Hata Model

- An empirical formula for propagation loss
  - Based on Okumura's measurement data
  - Propagation loss between isotropic antenna
  - Only for Quasi-smooth terrain
  - Standard formula : urban area propagation loss
- The propagation loss in an urban area

$$L_p = A + B \log_{10} R$$

  - A , B – functions of frequency(MHz) and antenna height (m)
  - R – distance (km)
- System designs for land mobile radio services
  - Frequency : 100 ~ 1500 (MHz) , Distance : 1 ~ 20 (km)
  - Base station antenna height : 30 ~ 200 (m)
  - Vehicular antenna height : 1 ~ 10 (m)

Propagation Loss Between Isotropic Antenna

- Received Power P_r

$$P_r\,(dBm) = P_u\,(dBm/m^2) + 10\log_{10}(A_{eff})$$

$$A_{eff} = \lambda^2/4\pi$$

$$P_u\,(dBm/m^2) = E\,(dB\mu V/m) - 10\log_{10}(120\pi) - 90$$

A_{eff} : Absorption cross section of an istropic antenna

P_u : Received power density

E : Received field strength of an isotropic antenna

- Propagation Loss L_p

$$\begin{aligned} L_p\,(dB) &= P_t - P_r \\ &= P_t\,(dBW) - E\,(dB\mu V/m) - 10\log_{10}(\lambda^2/4\pi) + 145.8 \end{aligned}$$

P_t : Effective radiated power of an istropic antenna

Okumura's Prediction Curves and Propagation Loss

- Transform the unit from ERP/dipole to EIRP
  - Absolute power gain of the dipole antenna : 2.2 dB

$$P_t\,(dBW\ EIRP) = P_t'(dBW\ ERP/dipole) + 2.2\,(dB)$$

  - P_t (dBW EIRP) = 32.2 dB [when P_t' = 1 kW (ERP/dipole)]

- Propagation Loss L_p (between the isotropic antenna)

$$L_p\,(dB) = 178 - 10\log_{10}(\lambda^2/4\pi) - E\,(dB\mu V/m)$$

$$= 139.45 + 20\log_{10} f_c - E\,(dB\mu V/m)$$

where f_c : carrier frequency (MHz)

E : Received field strength of an isotropic antenna

Empirical Formula for Propagation Loss

- The field strength E

$$E\,(dB\mu V\,/\,m) = \gamma + \beta \log_{10} R$$

$\gamma\,,\beta$: constans determined by $h_b\,(m)$ & $f_c\,(MHz)$

- Propagation Loss L_p

$$L_p\,(dB\,) = A + B\log_{10} R$$

$$A = 178 - 10\log_{10}(\lambda^2/4\pi) - \gamma - a(h_m)$$

$$B = -\beta$$

$a(h_m)$: the correction factor for the vehicular station antenna height $h_m\,(m)$

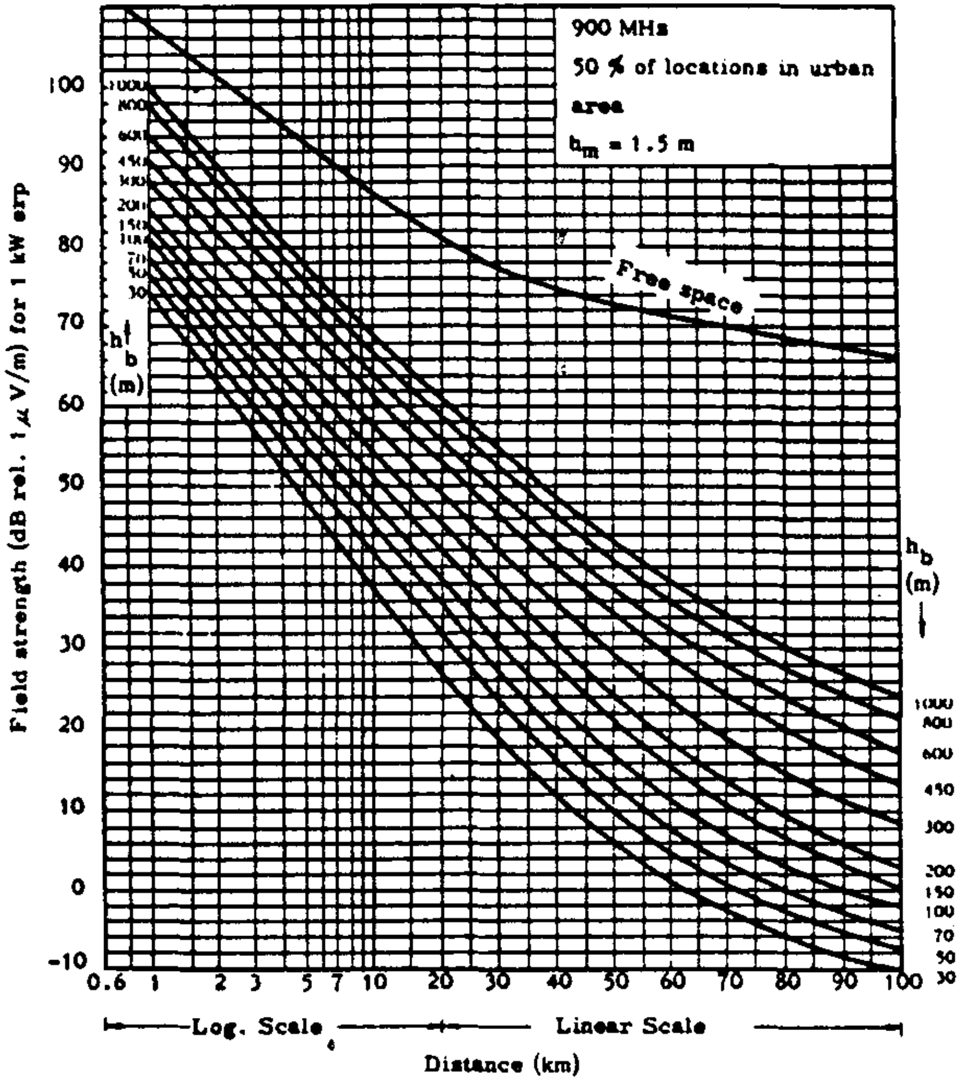


Fig. 1. Basic median field strength curve in the 900-MHz band.

Introduction of the Empirical Formula

- A : Value of the Propagation Loss at R = 1 (km)

	f_c (MHz)			
h_b (m)	150	450	900	1500
30	105.5	117.0	124.5	132.0
50	103.0	114.0	122.5	129.5
70	101.0	112.0	120.5	127.0
100	98.5	110.0	118.0	125.0
150	96.5	108.0	116.5	123.0
200	94.5	106.0	114.5	121.0

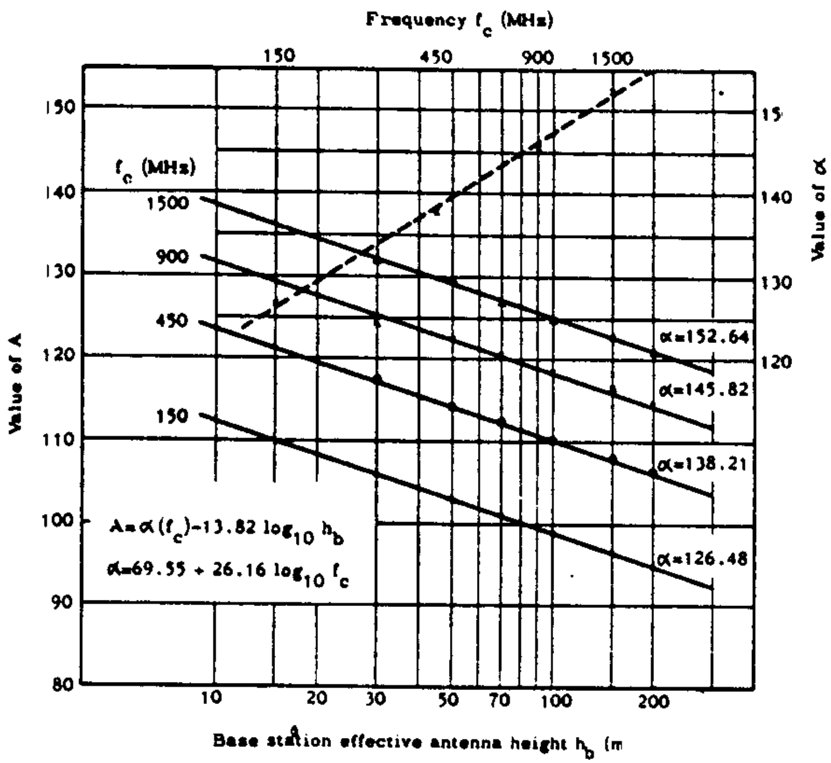


Fig. 2. Introduction of factor *A*

- $A = \alpha - 13.82\log_{10} h_b - a(h_m)$

$$\alpha = 69.55 + 26.16\log_{10} f_c$$

Introduction of the Empirical Formula (Cont'd)

- B : Slope of the Propagation Loss Curve

	f_c (MHz)			
h_b (m)	150	450	900	1500
30	35.0	35.0	35.7	35.7
50	33.4	34.1	33.8	34.1
70	33.2	32.5	32.2	33.4
100	31.5	31.3	32.5	32.2
150	30.4	30.4	31.1	30.9
200	29.9	29.4	29.9	29.9

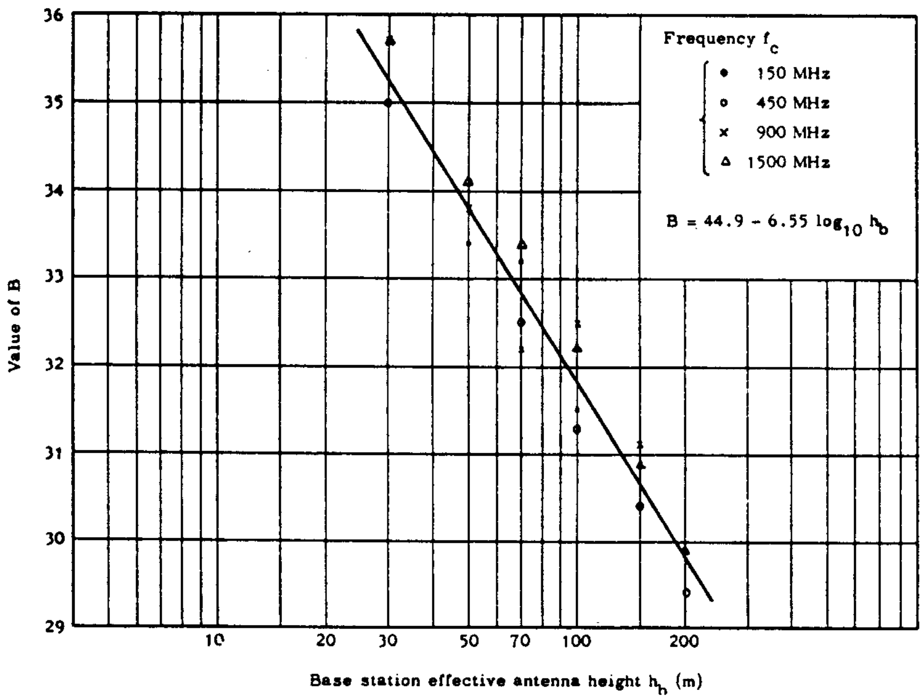


Fig. 3. Introduction of factor *B*.

- $B = 44.9 - 6.55\log_{10} h_b$

Empirical Formula for Propagation Loss

- $$L_p(dB) = A + B\log_{10} R$$
  $$= 69.55 + 26.16\log_{10} f_c - 13.82\log_{10} h_b$$
  $$- a(h_m) + (44.9 - 6.55\log_{10} h_b)\log_{10} R$$
  - Frequency (f_c) : 150 ~ 1500 MHz
  - Base station antenna height (h_b): 30 ~ 200 m
  - Distance (R) : 1 ~ 20 km
  - $a(h_m)$: correction factor for the vehicular station antenna height h_m(m)
- Correction factors
  - $a(h_m)$: Correction factors in a meium-small or large city
  - K_r : Corrections for Suburban
  - Q_r : Corrections for Open areas

Correction factors in a medium-small city (1/2)

- Correction curves shown by straight lines with h_m in linear scale
- The reference h_m of L_p : 1.5m

  $\Rightarrow$ $a_{1.5} = 0$ dB at $h_m = 1.5$ m
- $a_{1.5} = \xi(f_c)\cdot h_m - \eta(f_c)$
- $\xi(f_c) = 1.1\cdot\log_{10}(f_c) - 0.7$
- $\eta(f_c) = 1.56\cdot\log_{10}(f_c) - 0.8$

  ☞ For a median-small city

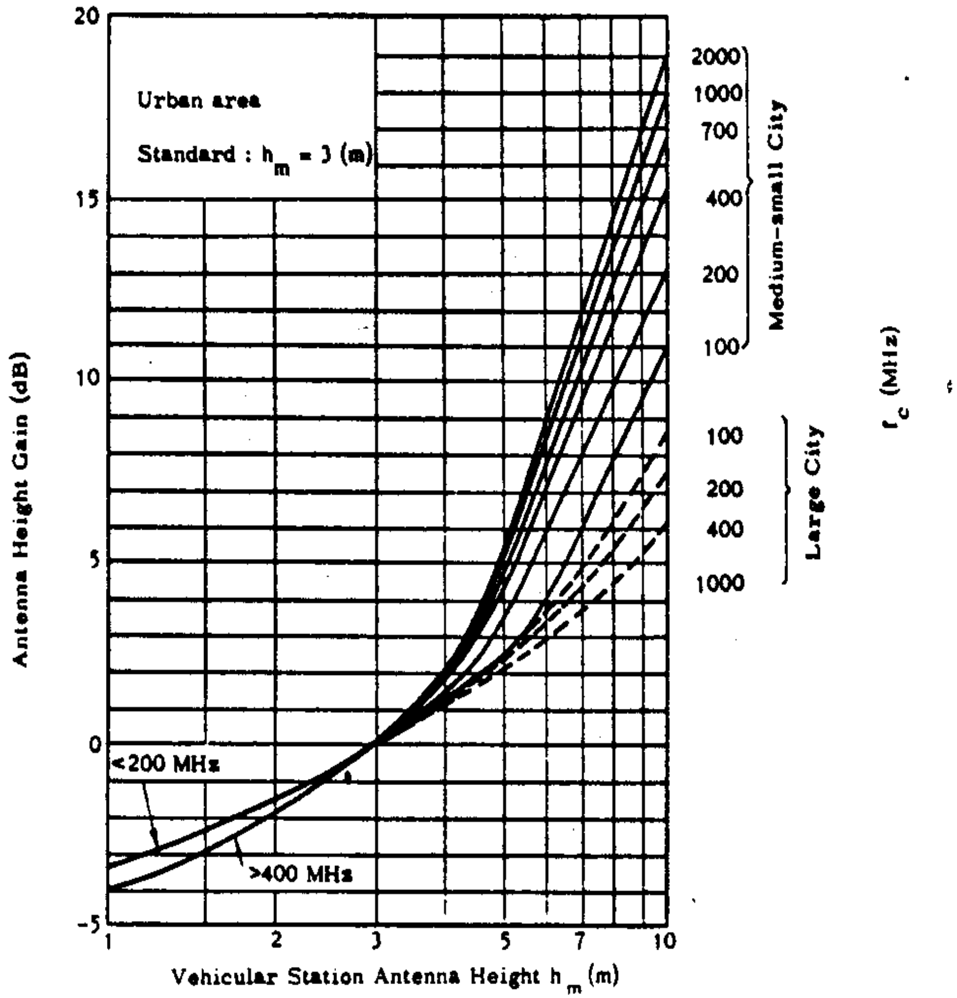


Fig. 4. Prediction curves for vehicular antenna height gain in an urban area.

Correction factors in a medium-small city (2/2)

- $a(h_m) = (1.1 \cdot \log_{10}(f_c) - 0.7) \cdot h_m - 1.56 \cdot \log_{10}(f_c) - 0.8$
  - ☞ $h_m : 1 \sim 10\ m,\ \ f_c : 150 \sim 1500\ MHz$
- Error to the linear approximation $\propto f_c$
- The maximum error ; $f_c = 1500$ MHz , $h_m = 4 \sim 5$ m

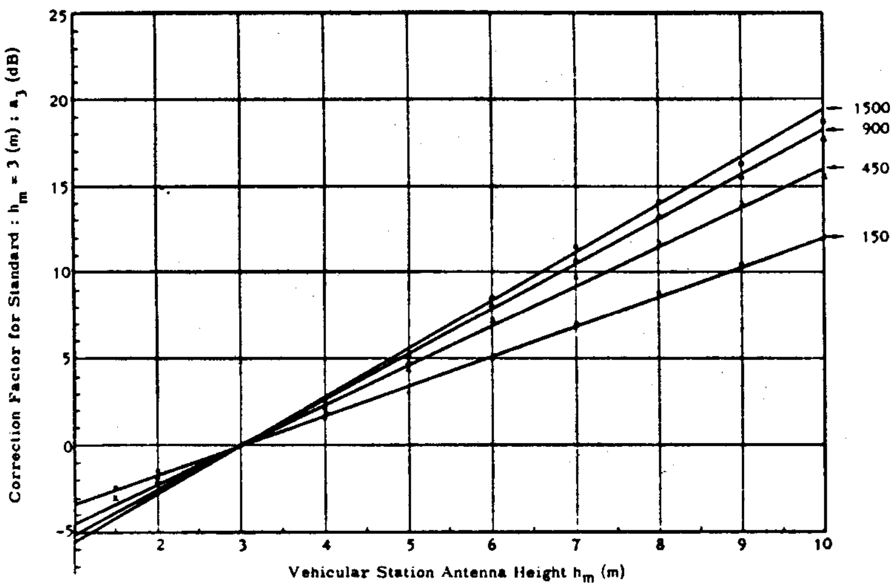


Fig. 5. Correction factors in a medium-small city (1).

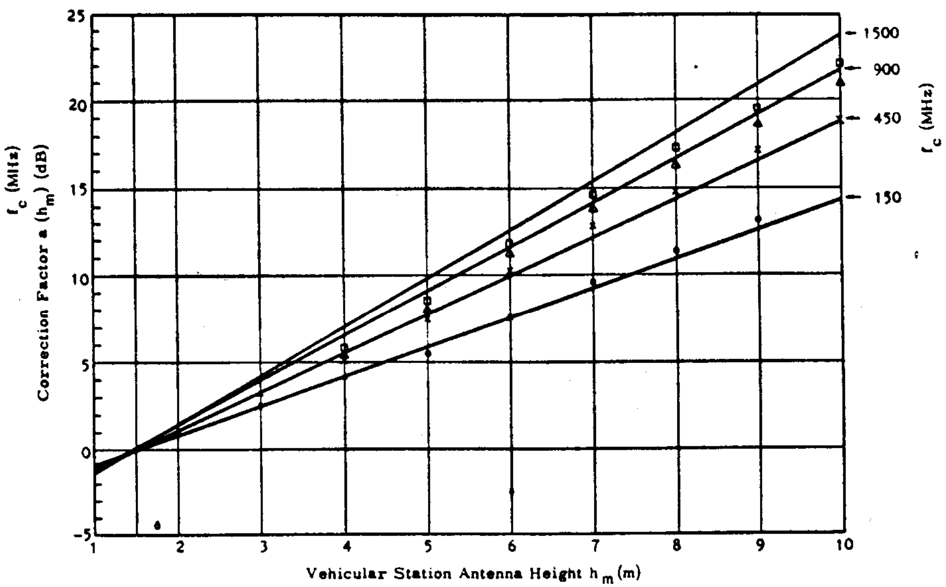


Fig. 11. Correction factors in a medium-small city (2).

Correction factors in a large city (1/2)

- Large city : the building height average ≥ 15 m
- Curves can be considered as parabolas
- $a_3' = 8.29 \cdot (\log_{10} 1.54\, h_m)^2 - 3.96\ (dB)$
  - ☞ $f_c \le 200\ MHz$
- $a_3' = 3.2 \cdot (\log_{10} 11.75\, h_m)^2 - 7.63\ (dB)$
  - ☞ $f_c \ge 400\ MHz$

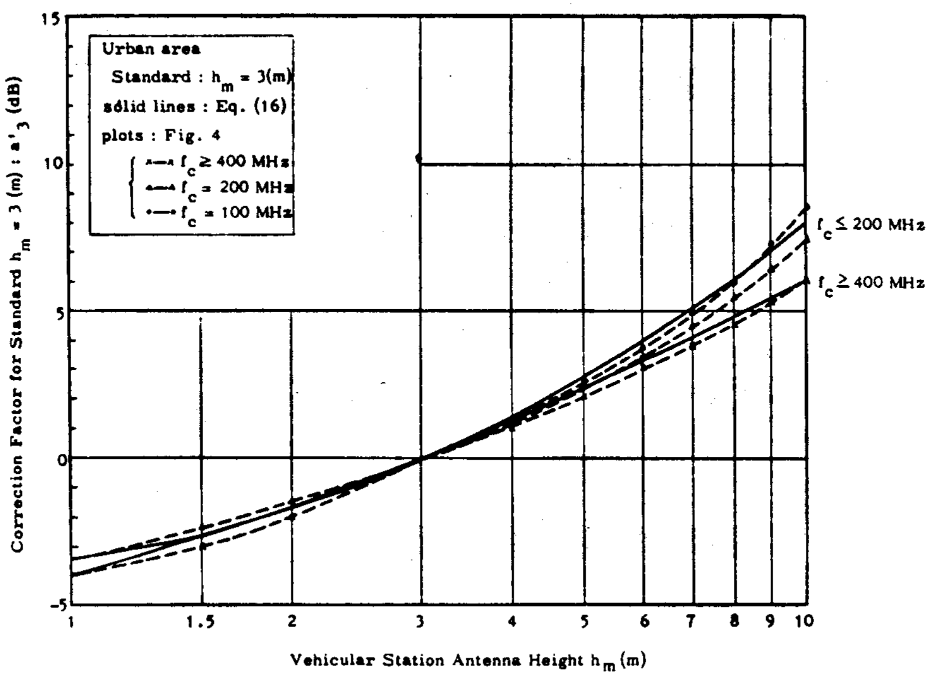


Fig. 7. Correction factors in a large city (1).

Correction factors in a large city (2/2)

- $a(h_m) = 8.29 \cdot (\log_{10} 1.54 h_m)^2 - 1.10 \ (dB)$
  - ☞ $f_c \le 200 \ MHz$
- $a(h_m) = 3.2 \cdot (\log_{10} 11.75 h_m)^2 - 4.97 \ (dB)$
  - ☞ $f_c \ge 400 \ MHz$
- Maximum error ; About 1 dB
  - ☞ $f_c \le 200$ MHz and $h_m \ge 5$ m

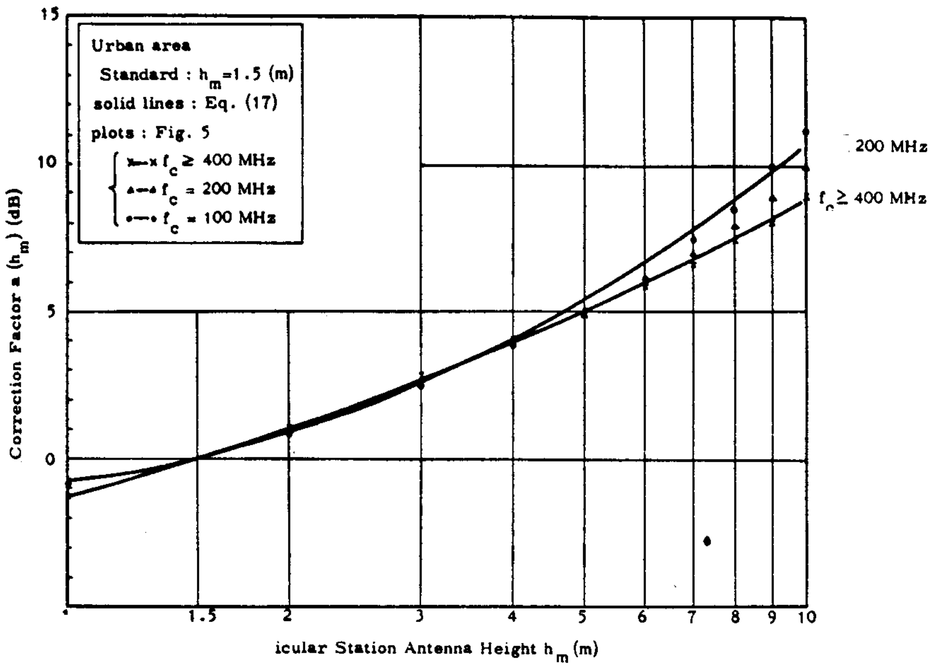


Fig. 8. Correction factors in a large city (2)

Estimation of the Approximation Error (1/2)

- The error for each frequency
  - very small(1-20 km)
  - Maximum error : 1 dB
  - Independent of the distance
- Only term **A** depends on freq.
- $A = \alpha - 13.82 \log_{10} h_b - a(h_m)$

  $\alpha = 69.55 + 26.16 \log_{10} f_c$

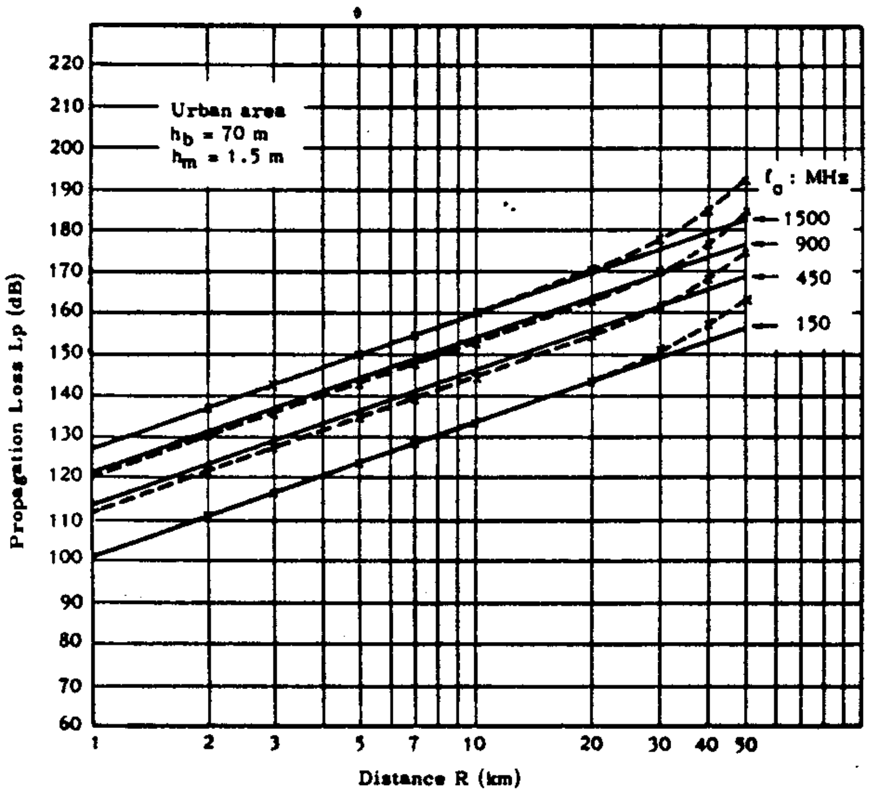


Fig. 9. Propagation loss in an urban area (1).

- Solid lines : Values from the formula
- Dashed lines : Values from the prediction curves

Estimation of the Approximation Error (2/2)

- The error for each h_b
  - Maximum value : 1 dB
  - Due to the linear approximation of **B**
- $B = 44.9 - 6.55\log_{10} h_b$

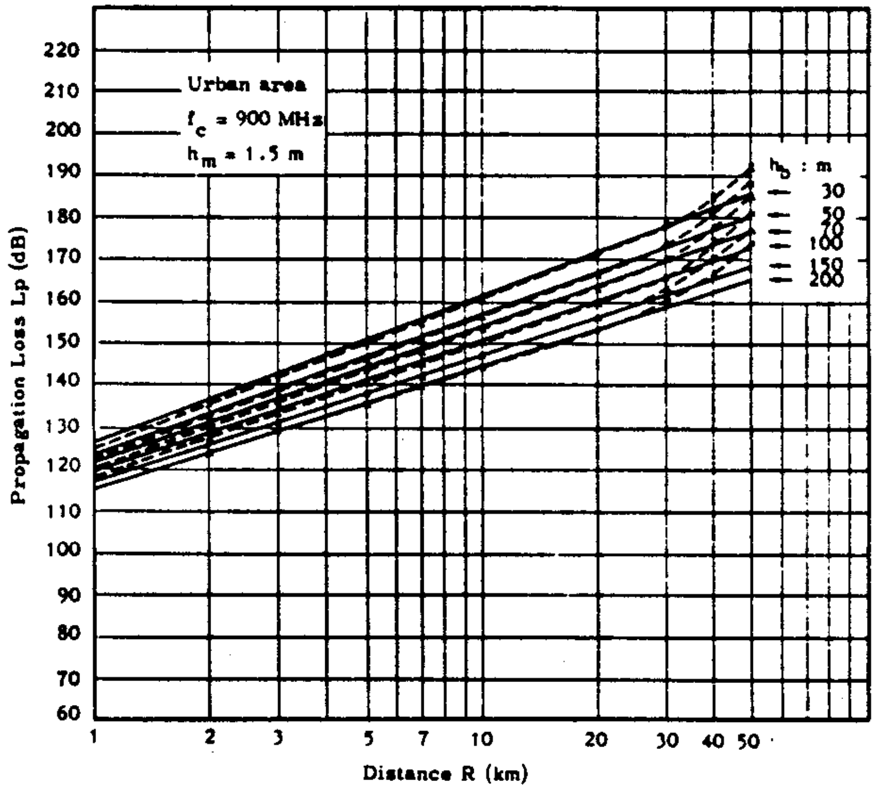


Fig. 10. Propagation loss in an urban area (2).

- Solid lines : Values from the formula
- Dashed lines : Values from the prediction curves

Corrections for Suburban

- The suburban correction factor K_r (dB)
- $K_r(dB) = 2\{\log_{10}(f_c/28)\}^2 + 5.4$
- The propagation loss in suburban area L_{ps} (dB)
- $L_{ps}(dB) = L_p(In\ \ urban) - K_r$

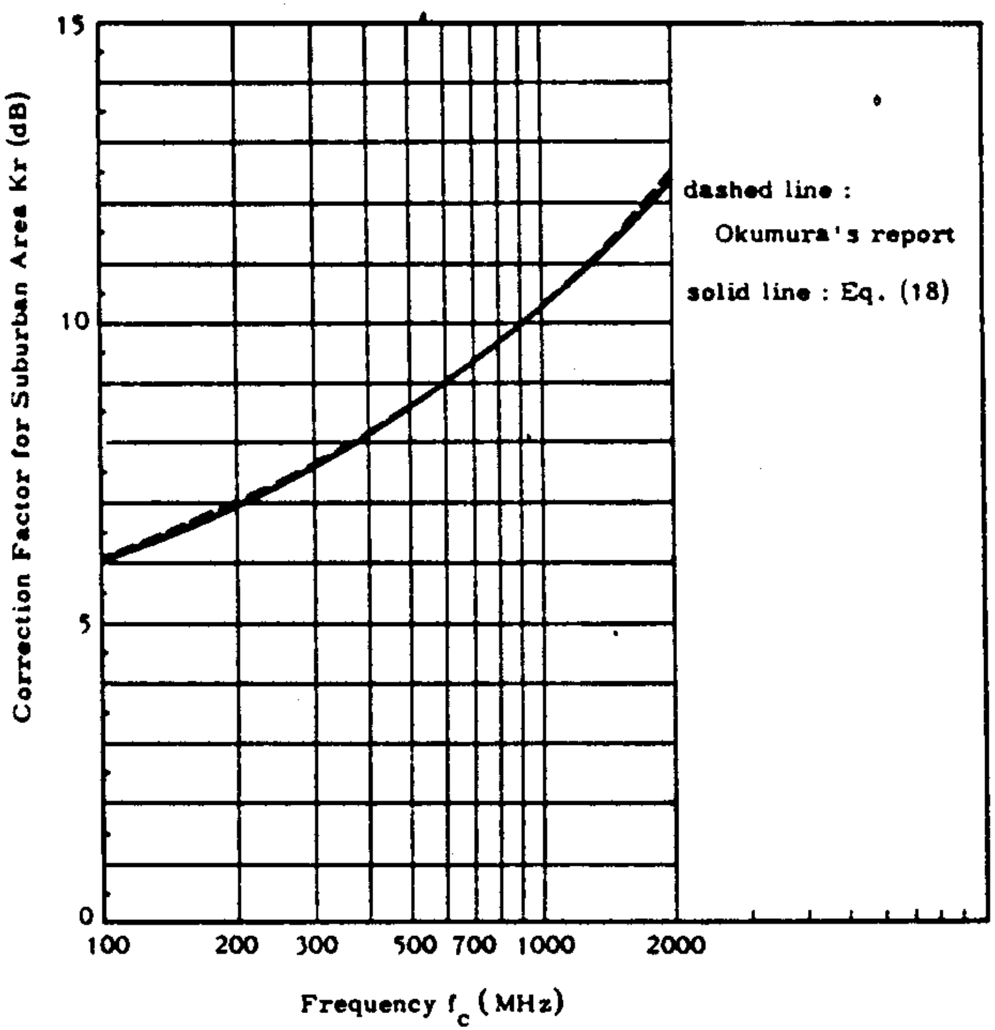


Fig. 12. Correction factor for suburban area.

Corrections for Open areas

- The open area correction factor Q_r (dB)
- $$Q_r(dB) = 4.78(\log_{10} f_c)^2 - 18.33\log_{10} f_c + 40.94$$
- The propagation loss in open area L_{po} (dB)
- $$L_{po}(dB) = L_p(In\ \ urban) - Q_r$$

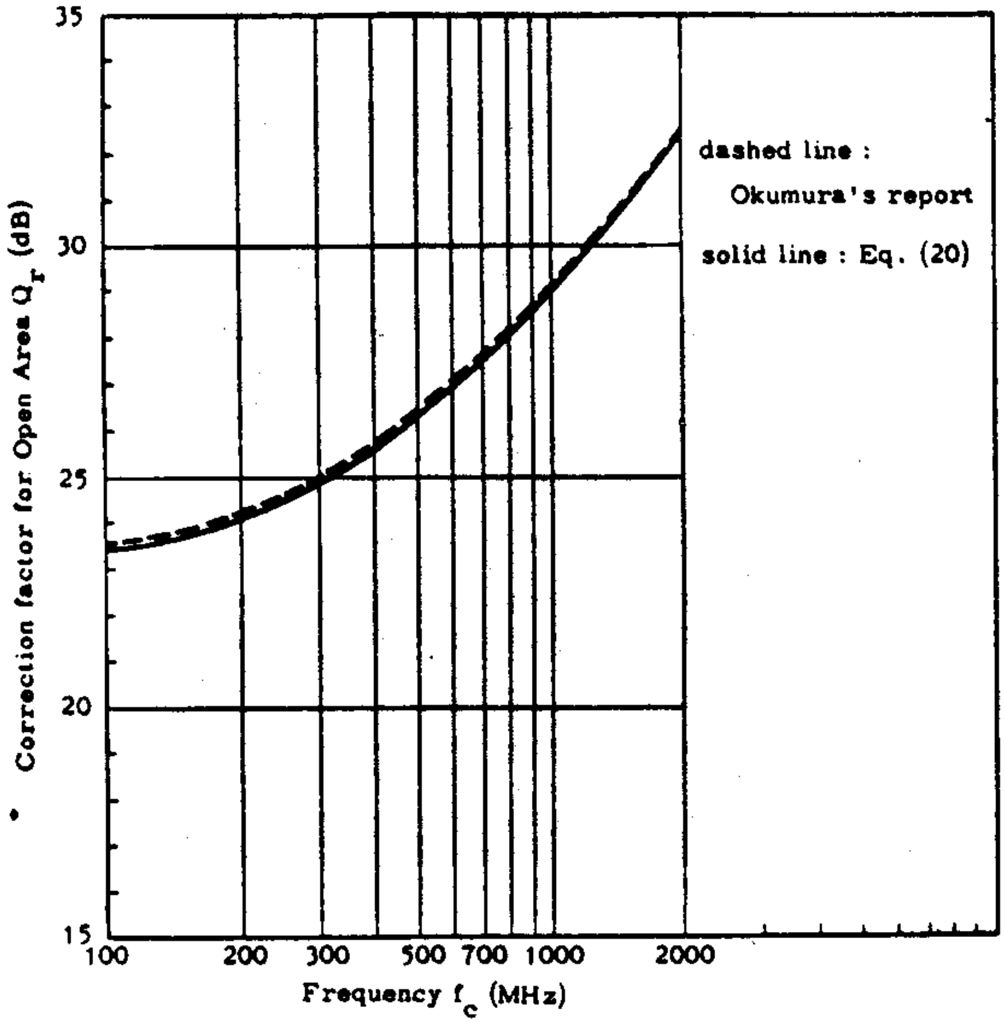


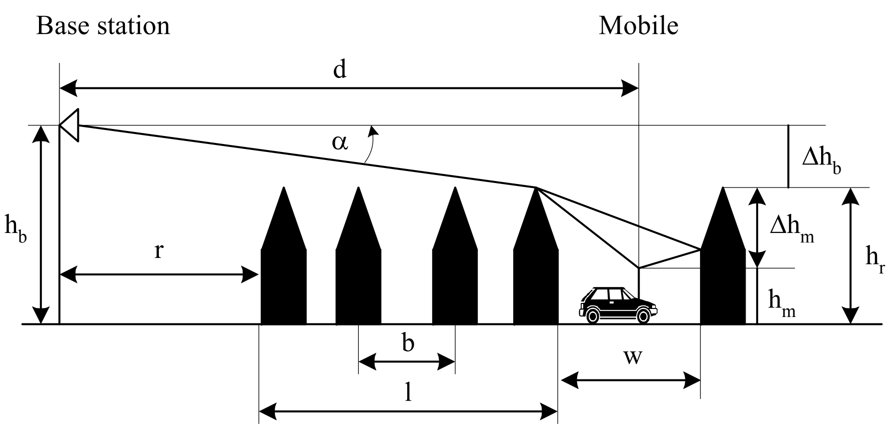
Fig. 13. Correction factor for open area.

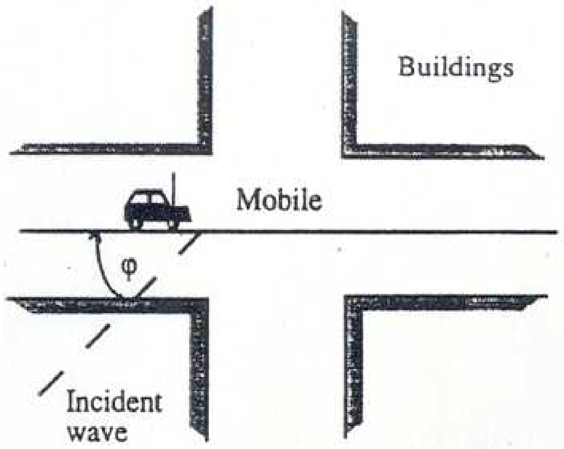
Semi-deterministic and empirical models for urban areas (COST 231-Hata model)

- COST 231 – Hata Model
  - Extension of Hata's model to the freq. band $1500 \le f_c \text{ (MHz)} \le 2000$
  - $$L_b(dB) = 46.3 + 33.9 \cdot \log f_c(MHz) - 13.82 \cdot \log h_b(m) - a(h_m) + \left[44.9 - 6.55 \cdot \log h_b(m)\right] \cdot \log d(km) + C_m$$
    - ✓ L_b: Basic Transmission Loss
  - where $$C_m = \begin{cases} 0\ dB & \text{for medium sized city and suburban centers with medium tree density} \\ 3\ dB & \text{for metropolitan centers} \end{cases}$$
  - restriction : $$\begin{cases} f_c = 1500 \sim 2000\ (MHz) \\ h_b = 30 \sim 200\ (m) \\ h_m = 1 \sim 10\ (m) \\ d = 1 \sim 20\ (km) \end{cases}$$

COST 231-Walfisch-Ikegami model (COST231-WI model) (1/4)

- A combination of the Walfisch and Ikegami models
- Improved path-loss estimation
  - Consider more data : h_r (heights of buildings)
    w (widths of roads), b (building separation)
    φ (road orientation w.r.t. the direct radio path)





- Distinguish LOS and non-LOS situations

COST231-WI model (2/4)

- LOS case (a simple propagation loss formula)
  - $L_b\,(dB) = 42.6 + 26\cdot\log d\,(km) + 20\cdot\log f_c\,(MHz)$ for d ≥ 20 m
    - ✓ To determine first constant, using free space loss for d = 20 m
- Non-LOS case
  - Composed of three terms
    - ✓ L_0 ; free space loss
    - ✓ L_{msd} ; multiple diffraction loss
    - ✓ L_{rts} ; rooftop-to-street diffraction and scatter loss
  - $$L_b = \begin{cases} L_0 + L_{rts} + L_{msd} & for \quad L_{rts} + L_{msd} > 0 \\ L_0 & for \quad L_{rts} + L_{msd} \le 0 \end{cases}$$
  - $$L_0\,(dB) = 32.4 + 20\cdot\log d\,(km) + 20\cdot\log f_c\,(MHz)$$

COST231-WI model (3/4)

- L_{rts} is mainly based on Ikegami's model
  - ☞ $L_{rts}(dB) = -8.2 - 10\cdot\log w(m) + 10\cdot\log f_c(MHz) + 20\cdot\log\Delta h_m(m) + L_{Ori}$

where $$L_{Ori} = \begin{cases} -10 + 0.354\cdot\varphi(\deg) & for\ \ 0^\circ \le \varphi < 35^\circ \\ 2.5 + 0.075\cdot[\varphi(\deg) - 35] & for\ \ 35^\circ \le \varphi < 55^\circ \\ 4.0 - 0.114\cdot[\varphi(\deg) - 55] & for\ \ 55^\circ \le \varphi \le 90^\circ \end{cases}$$

- L_{msd} is based on Walfisch and Bertoni model
  - ☞ $L_{msd}(dB) = L_{bsh} + k_a + k_d\cdot\log d(km) + k_f\cdot\log f_c(MHz) - 9\cdot\log b(m)$
    - ✓ L_{bsh} ; Path loss due to $\Delta h_b > 0$
    - ✓ $L_{bsh} = \begin{cases} -18\cdot\log_{10}\left(1 + \Delta h_b(m)\right) & , h_b \ge h_r \\ 0 & , h_b \le h_r \end{cases}$

COST231-WI model (4/4)

- k_a; the increase of the path loss for $\Delta h_b < 0$

- $$k_a = \begin{cases} 54 & , h_b > h_r \\ 54 - 0.8 \cdot \Delta h_b & , d \geq 0.5km \quad and \quad h_b \leq h_r \\ 54 - 1.6 \cdot \Delta h_b \cdot d(km) & , d < 0.5km \quad and \quad h_b \leq h_r \end{cases}$$

- k_d, k_f ; the multi-screen diffraction loss vs. distance and frequency

- $$k_d = \begin{cases} 18 & , h_b > h_r \\ 18 - 15 \cdot \dfrac{\Delta h_b(m)}{h_r(m)} & , h_b \leq h_r \end{cases}$$

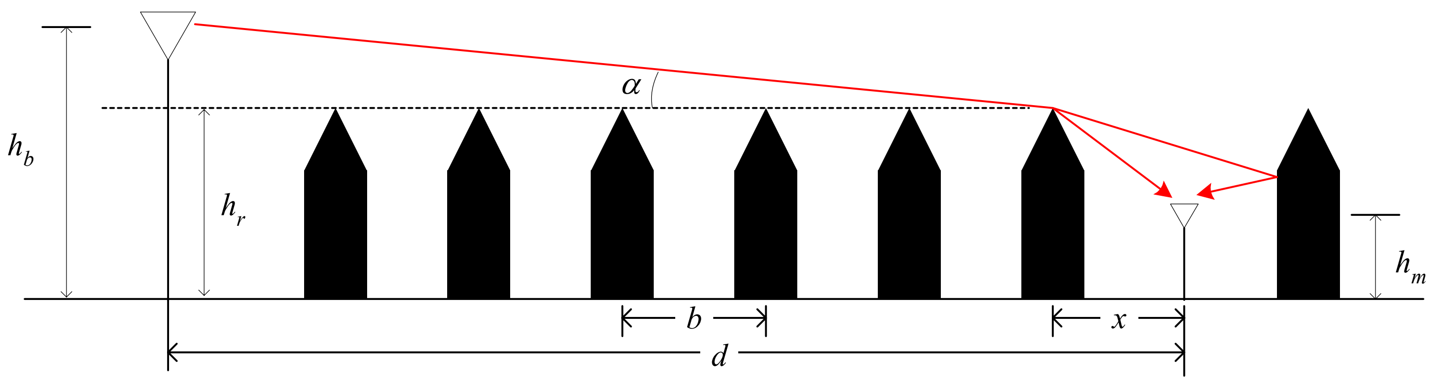
- $$k_f = -4 + \begin{cases} 0.7 \cdot \left[f_c(MHz)/925 - 1 \right] & \text{, medium sized city and suburban centers} \\ 1.5 \cdot \left[f_c(MHz)/925 - 1 \right] & \text{, metropolitan centers} \end{cases}$$

- Default values
  - $h_r = 3 \times$ (# of floors) + roof-height , roof-height = $\begin{cases} 3\ (m)\ ;\ \text{pitched} \\ 0\ (m)\ ;\ \text{flat} \end{cases}$
  - $b = 20 \sim 50$ m, $w = b / 2$, $\varphi = 90°$

- Restrictions
  - f_c : 800 ~ 2000 MHz, h_b: 4 ~ 50 m, h_m: 1~3 m, d: 0.02 ~ 5 km

Multiple screen diffraction (1/5)

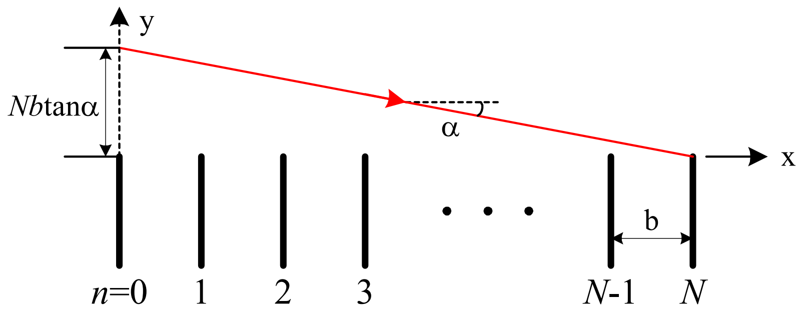
- Relatively uniform height buildings modeled as absorbing half-screens
- A process of multiple diffraction past rows of buildings
- Assumptions
  - Propagation perpendicular to the rows of buildings
  - Magnetic field polarized parallel to the ground (vertically polarized)
  - Consider the problem of plane-wave diffraction past a semi-infinite sequence of rows labeled n = 0, 1, 2, · · ·



Multiple screen diffraction (2/5)
Elevated antennas

- For elevated antennas
  - $$H_{n+1}(y) = \frac{e^{j\pi/4}}{2\sqrt{\lambda}} \int_0^{\infty} H_n(y') \frac{e^{-jkr}}{\sqrt{r}} (\cos\delta + \cos\alpha)\, dy'$$

    where $r = \sqrt{b^2 + (y-y')^2}$, $\cos\delta = b/r$
- Numerical results
  - $H_n(y = 0)$ for elevated antennas settles to a nearly constant value for n large enough
- Excess path loss due to multiple screen diffraction, L_e
  - $L_e = -10 \log (Q^2)$
  - Q depends on BS antenna height H & row spacing d through the dimensionless parameter



Multiple screen diffraction (3/5)
Elevated antennas

- The dimensionless parameter g_p
  - ☞ $g_p = \alpha\sqrt{\dfrac{b}{\lambda}}$ where $\alpha = \tan^{-1}\dfrac{h_b - h_r}{d} \approx \dfrac{h_b - h_r}{d}$
- $Q(g_p) = 2.35\, g_p^{\;0.9}$
  - ☞ Over the range of $0.01 < g_p < 0.4$
  - ☞ Ex) for 900 MHz, typical row spacing of $b = 40$ m, and $h_b - h_r = 10$ m

    $\Rightarrow$ Range of g_p correspond to $0.3 \text{ km} < d < 11 \text{ km}$
- In order to apply the theory for smaller values of d
- $Q(g_p) = 3.502 g_p - 3.327 g_p^{\;2} + 0.962 g_p^{\;3}$
  - ☞ Over the range of $0.01 < g_p < 1 \Rightarrow 0.11 \text{ km} < d < 11 \text{ km}$ (900 MHz)

Multiple screen diffraction (4/5)

Low antennas

- L_e for low antennas
  - The factor Q_N giving the reduction of the field at the top of last screen due to screens
  - $$Q_N = \sqrt{N+1}\left|\sum_{q=0}^{\infty}\frac{1}{q!}\left[2g_c\sqrt{j\pi}\right]^q I_{N,q}\right| \qquad \text{where } g_c = y_0\frac{1}{\sqrt{\lambda b}},\ y_0 = h_b - h_r$$

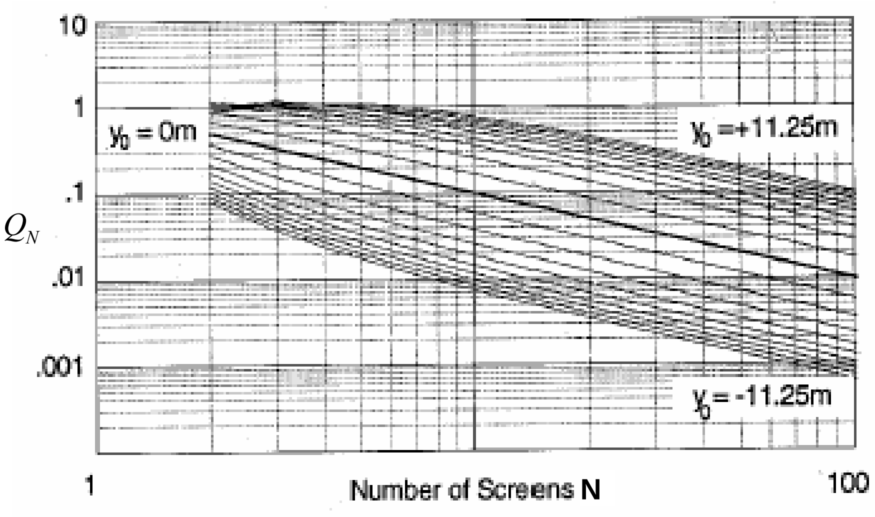
$$I_{N,q} = \frac{N(q-1)}{2(N+1)}I_{N,q-2} + \frac{1}{2\sqrt{\pi}(N+1)}\sum_{n=1}^{N-1}\frac{I_{N,q-1}}{(N-n)^{1/2}}$$

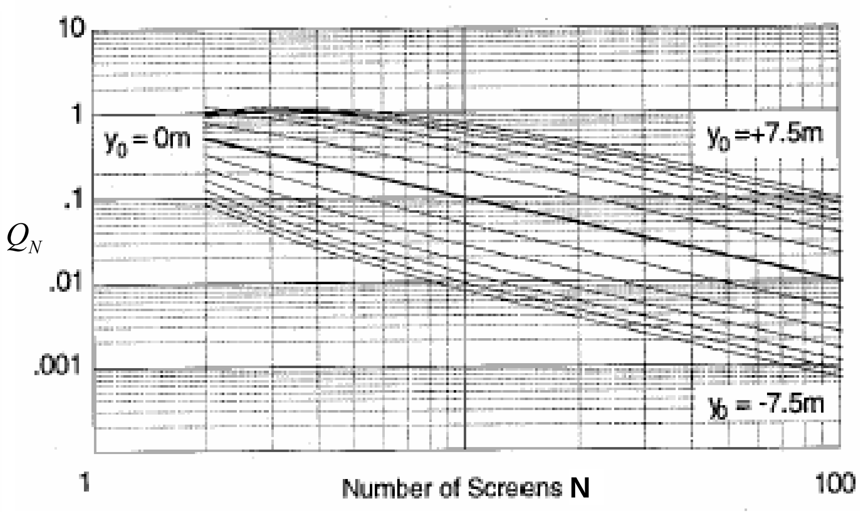
$$I_{N,0} = \frac{1}{(N+1)^{3/2}},\quad I_{N,1} = \frac{1}{4\sqrt{\pi}}\sum_{n=0}^{N}\frac{1}{n^{3/2}(N+1-n)^{3/2}} \quad (\text{initial condition})$$

  - Q_N depends on the source height y_0 above or below the rooftops and the row separation b

Multiple screen diffraction (5/5)
Examples

- Field after multiple diffraction over absorbing screens



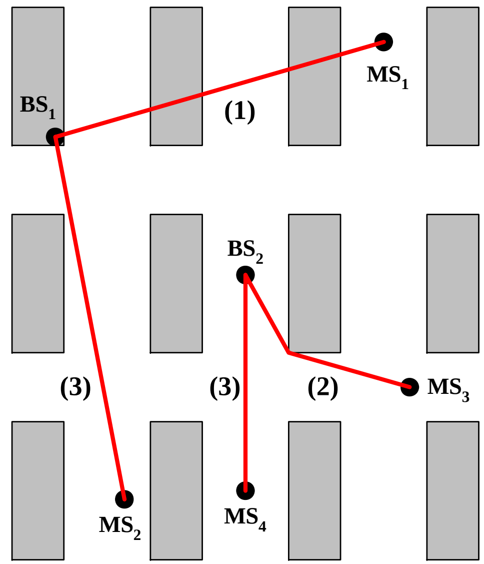


- f_c = 900 MHz and b = 50 m
- f_c = 1800 MHz and b = 50 m

- For antennas above the rooftops ($y_0 > 0$)
  - A rate of decrease for field is less than 1/N, but approaches 1/N
- For antennas below the rooftops ($y_0 < 0$)
  - The field initially decreases more rapidly than 1/N, but quickly approaches the 1/N variation

ITU-R P. 1411 model

- Estimating path loss for short-range(less than 1km) outdoor radio systems
- Propagation affected primarily by buildings and trees
- Classified into 3 categories according to propagation situation , rooftops-NLOS(1), street canyons-NLOS(2), LOS(3)
- Rooftops-NLOS model is similar to COST231-WI model



Rooftops NLOS model (P. 1411)

- The formula is same as the COST231-WI model
  - Extension of COST231-WI model to the freq. band f_c (MHz) $\leq$ 5000 for $\Delta h_b > h_r$ (ITU-R P.1411-3, March, 2005)
  - $k_a = 71.4$, $k_f = -8$ for $\Delta h_b > h_r$ and $f_c > 2000$ MHz
- Assumption
  - The roof−top heights differ only by an amount less than the 1st Fresnel-zone radius over a path of length l, h_r = the average roof−top height
  - The roof-top heights vary by much more than the 1st Fresnel−zone radius: a preferred method of knife-edge diffraction calculation due to the the highest buildings along the path is recommended to replace the multi-screen model
  - Where l : distance over which the buildings extend

Rooftops NLOS model (P. 1411)

- L_{msd} has two formulas according to Δh_b and incidence angle
- A criterion for grazing incidence : settled field distance d_s
  - $d_s = \dfrac{\lambda \cdot d^2}{\Delta h_b^{\,2}}$ where $\Delta h_b = h_b - h_r$
- When $l > d_s$, L_{msd} has same formula as COST231-WI model
  - Where l : distance over which the buildings extend
- When $l < d_s$
  - $L_{msd} = -10 \cdot \log_{10}(Q_N^{\,2})$

$$\theta = \arctan\left(\Delta h_b / b\right)$$

$$\rho = \sqrt{\Delta h_b^{\,2} + b^2}$$

$$Q_N = \begin{cases} 2.35 \cdot \left(\dfrac{\Delta h_b}{d} \sqrt{\dfrac{b}{\lambda}} \right)^{0.9} & , \ for \ h_b > h_r \\ \dfrac{b}{d} & , \ for \ h_b \approx h_r \\ \dfrac{b}{2\pi d} \sqrt{\dfrac{\lambda}{\rho}} \left(\dfrac{1}{\theta} - \dfrac{1}{2\pi + \theta} \right) & , \ for \ h_b < h_r \end{cases}$$

Street canyons NLOS model (P. 1411)

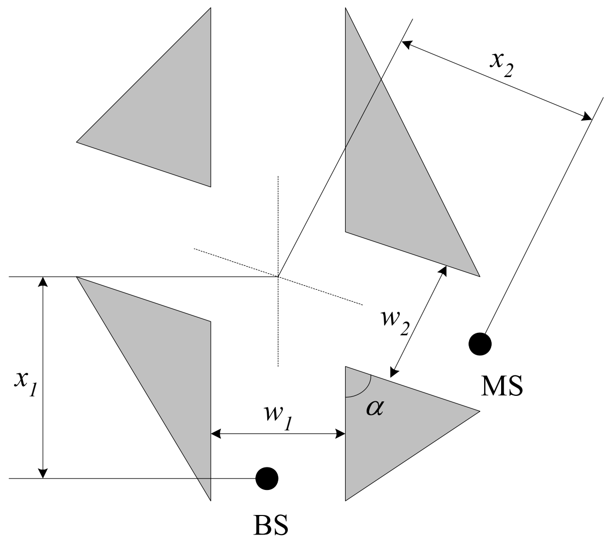
- Situations where both antennas are below roof-top level
- $L_{SC}(dB) = -10 \cdot \log_{10}\left(10^{-L_r/10} + 10^{-L_d/10}\right)$
  - L_r : reflection path loss
    - ✓ $L_r(dB) = 20\log_{10}(x_1 + x_2) + x_2 x_1 \dfrac{f(\alpha)}{w_1 w_2} + 20\log_{10}\left(\dfrac{4\pi}{\lambda}\right)$

$$f(\alpha) = \frac{3.86}{\alpha^{3.5}} \qquad where\ 0.6(\approx 34^\circ) < \alpha\ (rad) < \pi$$

  - L_d : diffraction path loss
    - ✓ $L_d(dB) = 10\log_{10}\left[x_2 x_1 (x_1 + x_2)\right] + 2D_a$

$$-0.1\left(90 - \alpha\frac{180}{\pi}\right) + 20\log_{10}\left(\frac{4\pi}{\lambda}\right)$$

$$D_a = \left(\frac{40}{2\pi}\right)\left[\arctan\left(\frac{x_2}{w_2}\right) + \arctan\left(\frac{x_1}{w_1}\right) - \frac{\pi}{2}\right]$$



LOS situations within street canyons (P. 1411)

- Basic transmission loss can be characterized by two slopes and a single breakpoint
- An approximate lower bound
  - ☞ $$L_{LOS,l} = L_{bp} + \begin{cases} 20\log_{10}(d/R_{bp}) & for\ \ d \le R_{bp} \\ 40\log_{10}(d/R_{bp}) & for\ \ d > R_{bp} \end{cases}$$

    where $R_{bp} \approx \dfrac{4h_b \cdot h_m}{\lambda}$: the breakpoint distance
- An approximate upper bound
  - ☞ $$L_{LOS,u} = L_{bp} + 20 + \begin{cases} 25\log_{10}(d/R_{bp}) & for\ \ d \le R_{bp} \\ 40\log_{10}(d/R_{bp}) & for\ \ d > R_{bp} \end{cases}$$

    where $L_{bp} = \left| 20\log_{10}\left(\dfrac{\lambda^2}{8\pi h_b h_m}\right) \right|$: the basic transmission loss at the break point

ITU-R P. 1546 model (1/4)

- Point-to-area predictions for terrestrial services
  - Frequency range : 30 MHz to 3000 MHz
  - The distance range : 1 km to 1000 km
- The propagation curves at nominal frequencies of 100, 600 and 2000 MHz as a function of various parameters used
  - Curves are based on measurement data
  - Represent the field-strength values for 1 kW e.r.p. exceeded for 50%, 10% and 1 % of time
- Interpolation and extrapolation for nominal values such as frequency, distance, percentage time, base antenna height and mixed land sea path are used

ITU-R P. 1546 model (2/4)

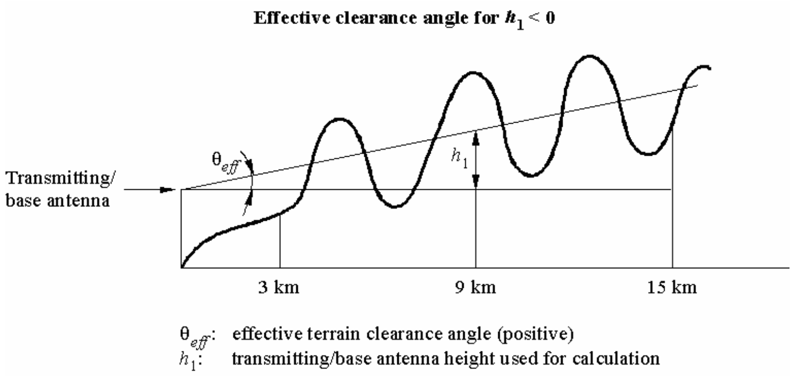
- Interpolation / Extrapolation
  - For frequency, distance and BS antenna height
  - $$E = E_{\inf} + (E_{\sup} - E_{\inf}) \frac{\log(h_b, d, f / h_{\inf}, d_{\inf}, f_{\inf})}{\log(h_{\sup}, d_{\sup}, f_{\sup} / h_{\inf}, d_{\inf}, f_{\inf})}$$
    - ✓ E_{inf}, E_{sup}: Field strength value for lower/higher nominal value
    - ✓ h_b, d, f: required value for prediction
    - ✓ h_{inf}, d_{inf}, f_{inf} / h_{sup}, d_{sup}, f_{sup}: lower/higher nominal value
  - For percentage time
  - $$E = E_{\sup}(Q_{\inf} - Q_t)/(Q_{\inf} - Q_{\sup}) + E_{\inf}(Q_t - Q_{\sup})/(Q_{\inf} - Q_{\sup})$$
    - ✓ $Q_t = Q_i(t/100)$, t: percentage time
    - ✓ $Q_i(x)$: inverse complementary cumulative normal distribution function

ITU-R P. 1546 model (3/4)

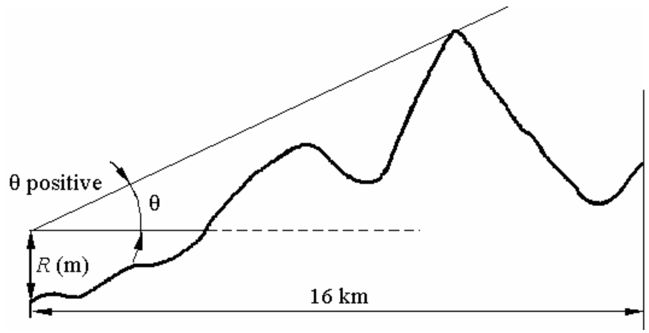
- Mixed paths
  - Step1. The total length of path that lies over land d_l
  - Step 2. The quantity Δ
    - ✓ $$\Delta = \begin{cases} d_l \left[E_{land}(1km) - E_{sea}(1km) \right] & , \ for\ d_l < 1\ km \\ E_{land}(d_l) - E_{sea}(d_l) & , \ otherwise \end{cases}$$
  - Step 3. The mixed path value at the MS antenna distance, d_{total}
    - ✓ $$E_{mix}(d_{total}) = E_{sea}(d_{total}) + \Delta$$
  - Step 4. The difference between mixed-path and land path field strength
    - ✓ $$\Delta E = E_{mix}(d_{total}) - E_{land}(d_{total})$$
  - Step 5. An interpolation factor
    - ✓ $$\chi = \alpha + (1-\alpha)\exp[-(\beta \cdot d_l^{\,2.42-0.0003527\,h_{BS}})] \quad \alpha = 0.3,\ \beta = 0.0001$$
  - Step 6. The field strength for the mixed path
    - ✓ $$E = E_{land}(d_{total}) + \Delta E \cdot \chi$$

ITU-R P. 1546 model (4/4)

- Corrections
  - MS antenna height
  - Effective terrain clearance angle θ_{eff} from BS antenna

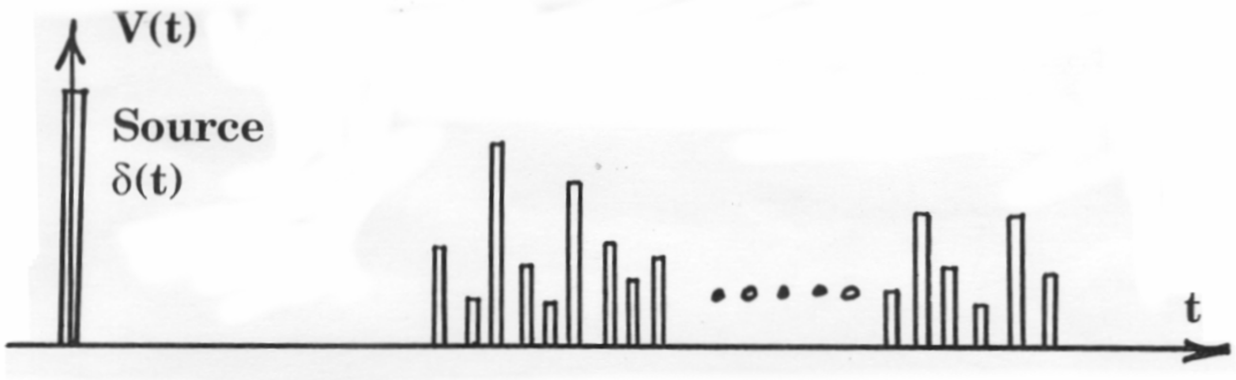


  - Terrain clearance angle θ from MS antenna



  - Location variability
- Equivalent basic transmission loss
  - $L_b = 139 - E + 20\log f_c$

Impulse response in a Multipath Environment

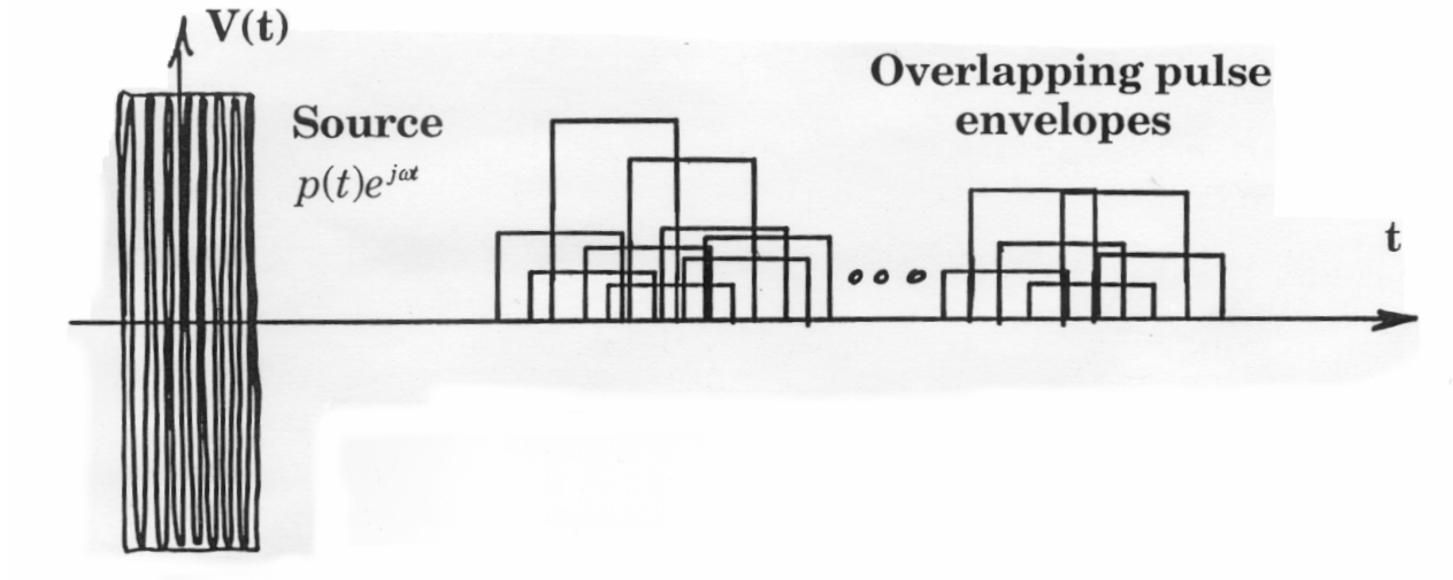


- Received Voltage: $V(t) = \sum_n a_n \delta(t - \tau_n)$
  - ☞ a_n=amplitude of n^{th} ray
  - ☞ $\tau_n = L_n/c$=Travel time of the n^{th} ray
- For non-overlapping impulses

$$P(t) = |V(t)|^2 = \sum_n \sum_m a_n a_m \delta(t - \tau_n)\delta(t - \tau_m) = \sum_n a_n^2 \delta^2(t - \tau_n)$$

$$= \text{sum of ray powers}$$

Finite Width Pulse Response in Multipath

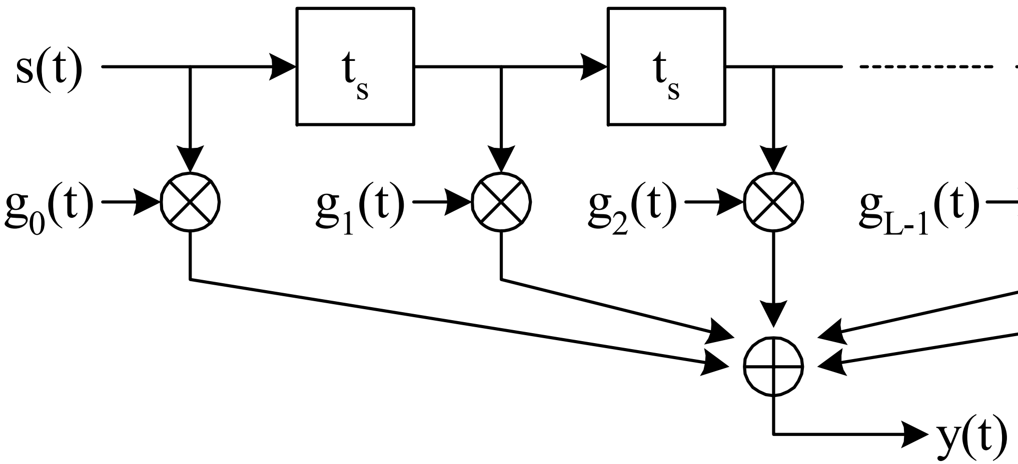


- Received voltage: $V(t) = \sum_n a_n p(t - \tau_n) e^{-jkL_n} e^{jwt} e^{j\phi_n}$
- For partially overlapping pulses

$$P(t) = |V(t)|^2 = \sum_n \sum_m a_n a_m^* p(t - \tau_n) p(t - \tau_m) e^{-jk(L_n - L_m)}$$

Tapped Delay Line Model

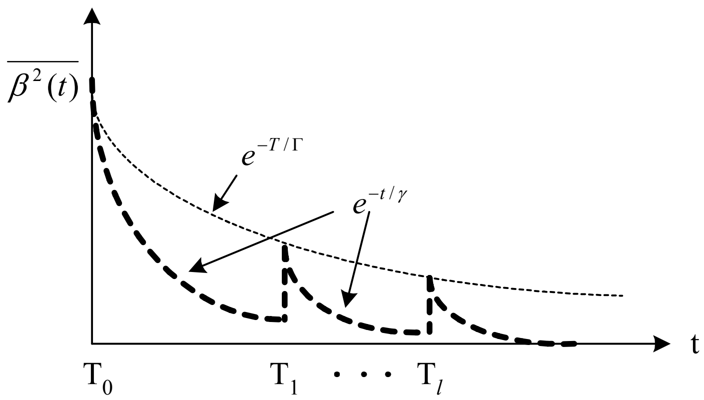
- The discrete time frequency-selective fading channel model
  - Tapped delay line (TDL) with spacing t_s and time varying coefficients $g(t)$

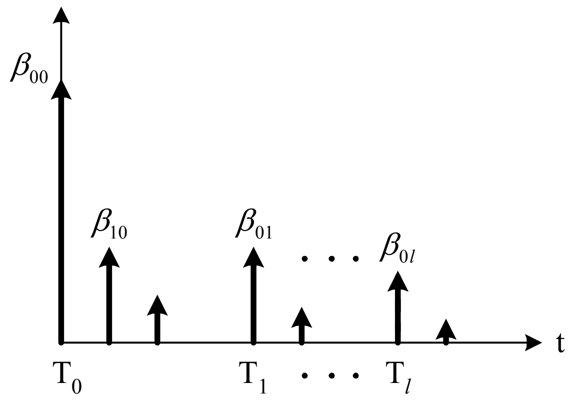


  - t_s: Poisson arrival distribution
  - $g(t)$: Rician or Rayleigh distribution

Saleh & Valenzuela Model

- Channel model
  - $h(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} \beta_{kl} e^{j\theta_{kl}} \delta(t - T_l - \tau_{kl})$
  - $\{\theta_{kl}\}$: statistically independent uniform r.v. over $[0, 2\pi)$
  - $\{\beta^2_{kl}\}$: monotonically decreasing functions of $\{T_l\}$ and $\{t_l\}$
  - The first rays of the clusters & subsequent rays
    - ✓ Poisson arrival distribution (rate Λ, γ)
    - ✓ $p(T_l|T_{l-1}) = \Lambda \exp[-\Lambda(T_l - T_{l-1})]$, $p(\tau_{kl} \mid \tau_{(k-1)l}) = \lambda \exp[-\lambda(\tau_{kl} - \tau_{(k-1)l})]$, $l, k > 0$





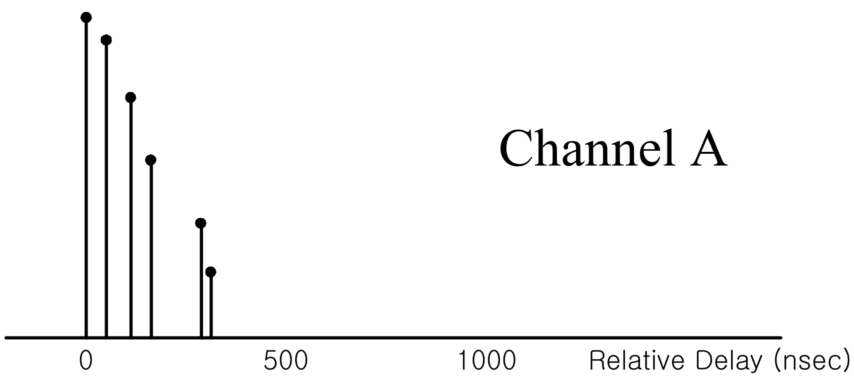
ETSI Channel Model

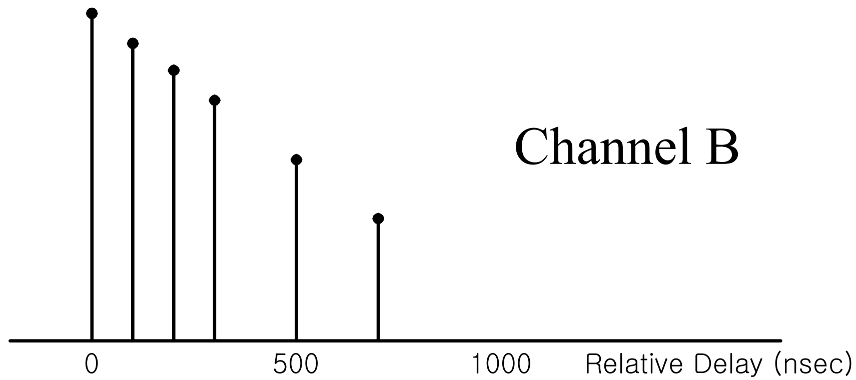
- Classify test environment into 3 cases
- Separate Channel w.r.t RMS delay spread

Test Environment	RMS delay of Channel A (nsec)	P(A) (%)	RMS delay of Channel B (nsec)	P(B) (%)
Indoor Office	35	50	100	45
Outdoor to Indoor and Pedestrian	45	40	750	55
Vehicular (High Antenna)	370	40	4000	55

Examples (ETSI Model)
Indoor office case

Tap	Channel A		Channel B		Doppler Spectrum
	Rel. Delay (nsec)	Avg. Power (dB)	Rel. Delay (nsec)	Avg. Power (dB)	
1	0	0	0	0	FLAT
2	50	-3.0	100	-3.6	FLAT
3	110	-10.0	200	-7.2	FLAT
4	170	-18.0	300	-10.8	FLAT
5	290	-26.0	500	-18.0	FLAT
6	310	-32.0	700	-25.2	FLAT





JTC Channel Model

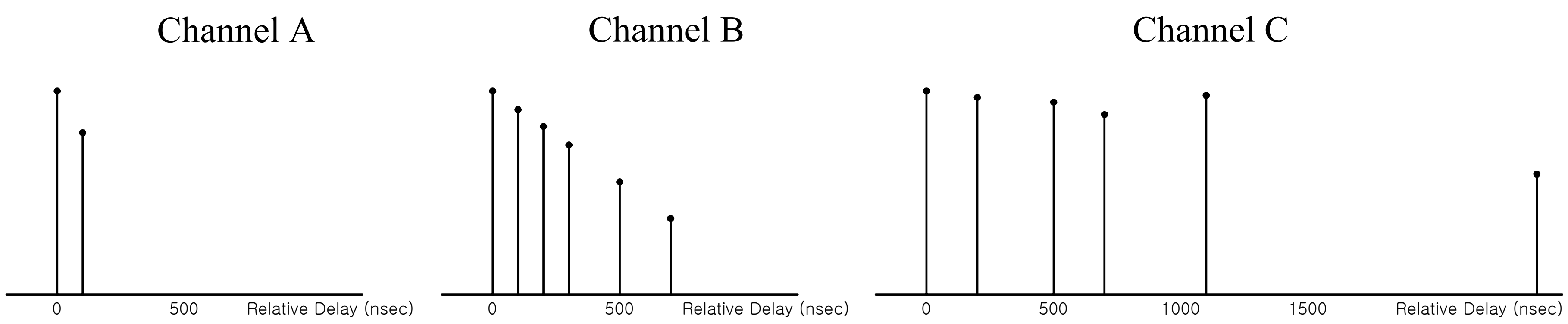
- Classify test environment into 9 cases
- Separate Channel w.r.t RMS delay spread

Indoor		Residential
		Office
		Commercial
Outdoor	Pedestrian	Urban High-Rise
		Urban/Suburban Low-Rise
		Residential
	Vehicular	Urban High-Rise
		Urban/Suburban Low-Rise
		Residential

Examples (JTC Model)

Indoor Office Case

Tap	Channel A		Channel B		Channel C		Doppler Spectrum
	Rel. Delay	Avg. Power	Rel. Delay	Avg. Power	Rel. Delay	Avg. Power	
1	0	0	0	0	0	0	FLAT
2	100	-8.5	100	-3.6	200	-1.4	FLAT
3			200	-7.2	500	-2.4	FLAT
4			300	-10.8	700	-4.8	FLAT
5			500	-18.0	1100	-1.0	FLAT
6			700	-25.2	2400	-16.3	FLAT



IEEE-802.11 WLANs TGn channel model

- Five delay profile models proposed for different indoor environments
- Include spatial information for channel model

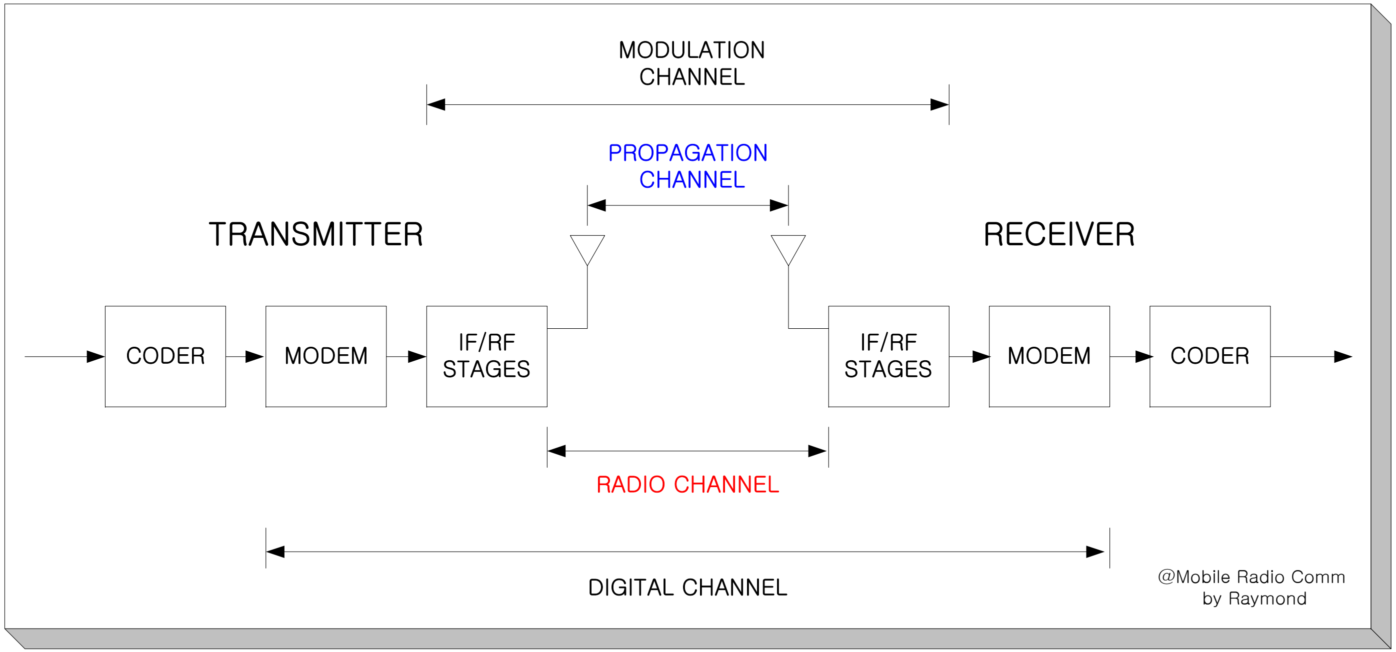
Model	Condition	K (dB) LOS/NLOS	RMS delay (ns) (NLOS)	# of clusters	Environments
A	LOS/NLOS	$0 / -\infty$	0	1 tap	Optional, 1 tap at 0 ns delay model
B	LOS/NLOS	$0 / -\infty$	15	2	Residential homes and small offices
C	LOS/NLOS	$0 / -\infty$	30	2	
D	LOS/NLOS	$3 / -\infty$	50	3	
E	LOS/NLOS	$6 / -\infty$	100	4	
F	LOS/NLOS	$6 / -\infty$	150	6	

Examples (WLANs TGn channel model B)

	Tap index	1	2	3	4	5	6	7	8	9
	Excess delay (ns)	0	10	20	30	40	50	60	70	80
Cluster 1	Power (dB)	0	- 5.4	-10.8	-16.2	-21.7				
AoA	AoA (°)	43	43	43	43	43				
AS(Rx)	AS (°)	14.4	14.4	14.4	14.4	14.4				
AoD	AoD (°)	225.1	225.1	225.1	225.1	225.1				
AS(Tx)	AS (°)	14.4	14.4	14.4	14.4	14.4				
Cluster 2	Power (dB)			- 3.2	- 6.3	- 9.4	- 12.5	- 15.6	- 18.7	- 21.8
AoA	AoA (°)			118.4	118.4	118.4	118.4	118.4	118.4	118.4
AS(Rx)	AS (°)			25.2	25.2	25.2	25.2	25.2	25.2	25.2
AoD	AoD (°)			106.5	106.5	106.5	106.5	106.5	106.5	106.5
AS(Tx)	AS (°)			25.4	25.4	25.4	25.4	25.4	25.4	25.4

Spatial Channel Model (SCM) (1/2)

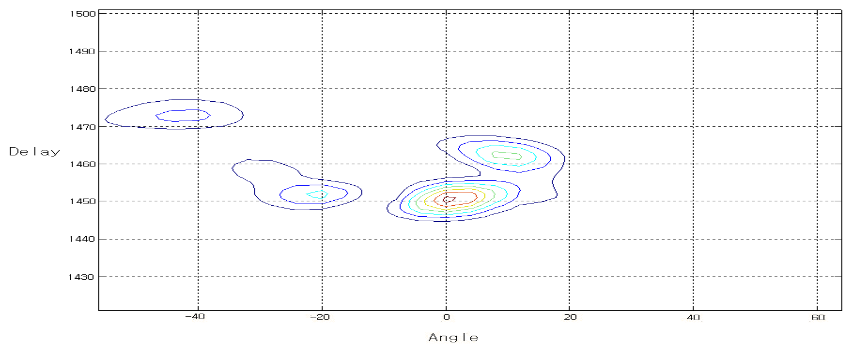
- Moving Focus : from Propagation Channel to Radio Channel
  - Spatial description of channel attributes (DoA, DoT, AS, DS, per-path PDP, etc)
  - Inclusion of the antenna pattern
  - Time-dependent trajectory of the MS

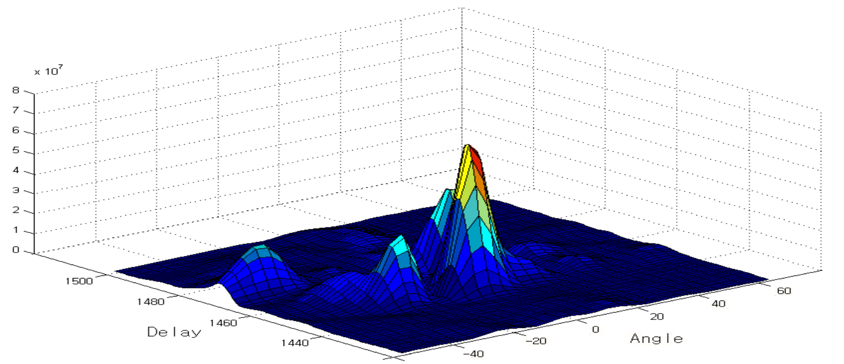


Spatial Channel Model (SCM) (2/2)

Example of spatial channel information

- Real Measurement Data : Angle vs Delay vs Power -

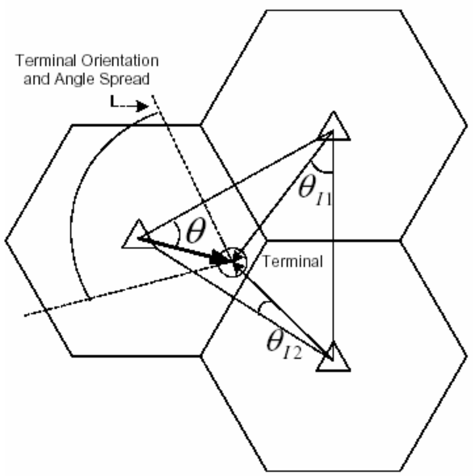




Link level vs System level SCM

- Link Level Spatial Channel Parameters (Base Station and Terminal Specific)
  - Mean Angle of Arrival
  - Rms Angle Spread
  - Power Azimuth Spectrum
  - Behavior per Resolvable Path
  - Ricean and Rayleigh Fading

- System Level Spatial Channel Parameters (System Wide Parameters)
  - BS, MS Positions
  - AOA, AS, PAS for each terminal
  - Random MS Orientation
  - Mixture of Channel Models
  - Explicit Spatial Interference Modeling
  - Per-path spatial parameters



Link Level SCM assumptions (1/3): parameters

- Only one snapshot of the channel behavior
- Not used to compare performance of different algorithms.
- Only for calibration : comparison of performance results from different implementations of a given algorithm.

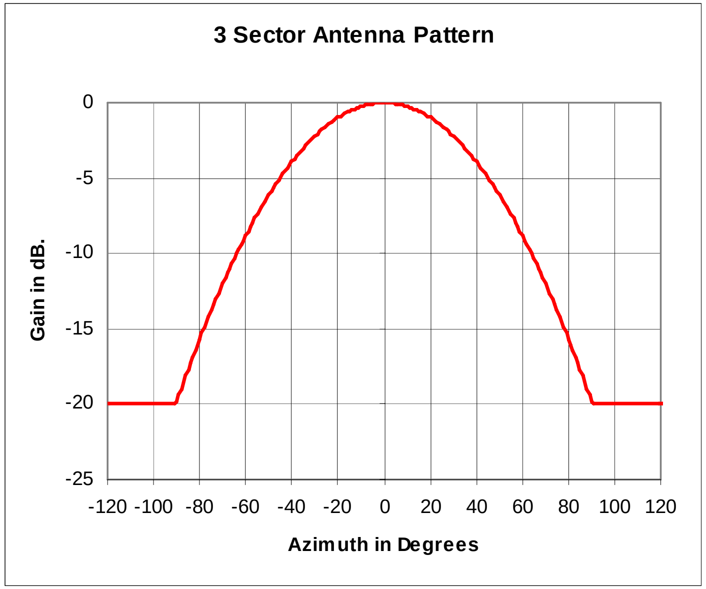
Model	Case I		Case II		Case III		Case IV	
Corresponding 3GPP Designator*	Case B		Case C		Case D		Case A	
Corresponding 3GPP2 Designator*	Model A, D, E		Model C		Model B		Model F	
PDP	Modified Pedestrian A		Vehicular A		Pedestrian B		Single Path	
# of Paths	1) 4+1 (LOS on, K = 6dB) 2) 4 (LOS off)		6		6		1	
Relative Path Power (dB) / Delay (ns)	1) 0.0 2) -Inf	0	0,0	0	0.0	0	0	0
	1) -6.51 2) 0.0	0	-1.0	310	-0.9	200		
	1) -16.21 2) -9.7	110	-9.0	710	-4.9	800		
	1) -25.71 2) -19.2	190	-10.0	1090	-8.0	1200		
	1) -29.31 2) -22.8	410	-15.0	1730	-7.8	1730		
			-20.0	2510	-23.9	3700		
Speed (km/h)	1) 3 2) 30, 120		3, 30, 120		3, 30, 120		3	

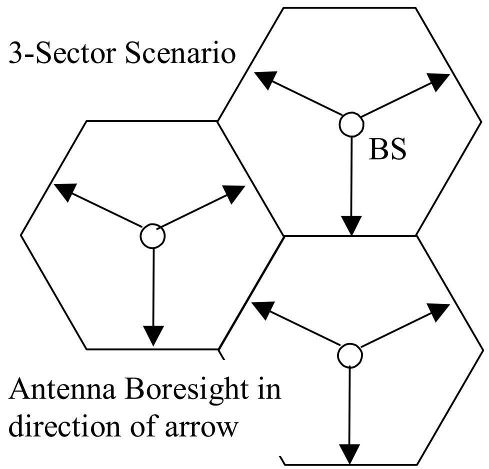
Link Level SCM assumptions (2/3): parameters

UE/Mobile Station	Topology	Reference 0.5?	Reference 0.5?	Reference 0.5?	N/A
	PAS	1) LOS on: Fixed AoA for LOS component, remaining power has 360 degree uniform PAS. 2) LOS off: PAS with a Lapacian distribution, RMS angle spread of 35 degrees per path	RMS angle spread of 35 degrees per path with a Lapacian distribution Or 360 degree uniform PAS.	RMS angle spread of 35 degrees per path with a Lapacian distribution	N/A
	DoT (degrees)	0	22.5	-22.5	N/A
	AoA (degrees)	22.5 (LOS component) 67.5 (all other paths)	67.5 (all paths)	22.5 (odd numbered paths), -67.5 (even numbered paths)	N/A
Node B/ Base Station	Topology	Reference: ULA with 0.5?-spacing or 4?-spacing or 10?-spacing			N/A
	PAS	Lapacian distribution with RMS angle spread of 2 degrees or 5 degrees, per path depending on AoA/AoD			N/A
	AoD/AoA (degrees)	50° for 2° RMS angle spread per path 20° for 5° RMS angle spread per path			N/A

Link Level SCM assumptions (3/3)
BS antnena parameters

- A_m is max attenuation 20 dB for 3 sector, 23dB for 6 sector
- θ_{3dB} is 70° for 3 sector, 35° for 6 sector





$$A(\theta) = -\min\left[12\left(\frac{\theta}{\theta_{3dB}}\right)^2,\ A_m\right] \quad \text{where} \quad -180 \le \theta \le 180$$

Link Level SCM Reference Values for calibration

- A_m is max attenuation 20 dB for 3 sector, 23dB for 6 sector
- θ_{3dB} is 70° for 3 sector, 35° for 6 sector

Table 2-2. Reference Correlation Values.

	Antenna Spacing	AS (degrees)	AOA (degrees)	Correlation (magnitude)	Complex Correlation
BS	0.5λ	5	20	0.9688	0.4743+0.8448i
	0.5λ	2	50	0.9975	-0.7367+0.6725i
	4λ	5	20	0.3224	-0.2144+0.2408i
	4λ	2	50	0.8624	0.8025+0.3158i
	10λ	5	20	0.0704	-0.0617+i0.034
	10λ	2	50	0.5018	-0.2762-i0.4190
MS	$\lambda/2$	104	0	0.3042	-0.3042
	$\lambda/2$	35	-67.5	0.7744	-0.6948-i0.342
	$\lambda/2$	35	22.5	0.4399	0.0861+0.431i
	$\lambda/2$	35	67.5	0.7744	-0.6948+i0.342

General description for System level SCM (1/3)

Assumptions

- Multiple cells environments : BSs & MSs
- Performance metrics (throughput, delay etc) are collected over *D* drops
- Quasi-static channel for each drop
  - the channel undergoes fast fading
  - the locations of the MSs are fixed for each drop.

Final Goal

- For an *S* element BS array and a *U* element MS array, obtain the channel coefficients for one of *N* multipath components

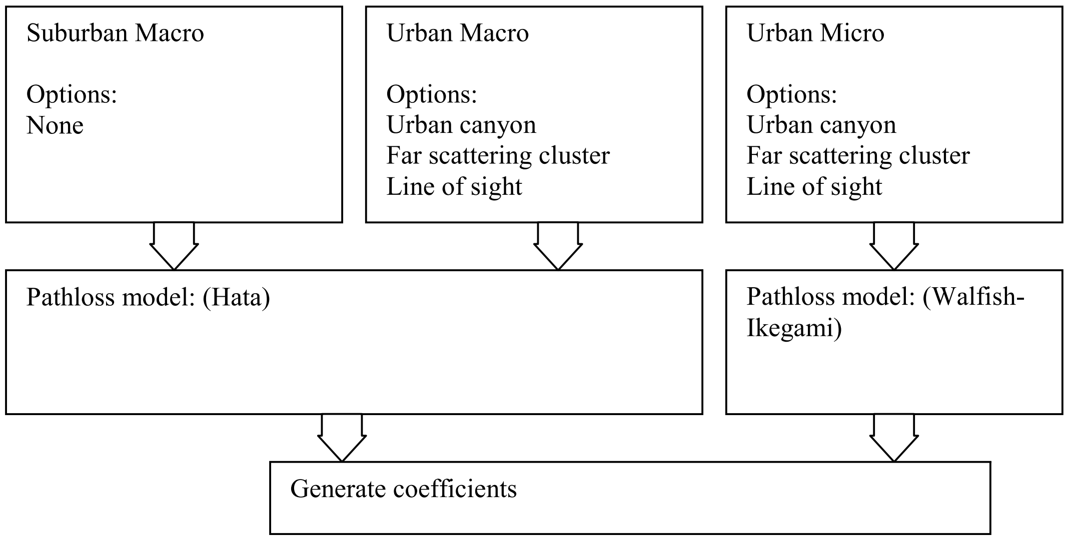
$\mathbf{H}_n(t)$ **S -by- U matrix of complex amplitudes at n^{th} path**

$$h_{s,u,n}(t) = \sqrt{\frac{P_n}{M}}\left(\sum_{m=1}^{M} \begin{matrix} \sqrt{G_{BS}(\theta_{n,m,AoD})}\exp\left(jkd_s\sin(\theta_{n,m,AoD})\right)\times \\ \sqrt{G_{MS}(\theta_{n,m,AoA})}\exp\left(j\left[kd_u\sin(\theta_{n,m,AoA})+\Phi_{n,m}\right]\right)\end{matrix}\right)\cdot\exp\left(jk\|\mathbf{v}\|\cos(\theta_{m,n,AoA}-\theta_v)\,t\right)$$

General description for System level SCM (2/3)

Procedure for generating the channel matrix $\mathbf{H}_n(t)$

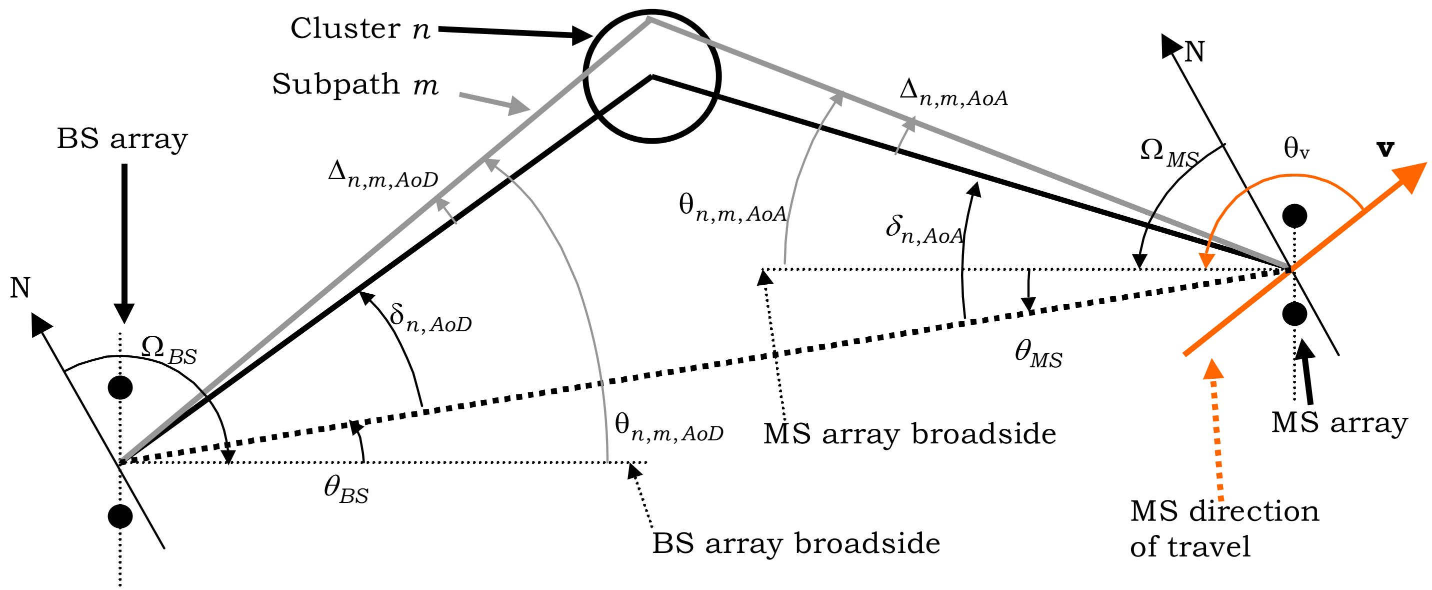
- Specify an environment : urban/suburban macro, or urban micro
- Obtain the parameters to be used in simulations
- Generate the channel coefficients



General description for System level SCM (3/3)

Ray-based Scattering Model

- N time-delayed multipath ($N = 6$ or 3)
- M subpaths per multipath ($M = 20$)



Scenario Parameters (1/2)

- Macrocell ; BS to BS 3 km with antennas above rooftop
- Microcell ; BS to BS 1 km with antennas at rooftop height

Channel Scenario	Suburban Macro	Urban Macro	Urban Micro
Number of paths (N)	6	6	3
Number of sub-paths (M) per path	20	20	20
Mean composite AS at BS	$E(\sigma_{AS})=5^0$	$E(\sigma_{AS})=8^0$, 15^0	N/A
r_{DS} ($\sigma_{delays}/\sigma_{DS}$)	1.4	1.7	N/A
r_{AS} ($\sigma_{AoD}/\sigma_{PAS}$)	1.2	1.3	N/A
Composite AS at BS as a lognormal RV when simulating with 6 paths $\sigma_{AS} = 10 \wedge (\varepsilon_{AS} x + \mu_{AS}),\ x \sim \eta(0,1)$	μ_{AS}= 0.69 ε_{AS}= 0.13	8^0 μ_{AS}= 0.810 ε_{AS}= 0.3295 15^0 μ_{AS}= 1.18 ε_{AS}= 0.210	N/A
Per path AS at BS (Fixed)	2 deg	2 deg	5 deg (LOS and NLOS)
BS Per path AoD Distribution st dev	N(0, σ^2_{AoD}), where $\sigma_{AoD} = r_{AS} * \sigma_{AS}$	N(0, σ^2_{AoD}), where $\sigma_{AoD} = r_{AS} * \sigma_{AS}$	U(-60deg, 60deg)

Scenario Parameters (2/2)

Channel Scenario	Suburban Macro	Urban Macro	Urban Micro
Mean of RMS composite AS at MS	$E(\sigma_{AS,\ comp,UE})=72^0$	$E(\sigma_{AS,\ comp,\ UE})=72^0$	$E(\sigma_{AS,\ comp,\ UE})=72^0$
Per path AS at MS (fixed)	35^0	35^0	35^0
MS Per path AoA Distribution	$N(0,\ \sigma^2_{AoA}\ (P_r))$	$N(0,\ \sigma^2_{AoA}\ (P_r))$	$N(0,\ \sigma^2_{AoA}\ (P_r))$
Mean total RMS Delay Spread	$E(\sigma_{DS})=0.17\ \mu s$	$E(\sigma_{DS})=0.65\ \mu s$	N/A
Narrowband composite delay spread as a lognormal RV when simulating with 6 paths $\sigma_{DS} = 10\ \wedge (\varepsilon_{DS} x + \mu_{DS}),\ x \sim \eta(0,1)$	$\mu_{DS} = -6.80$ $\varepsilon_{DS} = 0.288$	$\mu_{DS} = -6.18$ $\varepsilon_{DS} = 0.18$	N/A
Lognormal shadowing standard deviation	8dB	8dB	10dB

Path Loss Model

- Macrocell : Modified *Hata* Model
- Microcell : *Walfisch-Ikegami* Model

AoD for N multipath

- Angle of Departure (AoD) for N multipath

Wish to generate RVs : $\delta_{n,AoD}$ corresponding to n^{th} multipath

- $\delta_n' \sim \eta(0,\sigma^2_{AoD})$, $\sigma_{AoD} = r_{AS} * \sigma_{AS}$
- Proportional factor r_{AS} = angle occurrence (σ_{AoD}) / power weighted angular spread(σ_{AS})

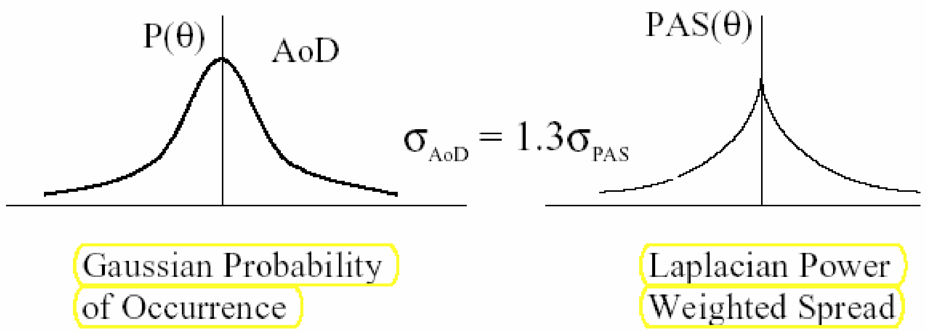


Figure 2. Relationship between AoD and PAS

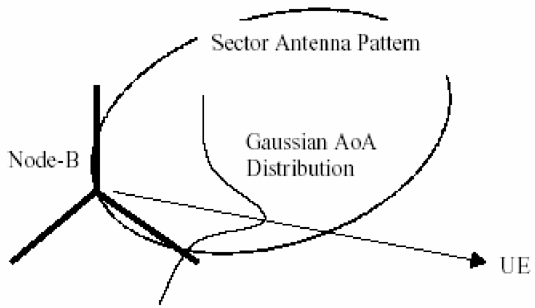


Figure 1. Gaussian distribution for angle of departure from Node-B

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- Obtain $\delta_{n,AoD}$ as increasing order : $\delta_{1,AoD} < \ldots < \delta_{n,AoD}$