburban and urban areas with uniform building height. It has been also found that the model presented in the previous section for the Category C (flat terrain, light tree density) is in a good agreement with the Cost 231 W-I model for suburban areas, providing continuity between the two proposed models.

Figure 1. compares a number of published path loss models for suburban morphology with an empirical model based on drive tests in the Dallas-Fort Worth area [9]. The Cost 231 Walfisch-Ikegami model (see Appendix A) was used with the following parameter settings

Frequency = 1.9 GHz
Mobile Height = 2 m
Base Height = 30 m
Building spacing = 50 m
Street width = 30 m
Street orientation = 90°

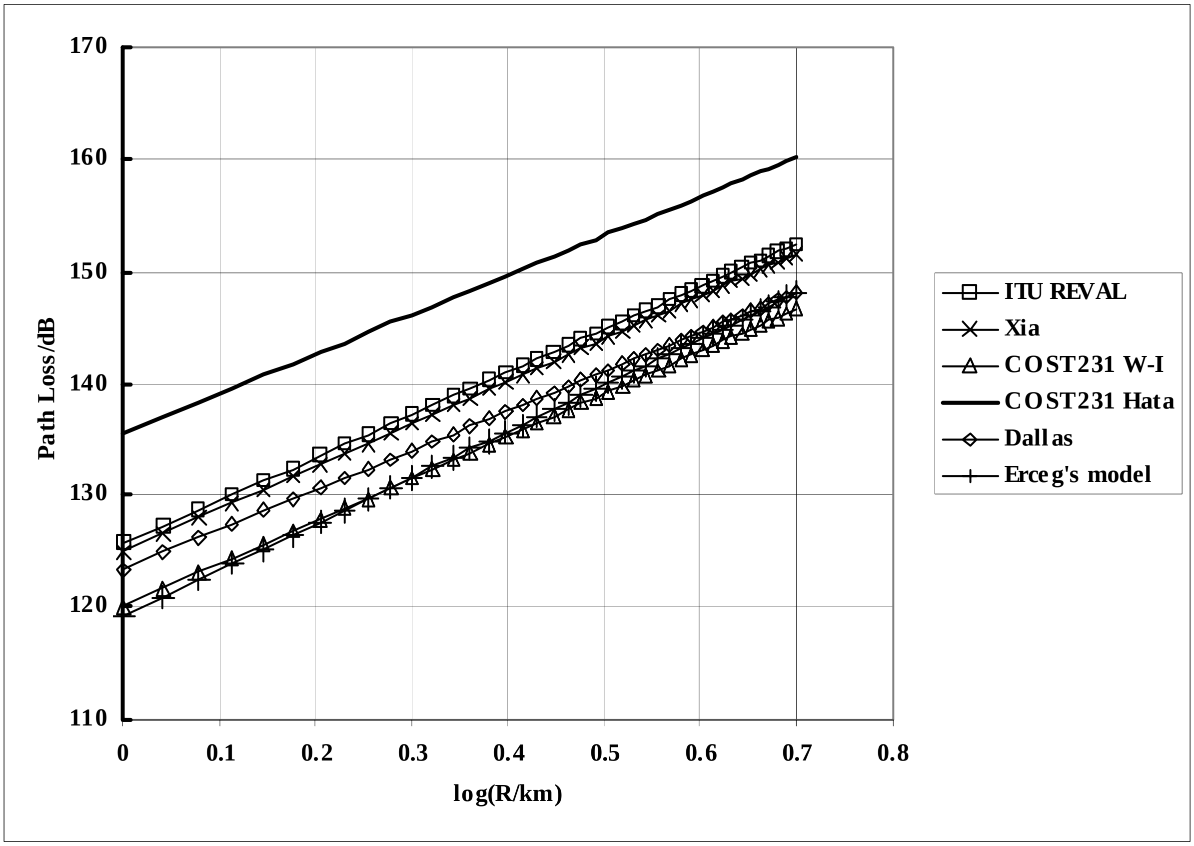


Figure 1. Comparison of suburban path loss models.

Note: COST 231 W-I, ITU Reval and Xia models all have a Hata correction term added for modeling the path loss variation with mobile height (see Appendix A).

It has also been found that the Cost 231 W-I model agrees well with measured results for urban areas, provided the appropriate building spacing and rooftop heights are used. It can therefore be used for both suburban and urban areas, and can allow for variations of these general categories between and within different countries.

Flat terrain models in conjunction with terrain diffraction modeling for hilly areas can be used in computer based propagation tools that use digital terrain databases. In [9] it was found that the weighting term for knife-edge diffraction should be set to 0.5 to minimize the lognormal standard deviation of the path loss.

Multipath Delay Profile

Due to the scattering environment, the channel has a multipath delay profile. For directive antennas, the delay profile can be represented by a spike-plus-exponential shape [10]. It is characterized by τ_{rms} (RMS delay spread of the entire delay profile) which is defined as

$$\tau^2_{rms} = \Sigma_j\ P_j\ \tau^2_j - (\tau_{avg})^2$$

where

$$\tau_{avg} = \Sigma_j\ P_j\ \tau_j\ ,$$

τ_j is the delay of the j th delay component of the profile and P_j is given by

P_j = (power in the j th delay component) / (total power in all components).

The delay profile has been modeled using a spike-plus-exponential shape given by

$$P(\tau) = A\ \delta(\tau) + B \sum^{\infty}_{i=0} \exp(-i\Delta\tau/\tau_0)\ \delta(\tau - i\Delta\tau),$$

where A, B and $\Delta\tau$ are experimentally determined.

RMS Delay Spread

A delay spread model was proposed in [11] 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

$$\tau_{rms} = T_1\ d^{\varepsilon}\ y$$

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 [11]. However, these results are valid only for omnidirectional antennas. To account for antenna directivity, results reported in [10,12] can be used. It was shown that 32^o and 10^o directive antennas reduce the median τ_{rms} values for omnidirectional antennas by factors of 2.3 and 2.6, respectively.

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 (microseconds).

Fading Characteristics

Fade Distribution, K-Factor

The narrow band received signal fading 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 [13], 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 [14], an excellent agreement with the model was reported using an independent set of experimental data collected in San Francisco Bay Area at 2.4 GHz and similar antenna heights. The narowband 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 presented in [13] is as follows

$$K = F_s\, F_h\, F_b\, K_o\, d^{\gamma}\, u$$

where

F_s is a seasonal factor, F_s =1.0 in summer (leaves); 2.5 in winter (no leaves)

F_h is the receive antenna height factor, $F_h = (h/3)^{0.46}$; (h is the receive antenna height in meters)

F_b is the beamwidth factor, $F_b = (b/17)^{-0.62}$; (b in degrees)

K_o and γ are regression coefficients, $K_o = 10$; $\gamma = -0.5$

u is a lognormal variable which has zero mean and a std. deviation of 8.0 dB.

Using this model, one can observe that the K-factor decreases as the distance increases and as antenna beamwidth increases. We would like to determine K-factors that meet the requirement that 90% of all locations within a cell have to be services with 99.9% reliability. The calculation of K-factors for this scenario is rather complex since it also involves path loss, delay spread, antenna correlation (if applicable), specific modem characteristics, and other parameters that influence system performance. However, we can obtain an approximate value as follows: First we select 90% of the users with the highest K-factors over the cell area. Then we obtain the approximate value by selecting the minimum K-factor within the set. For a typical deployment scenario (see later section on SUI channel models) this value of K-factor can be close or equal to 0.

Figure 2 shows fading cumulative distribution functions (CDFs) for various K factors. For example, for K = 0 dB (linear K = 1) a 30 dB fade occurs 10^{-3} of the time, very similar to a Rayleigh fading case (linear K = 0). For a K factor of 6 dB, the probability of a 30 dB fade drops to 10^{-4}. The significance of these fade probabilities depends on the system design, for example whether diversity or retransmission (ARQ) is provided, and the quality of service (QoS) being offered.

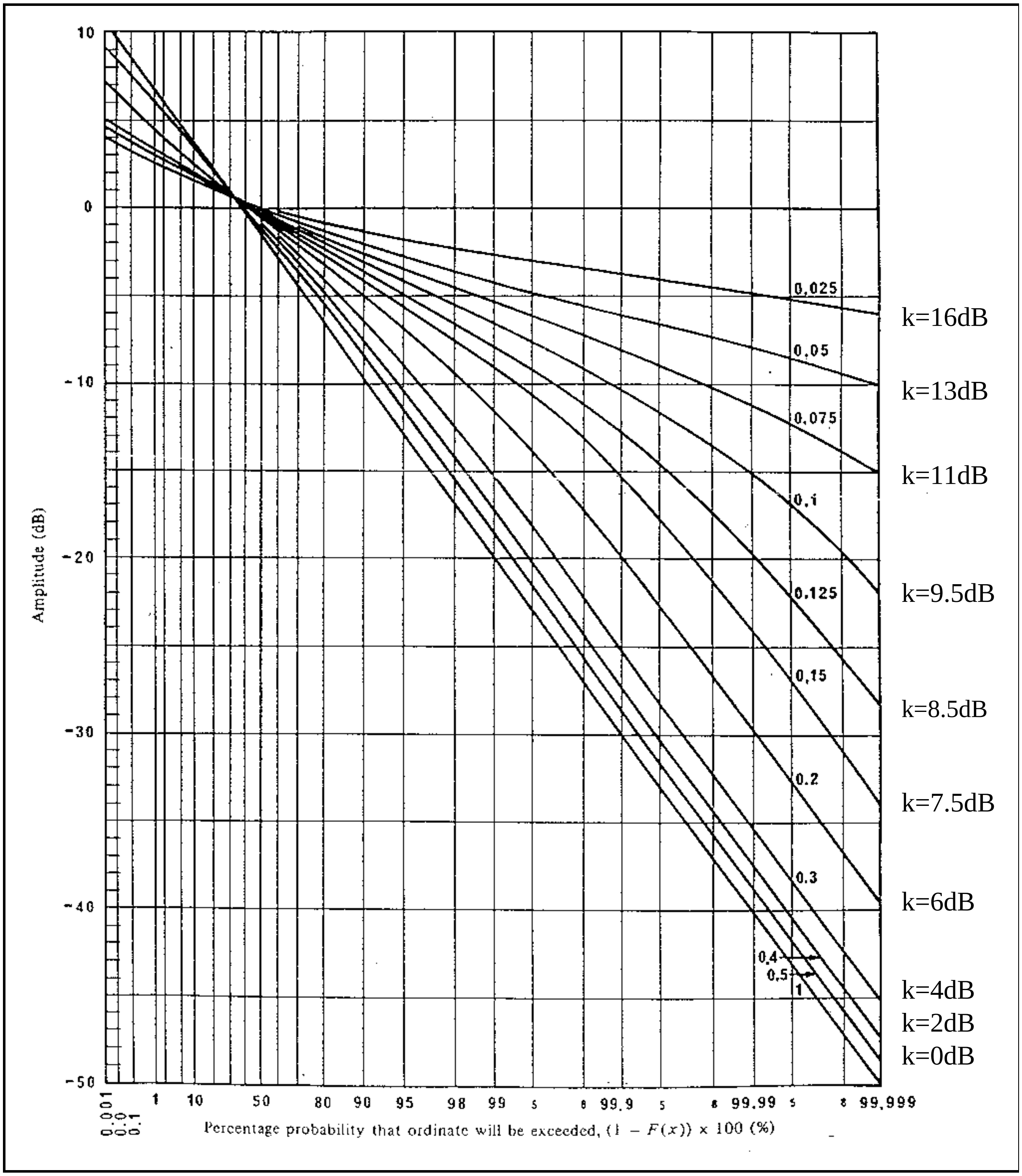


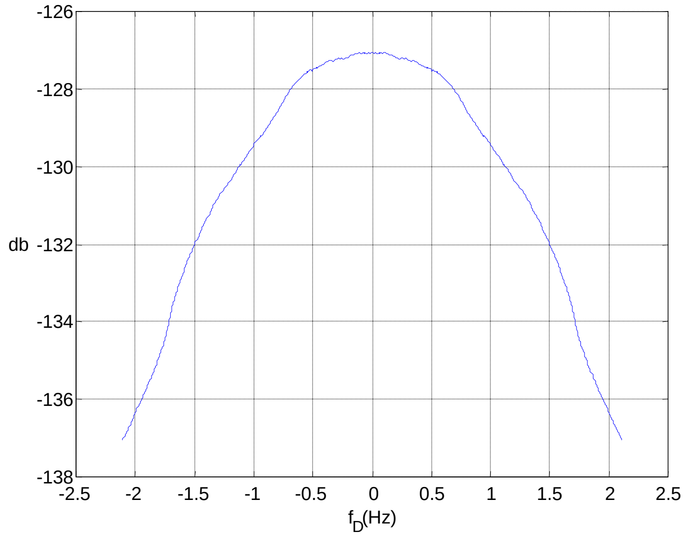
Figure 2. Ricean fading distributions.

Doppler Spectrum

Following the Ricean power spectral density (PSD) model in COST 207 [18], we define scatter and fixed Doppler spectrum components. In fixed wireless channels the Doppler PSD of the scatter (variable) component is mainly distributed around f = 0 Hz (Fig. 3a). The shape of the spectrum is therefore different than the classical Jake's spectrum for mobile channels. A rounded shape as shown in Fig. 3b can be used as a rough approximation to the Doppler PSD which has the advantage that it is readily available in most existing radio frequency (RF) channel simulators [17]. It can be approximated by:

$$S(f) = \begin{cases} 1 - 1.72 f_0^2 + 0.785 f_0^4 & |f_0| \le 1 \\ 0 & |f_0| > 1 \end{cases} \qquad \text{where} \quad f_0 = \frac{f}{f_m}$$

The function is parameterized by a maximum Doppler frequency f_m. Alternatively, the –3dB point can be used as a parameter, where f_{-3dB} can be related to f_m using the above equation. Measurements at 2.5 GHz center frequency show maximum f_{-3dB} values of about 2 Hz. A better approximation of fixed wireless PSD shapes are close to exponential functions [14]. Wind speed combined with foliage (trees), carrier frequency, and traffic influence the Doppler spectrum. The PSD function of the fixed component is a Dirac impulse at f = 0 Hz.



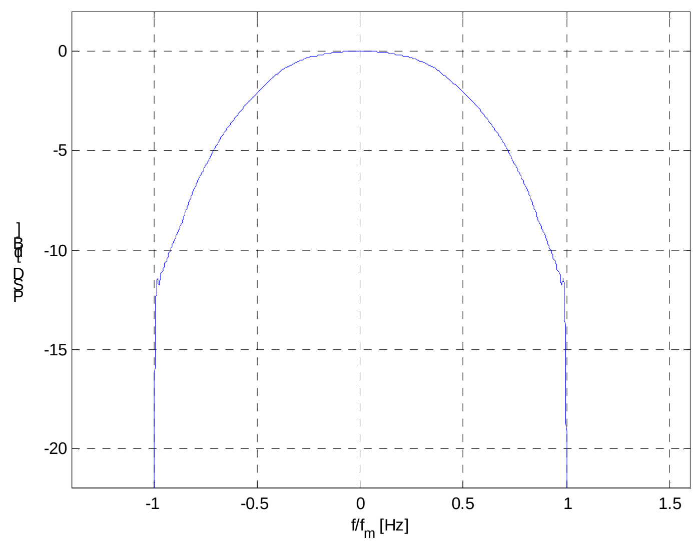


Figure 3. a) Measured Doppler spectrum at 2.5 Ghz center frequency (left)

b) Rounded Doppler PSD model (right)

Spatial Characteristics, Coherence Distance

Coherence distance is the minimum distance between points in space for which the signals are mostly uncorrelated. This distance is usually grater than 0.5 wavelengths, depending on antenna beamwidth and angle of arrival distribution. At the

BTS, it is common practice to use spacing of about 10 and 20 wavelengths for low-medium and high antenna heights, respectively (120^o sector antennas).

Co-Channel Interference

C/I calculations use a path loss model that accounts for median path loss and lognormal fading, but not for 'fast' temporal fading. In the example shown in Fig. 4, a particular reuse pattern has been simulated with r^2 or r^3 signal strength distance dependency, with apparently better C/I for the latter. However, for non-LOS cases, temporal fading requires us to allow for a fade margin. The value of this margin depends on the Ricean K-factor of the fading, the QoS required and the use of any fade mitigation measures in the system. Two ways of allowing for the fade margin then arise; either the C/I cdf is shifted left as shown below or the C/I required for a non-fading channel is increased by the fade margin. For example, if QPSK requires a C/I of 14 dB without fading, this becomes 24 dB with a fade margin of 10 dB.

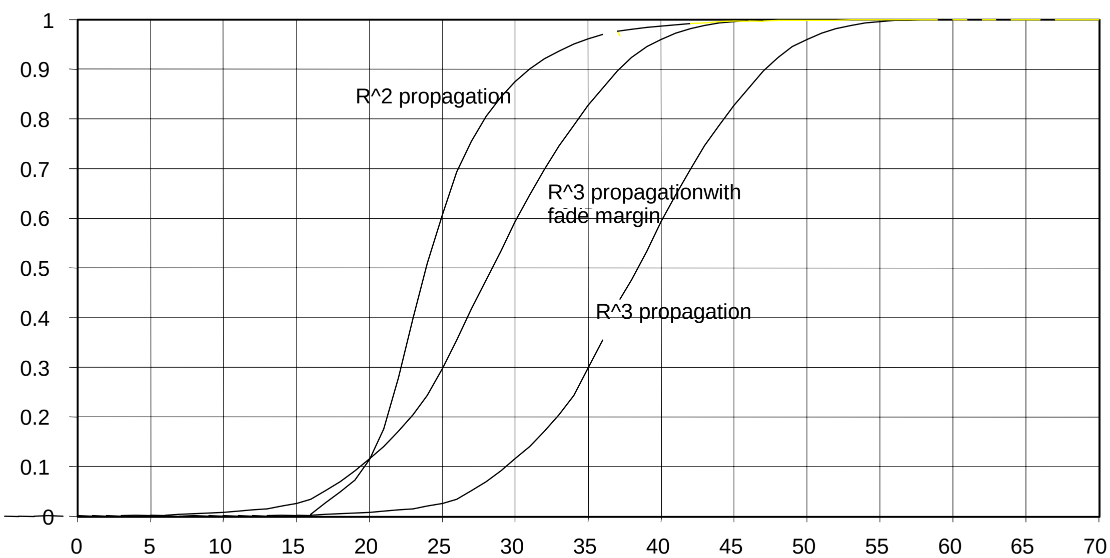


Figure 4. Effects of fade margin on C/I distributions.

Antenna Gain Reduction Factor

The use of directional antennas needs to be considered carefully. The gain due to the directivity can be reduced because of the scattering. The effective gain is less than the actual gain. This has been characterized in [15] as *Antenna Gain Reduction Factor* (GRF). This factor should be considered in the link budget of a specific receiver antenna configuration.

Denote ΔG_{BW} as the Gain Reduction Factor. This parameter is a random quantity which dB value is Gaussian distributed (truncated at 0 dB) with a mean (μ_{grf}) and standard deviation (σ_{grf}) given by

$$\mu_{grf} = - (0.53 + 0.1\ I) \ln (\beta/360) + (0.5 + 0.04\ I) (\ln (\beta/360))^2$$

$$\sigma_{grf} = - (0.93 + 0.02\ I) \ln (\beta/360),$$

β is the beamwidth in degrees

I = 1 for winter and I = -1 for summer

ln is the natural logarithm.

In the link budget calculation, if G is the gain of the antenna (dB), the effective gain of the antenna equals G - ΔG_{BW}. For example, if a 20-degree antenna is used, the mean value of ΔG_{BW} would be close to 7 dB.

In [12], a very good agreement was found with the model presented above, based on extensive measurements in a flat suburban area with base station antenna height of 43 m and receive antenna heights of 5.2, 10.4 and 16.5 m, and 10^o receive antenna beamwidth. By comparing Figs. 5 and 6 in the paper, one can observe about 10 dB median GRF (difference between the directional and omnidirectional antenna median path loss) for the 5.2 m receive antenna height and distances 0.5-10 km. However, for the 10.4 and 16.5 receive antenna heights the difference (GRF) is smaller, about 7. More experimental data and analysis is desirable to describe more accurately the effects of different antenna heights and terrain types on the GRF values.

In system level simulations and link budget calculations for high cell coverage, the standard deviation of the GRF can also be accounted for. For a 20^o antenna, the standard deviation σ_{grf} is approximately 3 dB. Furthermore, we can expect 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). In [8], a clear trend for the GRF to increase as the excess path loss over free space path loss increases was shown (see also Fig. 5 below). The correlation coefficient between GRF and excess path loss about median path loss (equivalent to shadow fading loss) was found to be 0.77. No significant distance dependency of the median GRF was found. (The correlation coefficient between GRF and distance was found to be 0.12.)

The combined shadow fading/GRF standard deviation σ_c can be calculated using the following formula

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

where ρ is the correlation coefficient and σ is the standard deviation of the lognormal shadow fading random variable s. For σ = 8 dB and σ_{grf} = 3 dB the formula yields σ_c of 8.5 and 10.5 dB for ρ = 0 and ρ = 0.77, respectively. Larger standard deviation results in a larger path loss margin for the 90% cell coverage (approximately 0.3 dB for ρ = 0 and 1.5 dB for ρ = 0.77).

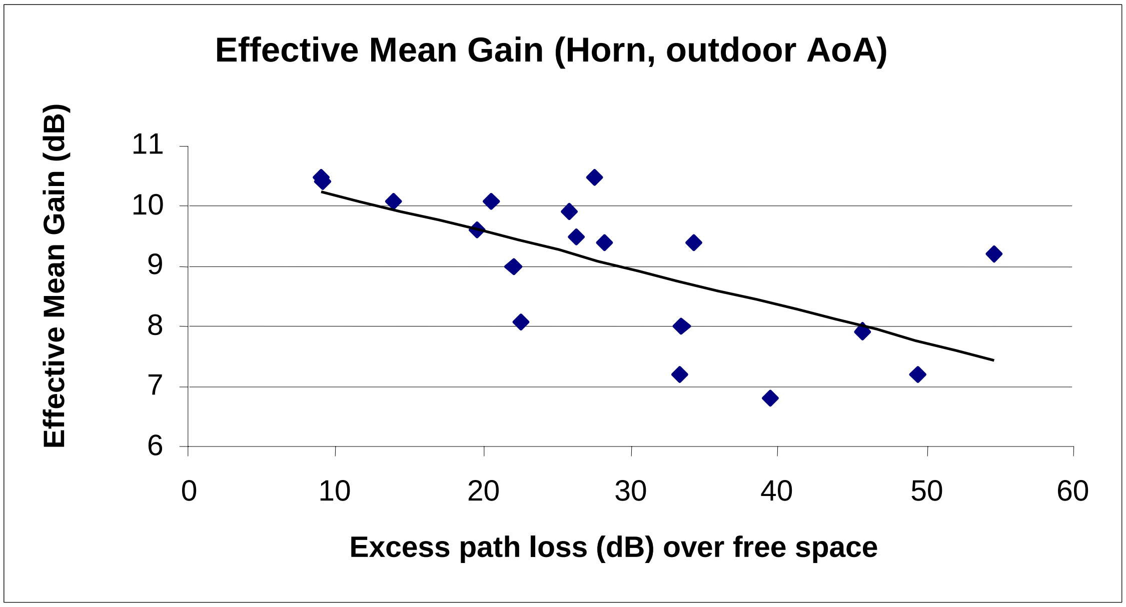


Figure 5. Effective mean (azimuth) gain for a 30-degree horn antenna.

For the results in Fig. 5, a BTS antenna height of 22 m was used, in a suburban area (Harlow, U.K.), in the summer. A 30^o subscriber antenna was used, raised to gutter height as near as possible to houses being examined. The antenna was rotated in 15 degree steps, and the effective gain calculated from the maximum signal compared to the average signal (signals averaged through any temporal fading). The peak gain was 10.4 dB (this only accounts for azimuthal directivity).

Multiple Antenna Channel Models (MIMO)

When multiple antennas are used at the transmitter and/or at the receiver, the relationships between transmitter and receiver antennas add further dimensions to the model. The channel can be characterized by a matrix.

Modified Stanford University Interim (SUI) Channel Models

Channel models described above provide the basis for specifying channels for a given scenario. It is obvious that there are many possible combinations of parameters to obtain such channel descriptions. A set of 6 typical channels was selected for the three terrain types that are typical of the continental US [4]. In this section we present SUI channel models that we modified to account for 30^{o} directional antennas. These models can be used for simulations, design, development and testing of technologies suitable for fixed broadband wireless applications. The parameters were selected based upon statistical models described in previous sections.

The parametric view of the SUI channels is summarized in the following tables.

Terrain Type	SUI Channels
C	SUI-1, SUI-2
B	SUI-3, SUI-4
A	SUI-5, SUI-6

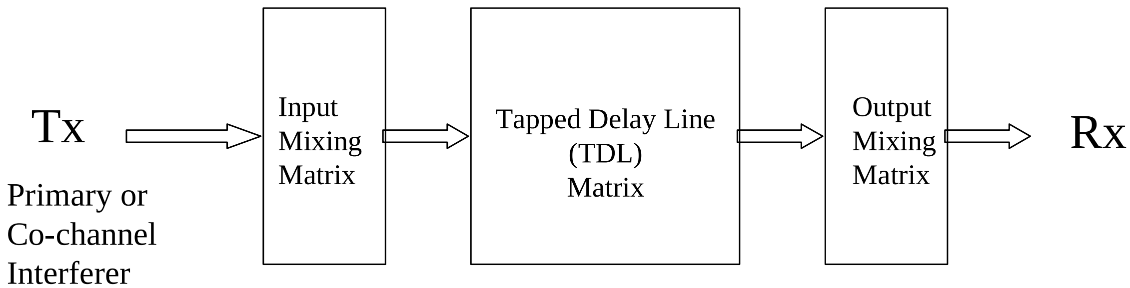
K-Factor: Low

Doppler	Low delay spread	Moderate delay spread	High delay spread
Low	SUI-3		SUI-5
High		SUI-4	SUI-6

K-Factor: High

Doppler	Low delay spread	Moderate delay spread	High delay spread
Low	SUI-1,2		
High			

The generic structure for the SUI Channel model is given below



The above structure is general for Multiple Input Multiple Output (MIMO) channels and includes other configurations like Single Input Single Output (SISO) and Single Input Multiple Output (SIMO) as subsets. The SUI channel structure is the same for the primary and interfering signals.

Input Mixing Matrix: This part models correlation between input signals if multiple transmitting antennas are used.

Tapped Delay Line Matrix: This part models the multipath fading of the channel. The multipath fading is modeled as a tapped-delay line with 3 taps with non-uniform delays. The gain associated with each tap is characterized by a distribution (Ricean with a K-factor > 0, or Rayleigh with K-factor = 0) and the maximum Doppler frequency.

Output Mixing Matrix: This part models the correlation between output signals if multiple receiving antennas are used.

Using the above general structure of the SUI Channel and assuming the following scenario, six SUI channels are constructed which are representative of the real channels.

Scenario for modified SUI channels:

- Cell size: 7 km
- BTS antenna height: 30 m

- Receive antenna height: 6 m
- BTS antenna beamwidth: 120°
- Receive Antenna Beamwidth: omnidirectional (360°) and 30 °.
  For a 30° antenna beamwidth, 2.3 times smaller RMS delay spread is used when compared to an omnidirectional antenna RMS delay spread [10]. Consequently, the 2nd tap power is attenuated additional 6 dB and the 3rd tap power is attenuated additional 12 dB (effect of antenna pattern, delays remain the same). For the omnidirectional receive antenna case, the tap delays and powers are consistent with the COST 207 delay profile models [18].
- Vertical Polarization only
- 90% cell coverage with 99.9% reliability at each location covered

For the above scenario, using the channel model, the following are the six specific SUI channels.

Notes:

1) The total channel gain is not normalized. Before using a SUI-X model, the specified normalization factors have to be added to each tap to arrive at 0dB total mean power (included in the tables).
2) The specified Doppler is the maximum frequency parameter (f_m) of the rounded spectrum, as described above.
3) The Gain Reduction Factor (GRF) is the total mean power reduction for a 30° antenna compared to an omni antenna. If 30° antennas are used the specified GRF should be added to the path loss. Note that this implies that all 3 taps are affected equally due to effects of local scattering.
4) K-factors have linear values, not dB values.
5) K-factors in the tables were rounded to the closest integer.
6) K-factors for the 90% and 75% cell coverage are shown in the tables, i.e. 90% and 75% of the cell locations have K-factors greater or equal to the K-factor value specified, respectively.

SUI – 1 Channel				
	Tap 1	**Tap 2**	**Tap 3**	**Units**

Delay	0	0.4	0.9	µs
Power (omni ant.) **90% K-fact. (omni)** **75% K-fact. (omni)**	0 4 20	-15 0 0	-20 0 0	dB
Power (30^o ant.) **90% K-fact. (30^o)** **75% K-fact. (30^o)**	0 16 72	-21 0 0	-32 0 0	dB
Doppler	0.4	0.3	0.5	Hz

Antenna Correlation: $\rho_{ENV} = 0.7$ **Gain Reduction Factor:** GRF = 0 dB **Normalization Factor:** F_{omni} = -0.1771 dB, $F_{30°}$ = -0.0371 dB	**Terrain Type:** C **Omni antenna:** τ_{RMS} = 0.111 µs, overall K: K = 3.3 (90%); K = 10.4 (75%) **30° antenna:** τ_{RMS} = 0.042 µs, overall K: K = 14.0 (90%); K = 44.2 (75%)

SUI – 2 Channel				
	Tap 1	**Tap 2**	**Tap 3**	**Units**
Delay	0	0.4	1.1	µs

Power (omni ant.) **90% K-fact. (omni)** **75% K-fact. (omni)**	0 2 11	-12 0 0	-15 0 0	dB
Power (30^o ant.) **90% K-fact. (30^o)** **75% K-fact. (30^o)**	0 8 36	-18 0 0	-27 0 0	dB
Doppler	0.2	0.15	0.25	Hz

Antenna Correlation: ρ_{ENV} = 0.5 **Gain Reduction Factor:** GRF = 2 dB **Normalization Factor:** F_{omni} = -0.3930 dB, $F_{30°}$ = -0.0768 dB	**Terrain Type:** C **Omni antenna:** τ_{RMS} = 0.202 µs, overall K: K = 1.6 (90%); K = 5.1 (75%) **30° antenna:** τ_{RMS} = 0.069 µs, overall K: K = 6.9 (90%); K = 21.8 (75%)

SUI – 3 Channel				
	Tap 1	**Tap 2**	**Tap 3**	**Units**
Delay	0	0.4	0.9	µs

Power (omni ant.) **90% K-fact. (omni)** **75% K-fact. (omni)**	0 1 7	-5 0 0	-10 0 0	dB
Power (30^o ant.) **90% K-fact. (30^o)** **75% K-fact. (30^o)**	0 3 19	-11 0 0	-22 0 0	dB
Doppler	0.4	0.3	0.5	Hz

Antenna Correlation: $\rho_{ENV} = 0.4$ **Gain Reduction Factor:** GRF = 3 dB **Normalization Factor:** $F_{omni} = -1.5113$ dB, $F_{30°} = -0.3573$ dB	**Terrain Type:** B **Omni antenna:** $\tau_{RMS} = 0.264$ µs, overall K: K = 0.5 (90%); K = 1.6 (75%) **30° antenna:** $\tau_{RMS} = 0.123$ µs, overall K: K = 2.2 (90%); K = 7.0 (75%)

SUI – 4 Channel

	Tap 1	Tap 2	Tap 3	Units
Delay	0	1.5	4	µs

Power (omni ant.) **90% K-fact. (omni)** **75% K-fact. (omni)**	0 0 1	-4 0 0	-8 0 0	dB
Power (30^o ant.) **90% K-fact. (30^o)** **75% K-fact. (30^o)**	0 1 5	-10 0 0	-20 0 0	dB
Doppler	0.2	0.15	0.25	Hz

Antenna Correlation: $\rho_{ENV} = 0.3$ **Gain Reduction Factor:** GRF = 4 dB **Normalization Factor:** $F_{omni} = -1.9218$ dB, $F_{30°} = -0.4532$ dB	**Terrain Type:** B **Omni antenna:** $\tau_{RMS} = 1.257$ µs overall K: K = 0.2 (90%); K = 0.6 (75%) **30° antenna:** $\tau_{RMS} = 0.563$ µs overall K: K = 1.0 (90%); K = 3.2 (75%)

SUI – 5 Channel				
	Tap 1	**Tap 2**	**Tap 3**	**Units**
Delay	0	4	10	µs

Power (omni ant.) **90% K-fact. (omni)** **75% K-fact. (omni)**	0 0 0	-5 0 0	-10 0 0	dB
Power (30^o ant.) **90% K-fact. (30^o)** **75% K-fact. (30^o)**	0 0 2	-11 0 0	-22 0 0	dB
Doppler	2	1.5	2.5	Hz

Antenna Correlation: $\rho_{ENV} = 0.3$ **Gain Reduction Factor:** GRF = 4 dB **Normalization Factor:** $F_{omni} = -1.5113$ dB, $F_{30°} = -0.3573$ dB	**Terrain Type:** A **Omni antenna:** $\tau_{RMS} = 2.842$ µs overall K: K = 0.1 (90%); K = 0.3 (75%) **30° antenna:** $\tau_{RMS} = 1.276$ µs overall K: K = 0.4 (90%); K = 1.3 (75%)

SUI – 6 Channel				
	Tap 1	**Tap 2**	**Tap 3**	**Units**
Delay	0	14	20	µs

Power (omni ant.) **90% K-fact. (omni)** **75% K-fact. (omni)**	0 0 0	-10 0 0	-14 0 0	dB
Power (30^o ant.) **90% K-fact. (30^o)** **75% K-fact. (30^o)**	0 0 2	-16 0 0	-26 0 0	dB
Doppler	0.4	0.3	0.5	Hz

Antenna Correlation: $\rho_{ENV} = 0.3$ **Gain Reduction Factor:** GRF = 4 dB **Normalization Factor:** F_{omni} = -0.5683 dB, $F_{30°}$ = -0.1184 dB	**Terrain Type:** A **Omni antenna:** τ_{RMS} = 5.240 µs overall K: K = 0.1 (90%); K = 0.3 (75%) **30° antenna:** τ_{RMS} = 2.370 µs overall K: K = 0.4 (90%); K = 1.3 (75%)

Optional Six Path Models

In order to account for the effects of local scattering and an additional further away scatterer, three more taps can be added the three path channel models described above.

We recommend the following delays and powers for the additional three Rayleigh fading paths:

	Path 4	Path 5	Path 6

Delay (μs)	Path 1 + 0.2 μs	Path 2 + 0.6 Path 2 (SUI1-5) Path 2 + 1.0 μs (SUI6)	Path 3 + 0.3 μs
Power (dB)	Path 1 – 3 dB	Path 2 – 2 dB	Path 3 – 3 dB
K-factor	0	0	0

Note that the additional paths will result in different K-factors, normalization factors, and τ_{RMS} values than for the three path models. However, the change will not be substantial.

Extension of Models to Other Frequencies

We expect that the proposed statistical models for delay spread, K-factor, and GRF can be "safely" used in the 1 – 4 GHz range (half and double frequency for which the models were derived). With appropriate frequency correction factors, path loss models can be also used in the extended frequency range [6]. However, the Doppler spectrum is a function of the center frequency and more work is required in this area.

Conclusion

The paper presents a set of channel models for fixed broadband wireless systems using macrocellular architecture. The path loss models and multipath fading models are presented. Based on these models six 3-tap channel models have been proposed which cover the diverse terrain types.

References

[1] Y. Okumura, E. Ohmori, T. Kawano, and K. Fukua, "Field strength and its variability in UHF and VHF land-mobile radio service," *Rev. Elec. Commun. Lab*., vol. 16, no. 9, 1968.

[2] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE Trans. Veh. Technol*., vol. 29, pp. 317-325, Aug. 1980.

[3] EURO-COST-231 Revision 2, "Urban transmission loss models for mobile radio in the 900 and 1800 MHz bands," Sept. 1991.

[4] V. Erceg et. al, “An empirically based path loss model for wireless channels in suburban environments,” *IEEE JSAC*, vol. 17, no. 7, July 1999, pp. 1205-1211.

[5] T.-S. Chu and L.J. Greenstein, “A quantification of link budget differences between the cellular and PCS bands,” *IEEE Trans. Veh. Technol.*, vol. 48, no. 1, January 1999, pp. 60-65.

[6] W.C. Jakes and D.O. Reudink, “Comparison of mobile radio transmission at UHF and X-band,” *IEEE Trans. Veh. Technol.*, vol. VT-16, pp. 10-13, Oct. 1967.

[7] K.V. S. Hari, K.P. Sheikh, and C. Bushue, “Interim channel models for G2 MMDS fixed wireless applications,” *IEEE 802.16.3c-00/49r2*

[8] M.S. Smith and C. Tappenden, “Additional enhancements to interim channel models for G2 MMDS fixed wireless applications,” *IEEE 802.16.3c-00/53*

[9] M.S. Smith, J.E.J. Dalley, “A new methodology for deriving path loss models from cellular drive test data”, *Proc. AP2000 Conference*, Davos, Switzerland, April 2000.

[10] V. Erceg et.al, “A model for the multipath delay profile of fixed wireless channels,” *IEEE JSAC*, vol. 17, no.3, March 1999, pp. 399-410.

[11] L.J. Greenstein, V. Erceg, Y.S. Yeh, and M.V. Clark, “A new path-gain/delay-spread propagation model for digital cellular channels,” *IEEE Trans. Veh. Technol.*, vol. 46, no. 2, May 1997.

[12] J.W. Porter and J.A. Thweatt, “Microwave propagation characteristics in the MMDS frequency band,” *ICC’2000 Conference Proceedings*, pp. 1578-1582.

[13] L.J. Greenstein, S. Ghassemzadeh, V.Erceg, and D.G. Michelson, “Ricean K-factors in narrowband fixed wireless channels: Theory, experiments, and statistical models,” *WPMC’99 Conference Proceedings*, Amsterdam, September 1999.

[14] D.S. Baum et.al., “Measurements and characterization of broadband MIMO fixed wireless channels at 2.5 GHz”, *Proceedings of ICPWC’2000*, Hyderabad, Dec. 2000.

[15] L. J. Greenstein and V. Erceg, “Gain reductions due to scatter on wireless paths with directional antennas,” *IEEE Communications Letters*, Vol. 3, No. 6, June 1999.

[16] V. Erceg, “Channel models for broadband fixed wireless systems,” *IEEE 802.16.3c-00/53*

[17] TAS 4500 RF Channel Emulator, Operations Manual

[18] "Digital Land Mobile Radio Communications - COST 207", Commission of the European Communities, Final Report, 14 March, 1984--13 September, 1988, Office for Official Publications of the European Communities, Luxembourg, 1989.

Appendix A

COST 231 WALFISCH-IKEGAMI MODEL

This model can be used for both urban and suburban environments. There are three terms which make up the model:

$$L_b = L_0 + L_{rts} + L_{msd}$$

L_0 = free space loss
L_{rts} = roof top to street diffraction
L_{msd} = multi-screen loss

free space loss :

$$L_0 = 32.4 + 20\log\left(\frac{R}{km}\right) + 20\log\left(\frac{f}{MHz}\right)$$

roof top to street diffraction

$$L_{rts} = -16.9 - 10\log\left(\frac{w}{m}\right) + 10\log\left(\frac{f}{MHz}\right) + 20\log\left(\frac{\Delta h_{mobile}}{m}\right) + L_{ori} \quad \text{for } h_{roof} \rangle h_{mobile}$$

$$= 0 \quad \text{for } L_{rts} < 0$$

where

$$L_{ori} = -10 + 0.354\frac{\varphi}{deg} \quad \text{for } 0 \le \varphi \le 35 \text{ deg}$$

$$= 2.5 + 0.075\left(\frac{\varphi}{deg} - 35\right) \quad \text{for } 35 \le \varphi \le 55 \text{ deg}$$

$$= 4.0 - 0.114\left(\frac{\varphi}{deg} - 55\right) \quad \text{for } 55 \le \varphi \le 90 \text{ deg}$$

and $\Delta h_{mobile} = h_{roof} - h_{mobile}$

The multi-screen diffraction loss

$$L_{msd} = L_{beh} + k_a + k_d \log\left(\frac{R}{km}\right) + k_f \log\left(\frac{f}{MHz}\right) - 9\log\left(\frac{b}{m}\right)$$

$$= 0 \quad \text{for } L_{msd} < 0$$

$$L_{beh} = -18 Log(1 + \frac{\Delta h_{base}}{m}) \quad \text{for } h_{base} \rangle h_{roof}$$

$$= 0 \quad \text{for } h_{base} \leq h_{roof}$$

$$k_a = 54 \quad \text{for } h_{base} \rangle h_{roof}$$

$$= 54 - 0.8\frac{\Delta h_{base}}{m} \quad \text{for } R \geq 0.5\text{km and } h_{base} \leq h_{roof}$$

$$= 54 - 0.8\frac{\Delta h_{base}}{m}\frac{R/km}{0.5} \quad \text{for } R < 0.5\text{km and } h_{base} \leq h_{roof}$$

$$k_d = 18 \quad \text{for } h_{base} \rangle h_{roof}$$

$$= 18 - 15\frac{\Delta h_{base}}{h_{roof}} \quad \text{for } h_{base} \leq h_{roof}$$

$$k_f = -4 + 0.7\left(\frac{f/MHz}{925} - 1\right)$$ for medium sized cities and suburban centres with moderate tree density.

$$= -4 + 1.5\left(\frac{f/MHz}{925} - 1\right)$$ for metropolitan centres.

Note that $\Delta h_{base} = h_{base} - h_{roof}$

This model is limited by the following parameter ranges:

f : 800....2,000MHz,

h base : 4....50m,

h mobile: 1....3m

R : 0.02.....5km

Hata correction term in COST 231 W-I model to account for mobile height variation

Comparison with some measurements made by Nortel in 1996 for a base antenna deployed in Central London well above the average rooftop height revealed that the COST 231 W-I model did not correctly model the variation of path loss with mobile height. In contrast, the COST 231 Hata model did show the correct trend, which is not surprising, since it is an empirically derived model based on the very extensive measurement data of Okumura. Consequently, a Hata correction term has been added to the COST 231 W-I model to account for path loss variations with mobile height. However, the Hata correction term simply added to the COST 231 W-I model results in a path loss variation with mobile height that is greater than that of the Hata model. This is because it adds to the variation that exists already in the COST 231 W-I model. In the COST 231 W-I model the path loss variation due to mobile height is governed by the following term:

$$20\log\left(h_{roof} - h_{mobile}\right)$$

Here the Hata correction term is made to be zero at a mobile height of 3.5m. Retaining this, a new correction term is proposed as follows :

$$a(h_m) = -\left[\left(1.1\log\left(\frac{f}{MHz}\right) - 0.7\right)h_{mobile} - \left(1.56\log\left(\frac{f}{MHz}\right) - A\right) + 20\log\left(h_{roof} - h_{mobile}\right) - 20\log\left(h_{roof} - 3.5\right)\right]$$

where

$$A = 1.56\log\left(\frac{f}{MHz}\right) - \left(1.1\log\left(\frac{f}{MHz}\right) - 0.7\right)3.5$$

The term $a(h_m)$ is the correction factor and ensures that the COST 231 W-I model has the same path loss variation with mobile height as the COST 231 Hata model.