IV. Propagation Characteristics Observed in Macro / Micro Cells

- Ray model of multipath propagation
- Effects caused by multipath for narrowband (CW) signals
- Shadow fading
- Range dependence in macrocells and microcells
Direct Observation of Multipath at the Mobile and at the Base Station

• Direction of arrival measurements at the mobile
• Time delay measurements
• Measurement of space-time rays
• Ray model of propagation
Angles of Arrival at a Street Level
- CW Measurement at 900 MHz in Tokyo using 22° spot beam antenna -

From base station

Rows of buildings

Mobile locations along street

Received signal versus azimuth for various elevations

Rays come in clusters that decay rapidly. Successive clusters have lower amplitudes.


Delay Spread for Continuous Time Signals

Mean Excess Delay

\[ T_0 = \frac{\int_0^\infty tP(t)dt}{\int_0^\infty P(t)dt} \]

RMS Delay Spread

\[ \tau_{RMS}^2 = \frac{\int_0^\infty (t - T_0)^2 P(t)dt}{\int_0^\infty P(t)dt} \]

CDF of $t_{\text{RMS}}$ for Outdoor Links

- Measured at 1800 MHz for many subscriber location in Sweden
- Signals received at base station by horizontal and vertical antennas for vertical subscriber antenna

RMS delay spread somewhat larger in urban areas than in suburban areas.

Co and cross Polarization have nearly the same RMS delay.

RMS delay of the average power delay profile is approximately the same as the mean RMS delay spread.

Greenstein Model of Measured DS in Urban and Suburban Areas

\[ DS = T_{1km} \sqrt{R_{km} \xi} \]

where \( T_{1km} \) is 0.3 - 1.0 \( \mu s \) and 
\[ 10\log \xi \]

is a Gaussian random variable with standard deviation 2 - 6

Space-Time Rays Measured at Street Level
- 890 MHz Measurement in Paris -

- Azimuth and time delay of arriving rays

- Measured with system having 0.1 μs time resolution

- Street runs North and South

- Many rays arrive along the street direction

Space-Time Rays at an Elevated Base Station
- 1800 MHz measurements in Aalborg, Denmark -

- Rays arrive at base station from a limited range of angles

- Rays are grouped into clusters

- Time delay between clusters ~ 1 µs, representing scattering from more distant buildings

- Time delay within a cluster ~ 100 µs

Delay Spread (DS) and Angle Spread (AS) for Discrete Arrivals

From mth ray from the jth mobile

\[ A_m^{(j)} = \text{amplitude} \]
\[ \tau_m^{(j)} = \text{arrival time delay} \]
\[ \phi_m^{(j)} = \text{angle of arrival at base station (measured from direction to mobile)} \]

**Delay Spread**

\[
DS^{(j)} = \sqrt{\frac{\sum_m |A_m^{(j)}|^2 \left( \tau_m^{(j)} - \overline{\tau_m^{(j)}} \right)^2}{\sum_m |A_m^{(j)}|^2}} \\
\text{where } \overline{\tau_m^{(j)}} = \frac{\sum_m |A_m^{(j)}|^2 \tau_m^{(j)}}{\sum_m |A_m^{(j)}|^2}
\]

**Angle Spread** (approximate expression for small spread)

\[
AS^{(j)} = \sqrt{\frac{\sum_m |A_m^{(j)}|^2 \left( \phi_m^{(j)} - \overline{\phi_m^{(j)}} \right)^2}{\sum_m |A_m^{(j)}|^2}} \\
\text{where } \overline{\phi_m^{(j)}} = \frac{\sum_m |A_m^{(j)}|^2 \phi_m^{(j)}}{\sum_m |A_m^{(j)}|^2}
\]
Coordinate Invariant Method for Computing AS

Coordinate invariant method:

Ray arrival angle $\phi_n$ measured from any x-axis

Define the vector: $u_n = (a_x \cos \phi_n + a_y \sin \phi_n)$

$$AS = \left(\frac{180}{\pi}\right)\sqrt{\sum_n |u_n - \overline{U}|^2 A_n^2 / \sum_n A_n^2} = \left(\frac{180}{\pi}\right)\sqrt{\left(1 - \overline{U}^2\right)}$$

where $\overline{U} = \sum_n (u_n) A_n^2 / \sum_n A_n^2$
CDF of RMS Angle Spreads

- Measured at 1800 MHz for many subscriber locations in Sweden
- Signals received at base station by horizontal and vertical antennas for vertical subscriber antenna

RMS angle spread is larger in urban areas than in suburban areas.

Co- and cross polarization have nearly the same RMS angle spread.

Ray Model for Street Level Mobiles

Rays arrive from all directions in the horizontal plane and up to 45° in the vertical direction.

Ray paths shown for propagation from base station to subscriber. Reverse directions of arrows for propagation from subscriber to base station.

\[ \Delta L \approx 30 \, \text{m} \]
\[ \Delta t \approx 100 \, \text{ns} \]

\[ \Delta L \approx 3 \, \text{km} \]
\[ \Delta t \approx 10 \, \mu \text{s} \]
Ray Model of Received Voltage and Power

Complex received voltage envelope at position $x$ along the street

$$V(x)e^{j\psi(x)} = \sum_n A_n e^{-jkL_n} e^{j\phi_n}$$

where

$A_n =$ amplitude of the ray contribution
$L_n =$ path length of ray
$\phi_n =$ additional phase changes upon reflection, scattering

$$k = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$$

Received power

$$P_R(x) = \left| V(x)e^{j\psi(x)} \right|^2 = \sum_n \sum_m A_n A_m e^{j(\phi_n-\phi_m)} e^{-jk(L_n-L_m)}$$
Ray Fields Are Locally Like Plane Waves

For narrow bundle of rays, \( A_n \) and \( \phi_n \) are approximately constant over a distance of several wave lengths. Over a small region of space the phase front is approximately a plane perpendicular to the direction \( \vec{v}_n \) of the central ray.
Relation to Plane Wave Interference

Phase variation for small displacement $s$ about a location $x$, is approximately that of a plane wave

$$kL_n(x + s) \approx kL_{n0} + (k\nu_n) \cdot (s\alpha_x) = kL_{n0} + ks(\nu_n)_x$$

where $(\nu_n)_x$ is the $x$ component of the unit vector $\nu_n$ and $kL_{n0}$ is the phase of the central ray

Received voltage is then

$$V(x)e^{j\psi(x)} = \sum_n A_n e^{j(\phi_n - kL_{n0})} \exp[-jks(\nu_n)_x]$$

This expression is like that found for plane waves having complex amplitude $A_n e^{j(\phi_n - kL_{n0})}$ and $(\nu_n)_x = \cos \theta_n$
Small Area Average Power

Received power \( P_R(x) = |V(x)e^{j\psi(x)}|^2 = \sum \sum A_n A_m e^{j(\phi_n-\phi_m)} e^{-jk(L_n-L_m)} \)

The spatial average \( \langle P_R(x) \rangle \) of the power over \( x \) is

\[
\frac{1}{2W} \int_{-W}^{W} P_R(x+s)ds = \\
\sum \sum A_n A_m e^{j(\phi_n-\phi_m)} e^{-jk(L_n0-L_m0)} \frac{1}{2W} \int_{-W}^{W} \exp[-jks(\nu_n-\nu_m)_x]ds
\]

Provided \( 2W > 1/k(\nu_n-\nu_m)_x \) for \( n \neq m \), \( \frac{1}{2W} \int_{-W}^{W} \exp[-jks(\nu_n-\nu_m)_x]ds \approx 0. \)

Hence \( \frac{1}{2W} \int_{-W}^{W} \exp[-jks(\nu_n-\nu_m)_x]ds \approx \delta_{n,m} \) and \( \langle P_R(x) \rangle = \sum A_n^2 \)

Thus the spatial average power is equal to the sum of the ray powers.
Summary of the Ray Model of Propagation

- Propagation to or from the mobile can take place along multiple paths (rays)
- Multiple rays give RMS delay spreads $\sim 0.5$ $\mu$s at $R = 1$ km
- Rays arrive at the mobile from all directions in the horizontal plane, and up to 45° in the vertical plane
- Rays at the base station arrive in a wedge of width $\sim \pm 10^\circ$
- Interference effects of multipath contributions over distances $\sim$ 10 m are like those of plane waves
Effects Caused by Multipath for CW Excitation

- Fast fading at street level
- Correlation at mobile and base station
- Other effects
  - Doppler spread
  - Slow time fading
  - Cross polarization coupling
Multipath Arrivals Set Up a Standing Wave Pattern in Space
Interference Effects of Multiple Rays

\[ V(x) = \left| \sum_n A_n e^{-jkL_n} e^{j\phi_n} \right| = \left\{ \sum_n \sum_m A_n A_m e^{j(\phi_n - \phi_m)} e^{-jk(L_n - L_m)} \right\}^{1/2} \]

Scattered rays coming from all directions result in:

1. Spatial fading - as subscriber moves a distance \( \Delta x \sim \lambda \),
   the phases \( k(L_n - L_m) \) change by \( \sim 2\pi \)

2. Doppler spread - a subscriber moving with velocity \( u \) sees
   an apparent frequency changes \( \nu = \frac{1}{2\pi} k \frac{d}{dt} L_n = \frac{u \cos \theta}{\lambda} \)

3. Frequency fading - the phase \( k(L_n - L_m) = (\omega/c)(L_n - L_m) \)
   changes with frequency

4. Slow time fading - moving scatterers change some \( L_n \)'s
Received Signal as Omni Antenna Moves Through Standing Wave Pattern

- Rapid Fluctuation of 20dB or more
- Separations between minima ~ 0.2 m
- Wavelength at 910 MHz is $\lambda = 0.33$ m
- Slow fluctuation of the small area average

Small area average

$$\bar{V}(x) = \frac{1}{L} \int_{-L/2}^{L/2} V(x + s) ds$$

Define the random variable
\[ r = \frac{V(x)}{\overline{V}(x)} \]

For line-of-sight (LOS) paths, \( r \) is approximately Rician

For non-LOS paths, \( r \) is approximately Rayleigh
Complex Autocorrelation Function

Measures the degree to which the signal $V(x)e^{j\psi(x)}$ received at one antenna is predicted by the signal $V(x-s)e^{j\psi(x-s)}$ received at a second antenna separated by a distance $s$.

Ergodic assumption: Statistical dependence over different embodiments is same as averaging over many locations $x$.

For complex signals

$$C(s) = \left\{ \frac{1}{2W} \int_{-W}^{W} V(x)e^{j\psi(x)}V(x-s)e^{-j\psi(x-s)}\,dx \right\} \Bigg/ \left\{ \frac{1}{2W} \int_{-W}^{W} [V(x)]^2 \,dx \right\}$$

where $2W >> \lambda$ is the correlation window, assumed to be centered at $x = 0$. 
Autocorrelation Function for Ray Fields

If the voltage is the sum of ray fields

\[ V(x)e^{j\psi(x)} = \sum_n A_n e^{-jkL_n(x)} e^{j\phi_n} \]

Over distances of 10 - 20\(\lambda\), we may approximate \(L_n(x) \approx L_{n0} + x(\nu_n)_x\). Then

\[
\frac{1}{2W} \int_{-W}^{W} V(x)e^{j\psi(x)}V(x-s)e^{-j\psi(x-s)}\,dx =
\]

\[
= \sum_n \sum_m A_n A_m e^{j(\phi_n - \phi_m)} e^{-jk(L_{n0} - L_{m0})} \exp\left(-jks(\nu_n - \nu_m)_x\right) \left\{ \frac{1}{2W} \int_{-W}^{W} \exp[-jks(\nu_n - \nu_m)_x]\,dx \right\}
\]

\[
\approx \sum_n \sum_m A_n A_m e^{j(\phi_n - \phi_m)} e^{-jk(L_{n0} - L_{m0})} \exp\left(-jks(\nu_n - \nu_m)_x\right) \left\{ \delta_{nm} \right\} = \sum_n A_n^2 e^{-jks(\nu_n)_x}
\]

Similarly

\[
\frac{1}{2W} \int_{-W}^{W} [V(x)]^2\,dx \approx \sum_n A_n^2
\]

so that

\[
C(s) = \sum_n A_n^2 e^{-jks(\nu_n)_x} \bigg/ \sum_n A_n^2
\]
C(s) Measured Street Level

Measurements made at
f = 821 MHz
λ = 0.365 m

Signal de-correlated
after s > λ /4

Correlation at Elevated Base Station

Ray theory for small $\theta_M$:

$$|C(s)| \approx \left| \frac{\sin(ks\theta_M \sin \alpha)}{ks\theta_M \sin \alpha} \right|$$

For $\alpha \to 0$, $|C(s)| \to 1$

For $\alpha = 90^\circ$

$$|C(s)| \approx \left| \frac{\sin(k s \theta_M)}{k s \theta_M} \right|$$

has first zero at

$$s = \frac{\lambda}{2 \theta_M}$$

If $\theta_M = 5^\circ = \pi/36$ rad

then $s = 6\lambda$

---

Measured at 900 MHz in Liverpool, England

Summary of Fading at Both Ends of Link for an Elevated Base Station

Elevated Base Station

Mobile in Clutter

Signal
Measured Doppler Spread

\[ f = 1800 \text{ MHz} \]

Frequency Fading Due to Multipath  
(910 MHz in Toronto)

Individual terms in the expression for $V(x)$ go through $2\pi$ phase change for frequency changes $\Delta f$ satisfying

$$\frac{2\pi\Delta f}{c}(L_i - L_j) = 2\pi$$

solving for $\Delta f$

$$\Delta f = \frac{c}{(L_i - L_j)}$$

For differences in path length $(L_i - L_j) \approx 1.2$ km

$\Delta f = 0.25$ MHz

Slow Time Fading Measured by a Stationary Subscriber (900 MHz)

For a wave incident on a moving scatterer at angle $\theta$ relative to the velocity $u$ of the scatterer, the scattered wave will undergo $2\pi$ phase change in time such that $u\Delta t \sim \lambda$.

At walking speed $u = 1$ m/s, and at 900 MHz, $\Delta t \sim 0.33$ sec.

Local Scattering Produces Cross-Polarization
Cross Polarization Coupling Measured at Base Stations in Sweden

Measured ratios of the sector average power received in the horizontal and vertical polarized fields (H/V) at 1800 MHz.

The error limits represent one standard deviation.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Mobile configuration</th>
<th>Horizontal-to-vertical power ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kungsholmen, urban</td>
<td>Roof-mounted</td>
<td>-7 ± 2</td>
</tr>
<tr>
<td></td>
<td>Portable, outdoors</td>
<td>-4 ± 2</td>
</tr>
<tr>
<td></td>
<td>Portable, inside van</td>
<td>-3 ± 2</td>
</tr>
<tr>
<td></td>
<td>Portable, indoors</td>
<td>-1 ± 4</td>
</tr>
<tr>
<td>Kista, suburban</td>
<td>Roof-mounted</td>
<td>-8 ± 2</td>
</tr>
<tr>
<td></td>
<td>Portable, outdoors</td>
<td>-2 ± 1</td>
</tr>
<tr>
<td></td>
<td>Portable, inside van</td>
<td>-1 ± 1</td>
</tr>
<tr>
<td></td>
<td>Portable, indoors</td>
<td>-3 ± 1</td>
</tr>
<tr>
<td>Veddesta, suburban</td>
<td>Roof-mounted</td>
<td>-13 ± 1</td>
</tr>
<tr>
<td></td>
<td>Portable, outdoors</td>
<td>-6 ± 1</td>
</tr>
<tr>
<td></td>
<td>Portable, inside van</td>
<td>-7 ± 1</td>
</tr>
<tr>
<td></td>
<td>Portable, indoors</td>
<td>-7 ± 1</td>
</tr>
</tbody>
</table>

Lotse, et al., "Base Station Polarization Diversity Reception in Macrocellular Systems at 1800 MHz", Proc. VTC 96, pp. 1643 - 1646
Cross Correlation of Complex and Real Signals

Cross correlation of two complex functions with zero mean

\[ C_R = \frac{E\{U(x)V^*(x)\}}{\sqrt{E\{|U(x)|^2\} E\{|V(x)|^2\}}} \]

Cross correlation of two real functions with non-zero mean

\[ C_R = \frac{E\left\{\left[U(x) - \langle U(x)\rangle\right]\left[V(x) - \langle V(x)\rangle\right]\right\}}{\sqrt{E\left\{|U(x) - \langle U(x)\rangle|^2\} E\left\{|V(x) - \langle V(x)\rangle|^2\}\right\}}} \]

\( E\{\bullet\} \) is the expectation value or average.
Fast Fading Patterns of Horizontal and Vertical Polarization Are Uncorrelated

Cross correlations of the signals received by horizontally and vertically polarized base station antennas for a roof mounted mobile antenna. Integration taken as the mobile travels over a travel distance $2W = 10\lambda$.

Summary of Multipath Effects

• Multipath arrivals set up a standing wave pattern in space that is perceived as fast fading by a moving mobile
• Fast fading approximates Rayleigh statistics on Non-LOS links
• Interference patterns have correlation length of \( \lambda/4 \) at the mobile, and \( 6\lambda \) or greater at an elevated base station
• Multipath causes frequency fading, Doppler spread and slow time fading
• The scattering processes that create multipath also cause depolarization of the waves
Statistical Properties of the Shadow Fading

- Separating the shadow fading from fast fading and range dependence
- Statistical distribution of shadow fading
- Correlation distance of shadow fading
- Correlation of shadow fading for signals from different base stations
How to Find Shadow Fading From Drive Test Measurements

- Drive tests conducted over many small areas of length > 20λ at different distances R from base station
- Find $U_k(R) = 10\log \langle V(x)^2 \rangle$ for each small area $k = 1, 2, ...$
- Plot $U_k(R)$ versus log $R$ and fit data with a least squares line having dependence of the form

$$\overline{U}_{LS}(R) = 10\log A - 10n\log R$$

- For each sector compute $U_k(R) - \overline{U}_{LS}(R)$. For the resulting set of numbers form the distribution function

$$P\left(U_k(R) - \overline{U}_{LS}(R)\right)$$

- The distribution function is typically found to be Gaussian
Separating Shadow Fading from Range Dependence

Small area average power plotted versus log\(R\)

\[ \bar{U}_{LS} = 10\log P_T + 10\log A - n10\log R \]

corresponds to power law

\[ P = P_T A / R^n \]

Small Area Average
CDF of Shadow Fading Measured Simultaneously at Two Frequencies (955 MHz and 1845 MHz)

Fading distributions of small area averages normalized to Standard deviation $\sigma$ for:

Small area averages $\sigma$

| $U_k(955)$ | 8.0dB |
| $U_k(1845)$ | 8.1dB |

Difference  Mean $\sigma$

| $U_k(955)$ | 10.5 | 3.3dB |
| $- U_k(1845)$ | |

Straight line plots for distorted scale indicate that $(U_k - \bar{U}_{LS})/\sigma$ is Gaussian

At each frequency the shadow loss fluctuates by $\sigma = \pm 8$ dB about its average.

Shadow loss at the two frequencies are highly correlated, differing from each other by only $\sigma = \pm 3.3$ dB (correlation coefficient $C = 0.92$).

Shadow loss has weak frequency dependence.
Multiple Distance Scales of Signal Variation

- Travel distances $\sim \lambda/2$ -- Fast fading
- Travel distances $\sim 10 \text{ m} \sim 20\lambda$ -- Shadow fading
- Entire cell out to $\sim 20 \text{ km}$ -- Range dependence $A/R^n$
Shadow Fading Statistics

- For many small areas (sectors) $k = 1, 2, \ldots$ at the same distance $R$ from the base station
- Treat $\langle V(x)^2 \rangle$ over each small area as a random variable
- Define new random variable $U_k = 10\log \langle V(x)^2 \rangle$
- Probability distribution of $U_k$ about its mean value $\bar{U}$ is typically found to be the Gaussian distribution

$$p(U - \bar{U}) = \frac{1}{\sqrt{2\pi}\sigma_{SF}} \exp \left[ -\frac{(U - \bar{U})^2}{2\sigma_{SF}^2} \right]$$

- In cities $\sigma_{SF} \approx 8 \text{ - } 10 \text{ dB}$
- Note: if $V(x)$ is Rayleigh distributed, then $\langle V(x)^2 \rangle = \frac{4}{\pi} \left[ \overline{V(x)} \right]^2$
Autocorrelation of the Shadow Fading at 900MHz

Suburban Environment

250 m Decorrelation Distance 5 m

Urban Environment

Cross Correlation of the Shadow Loss for Links to Two Different Base Stations

Propagation Model for Shadow Fading

As the subscriber moves along street, the received signal passes over buildings of different height, or misses the last row of buildings.

Full width of Fresnel zone near one end of link:

\[ 2w_F = 2\sqrt{\lambda s} \]

For 900 MHz at mid street:

\[ s = 20 \text{ m}, \quad \lambda = 1/3 \text{ m} \]

\[ 2w_F = 5.2 \text{ m} \]

about the width of a house. Shadow loss is not sensitive to frequency.
Summary of Shadow Fading Statistics

- Shadow fading has lognormal distribution (power in dB has a normal distribution)
- Shadow fading has weak frequency dependence
- Correlation length of the shadow fading is on the order of building dimensions in cities and on street length in suburban areas
- There is correlation of the fading to different base stations when they are located in the same direction from the mobile
Range Dependence of the Received Signal

- High base station antenna measurements for macrocells (for $R$ out to 20 km)
- Low base station antenna measurements for microcells (for $R$ out to 2 km)
  - Line of sight (LOS) paths
  - Obstructed paths
Range Dependence of Macrocells & Microcells

• Early system using macrocells \((R < 20 \text{ km})\)
  – Base station antennas well above buildings
  – Isotropic propagation with range variation \(A/R^n\)
  – Hexagonal tessellation of plane
  – Frequency reuse independent of antenna height

• Modern systems using microcells \((R < 2 \text{ km})\)
  – Base station antenna near (or below) rooftops
  – Anisotropic propagation- \(A, n\) depend on:
    • Direction of propagation relative to street grid
    • Base station antenna height, location relative to buildings
  – Cell shape is open issue
Scale of City Blocks Compare to Cell Size
Measurements of Propagation Characteristics in Different Cities for High Base Station Antennas

- Field Strength and Its Variability in VHF and UHF Land-Mobil Radio Service

Yoshihisa OKUMURA, Eiji OHMORI, Tomihiko KAWANO, and Kaneharu FUKUDA

Detailed propagation tests for land-mobile radio service were carried out at VHF (200 MHz) and UHF bands (450, 922, 1310, 1430, 1920 MHz) over various situations of irregular terrain and of environmental clutter. The results analyzed statistically are described for distance and frequency dependences of median field strength, location variabilities and antenna height gain factors for the base and the vehicular station, in urban, suburban and open areas over quasi-smooth terrain.

The correction factors corresponding to respective terrain parameters for irregular terrain, such as rolling-hill terrain, isolated mountain area, general sloped terrain, and mixed land-sea path are discussed.

As a result, a method is presented for predicting the field strength and service area for a given terrain of the land-mobile radio system, over the frequency ranges of 150 to 2000 MHz, for distances of 1 to 100 km, and for base station effective antenna heights of 30 to 1000 m.

The results of comparison of predicted field strength with measured data published in another paper suggests that a reasonable degree of accuracy is obtainable.

Range Dependence Measured in Tokyo

Range Dependence Measurements in Philadelphia at 820 MHz


Base station in a high rise Building environment

Base station in a residential environment
Power law variation

\[ P_{dBm} = \left( P_T \right)_{dBm} + 10\log A - n10\log R \]

or

\[ P = P_T \left( A/R^n \right) \]

Path loss index

\[ n = 3.68 \]

Definition of Path Loss and Path Gain

\[ PG \equiv \text{Path Gain} = \frac{\text{Power Received}}{\text{Power Transmitted}} \]

(\( PG \) is always less than 1)

\[ PL \equiv \text{Path Loss} = \frac{\text{Power Transmitted}}{\text{Power Received}} = \frac{1}{PG} \]

(\( PL \) is always greater than 1)

When expressed in dB, \( PG_{dB} = 10\log PG = -L \) where \( L \equiv 10\log PL \)

If \( P = P_T A / R^n \), then \( PG_{dB} = 10\log A - 10n \log R \) and \( L = -10\log A + 10n \log R \)
Hata-Okumura Model for Median Path Loss

• Urban area:

\[ L_{50} = 69.55 + 26.16 \log f_c - 13.82 \log h_b - a(h_m) + (44.9 - 6.55 \log h_b) \log R \]

where

- \( f_c \) frequency (MHz)
- \( L_{50} \) mean path loss (dB)
- \( H_b \) base station antenna height
- \( a(h_m) \) correction factor for mobile antenna height (dB)
- \( R \) distance from base station (km)

– The range of the parameters for which Hata’s model is valid is

\[ 150 \leq f_c \leq 1500 \text{ MHz} \]
\[ 30 \leq h_b \leq 200 \text{ m} \]
\[ 1 \leq h_m \leq 10 \text{ m} \]
\[ 1 \leq R \leq 20 \text{ km} \]
Hata-Okumura Model (cont.)

• Urban area (cont.):
  - For a small or medium-sized city:
    \[ a(h_m) = (1.1 \log f_c - 0.7) h_m - (1.56 \log f_c - 0.8) \text{ dB} \]
  - For a large city:
    \[ a(h_m) = \begin{cases} 8.29(\log 1.54 h_m)^2 - 1.1 \text{ dB}, & f_c \leq 200 \text{ MHz} \\ 3.2(\log 11.75 h_m)^2 - 4.97 \text{ dB}, & f_c \geq 400 \text{ MHz} \end{cases} \]

• Suburban area:

\[ L_{50} = L_{50(urban)} - \left\{ 2 \left[ \log \left( \frac{f_c}{28} \right) \right]^2 + 5.4 \right\} \text{ dB} \]

• Open Area:

\[ L_{50} = L_{50(urban)} - 4.78 (\log f_c)^2 + 18.33 (\log f_c) - 40.94 \]
Range index of Hata-Okumura Model

\[ n = \frac{44.9 - 6.55 \log h_b}{10} \]

![Graph showing the relationship between range index \( n \) and base station height \( h_b \) in meters. The graph includes points at \( h_b = 20 \) meters with \( n = 3.84 \) and \( h_b = 200 \) meters with \( n = 2.98 \).]
Measurement of Path Loss for Low Base Station Antennas of Microcells
Drive Routes for Microcell Measurements in San Francisco

- LOS drive route
- Staircase drive route
- Zig-Zag drive route
  - Transverse paths - directly over buildings
  - Lateral paths - to side streets perpendicular to the LOS street
Drive Routes In the Mission District
Received Signal on LOS Route in Mission

\[ f = 1937 \text{ MHz}, \ h_{BS} = 3.2 \text{ m}, \ h_m = 1.6 \text{ m} \]

Received Signal on Staircase Route in the Sunset District vs. Distance Traveled

\[ f = 1937 \text{ MHz}, \quad h_{BS} = 8.7 \text{ m}, \quad h_m = 1.6 \text{ m} \]
Regression Fit to Received Signal Versus $R$ on Staircase Route in Sunset District.

Received Signal on Zig-Zag Route in the Sunset District vs. Distance Traveled

\[ f = 1937 \text{ MHz}, \ h_{BS} = 8.7 \text{ m}, \ h_m = 1.6 \text{ m} \]

Regression Fit to Received Signal Versus $R$ on the Transverse Portions of the Zig-Zag Route

Regression Fit to Received Signal Versus $R$ on the Lateral Portions of the Zig-Zag Route

Comparison of Regression Fits on Different Paths in Sunset

Har-Xia-Bertoni Model for Low Base Station Antennas

• Expressions fit to regression lines for:
  – 900 MHz and 1900 MHz
  – $h_{BS} = 3.2, 8.7$ and $13.4$ m
  – $h_m = 1.6$ m

• Separate expressions for:
  – LOS paths
  – Obscured paths in residential environment
  – Obscured paths in high rise environment
Har-Xia-Bertoni Model for LOS Paths

\[ f_G = \text{frequency in GHz} \]
\[ R_k = \text{distance in km} \]

\[ R_{bk} \equiv \frac{4h_b h_m}{1000\lambda} \quad (h_m = 1.6 \text{ m}) \]

Near - in segment \((R_k < R_{bk})\)
\[ L(R_k) = 81.14 + 39.40 \log f_G - 0.09 \log h_b + (15.80 - 5.73 \log h_b) \log R_k \]

Far - out segment \((R_k > R_{bk})\)
\[ L(R_k) = \left[ 48.38 - 32.10 \log R_{bk} \right] + 45.70 \log f_G + (25.34 - 13.90 \log R_{bk}) \log h_b \\
+ (32.10 + 13.90 \log h_b) \log R_k \]
Har-Xia-Bertoni Model for Obscured Paths in Residential Environments

\( f_G \) = frequency in GHz  
\( R_k \) = distance in km  
\( \Delta h \) = height of base station above (below) buildings in m

Combined staircase and transverse paths:

\[
L(R_k) = [138.31 + 38.88 \log f_G] - [13.74 + 4.58 \log f_G] \sgn(\Delta h) \log(1 + |\Delta h|) \\
+ [40.06 - 4.35 \sgn(\Delta h) \log(1 + |\Delta h|)] \log R_k
\]

Lateral Paths:

\[
L(R_k) = [127.39 + 31.63 \log f_G] - [13.05 + 4.35 \log f_G] \sgn(\Delta h) \log(1 + |\Delta h|) \\
+ [29.18 - 6.70 \sgn(\Delta h) \log(1 + |\Delta h|)] \log R_k
\]
Har-Xia-Bertoni Model for Obscured Paths in High Rise Environments

\[ f_G = \text{frequency in GHz} \]
\[ R_k = \text{distance in km} \]
\[ h_b = \text{height of base station above ground in m} \]

Combined staircase paths and transverse paths
\[ L(R_k) = 143.21 + 29.74 \log f_G - 0.99 \log h_b + (47.23 + 3.72 \log h_b) \log R_k \]

Lateral paths
\[ L(R_k) = 135.41 + 12.49 \log f_G - 4.99 \log h_b + (46.84 + 2.34 \log h_b) \log R_k \]
Comparison of Hata and Har Models

For base station antenna heights outside measurement limits of both models

For $f = 1$ GHz

Hata urban area

$$L = 69.55 + 26.16 \log 1000 - 13.82 \log 20 + \left(44.9 - 6.55 \log 20\right) \log R_k$$

$$= 130.0 + 36.4 \log R_k$$

Har combined staircase and transverse (residential)

$$L = 138.31 - 13.74 \log (1 + 9) + \left[40.06 - 4.35 \log (1 + 9)\right] \log R_k$$

$$= 124.6 + 35.7 \log R_k$$

Two models go into each other for middle height base station antennas
Summary of Range Dependence

- Range dependence over large distances takes the form
  \[ \frac{P_R}{P_{Tr}} = \frac{A}{R^n} \text{ in watts or} \]
  \[ 10\log \left( \frac{P_R}{P_{Tr}} \right) = 10\log A + 10n\log R \text{ in dB} \]
- The slope index \( n \) ranges between 3 and 4 for base station antennas above the rooftops, and is the same for all cities
- Simple formulas fit to measurements give the path gain or path loss as a function of antenna height and frequency
- Measurements made with high base station antennas match continuously with measurements made with low antennas