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Cellular Network Planning and Optimization Part II: Fading

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TKK, 17.1.2007

Outline

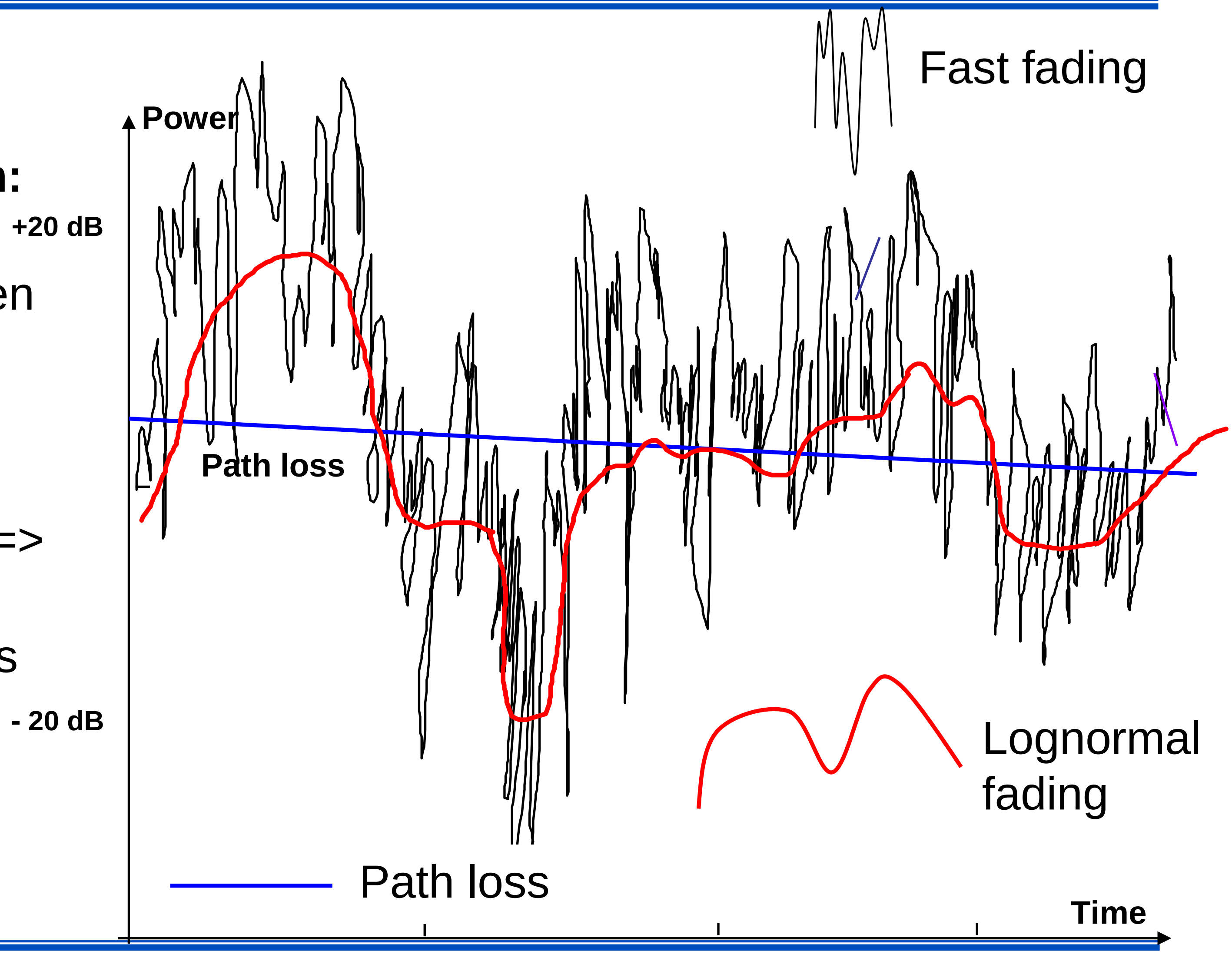
- Modeling approaches
- Path loss models
- Shadow fading
- Fast fading

Modeling approaches

Fading seen by moving terminal

Modeling approach:

1. Distance between TX and RX => path loss
2. Shadowing by large obstacles => shadow fading
3. Multi-path effects => fast fading



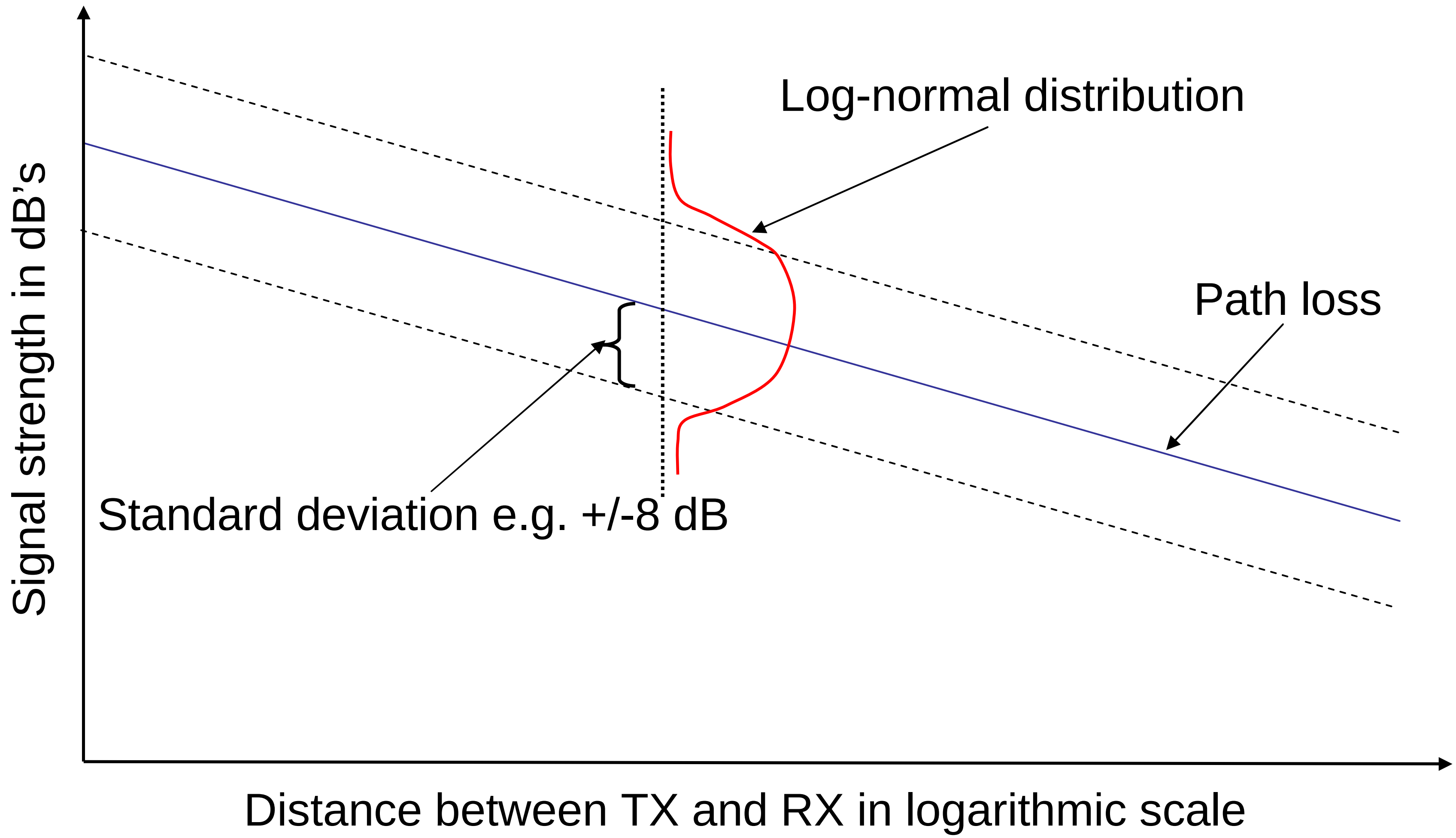
Path Loss

- Path loss is distance dependent mean attenuation of the signal.
- Once the allowed path loss of a certain system is known we can solve the maximum distance between transmitter and receiver and compute the relative coverage area.
- Suitable path loss model depends on the environments (macro-cell, micro-cell, indoor)
  - Outdoor to outdoor models
  - Outdoor to indoor models
  - Indoor models

Shadow Fading

- Shadow fading is used to model variations in path loss due to large obstacles like buildings, terrain conditions, trees.
- Shadow fading is also called as log-normal fading since it is modeled using log-normal distribution
- In cell dimensioning/link budget shadow fading is taken into account through a certain margin (=shadow fading margin)

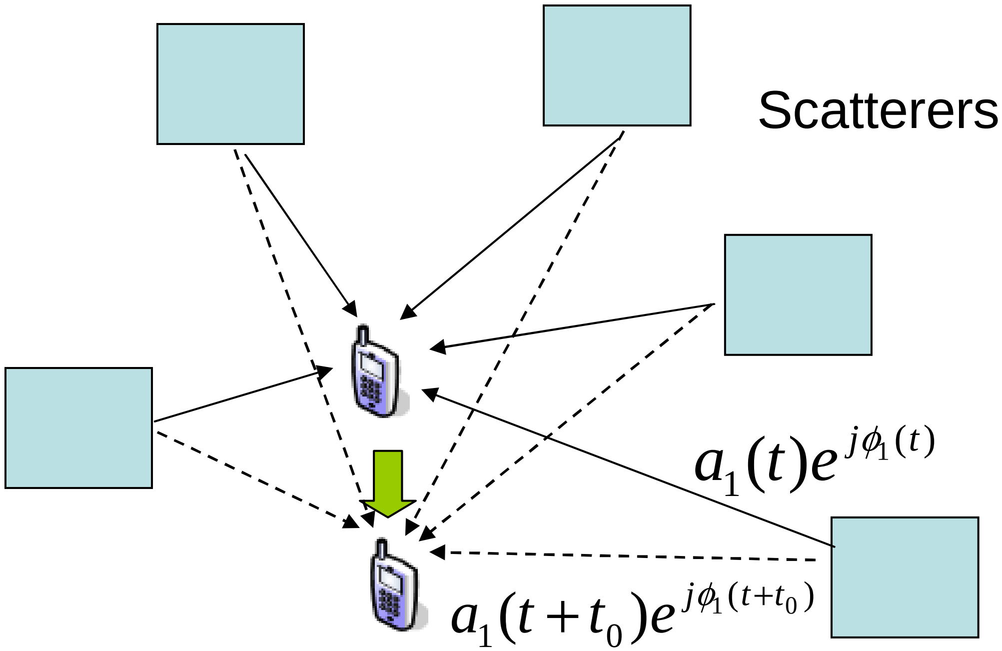
Path loss + shadow fading



Fast Fading

- Fast fading is also called as multi-path fading since it is mainly caused by multi-path reflections of a transmitted waves by local scatterers such as human build structures or natural obstacles
  - Fast fading occurs since MS and/or scatterers nearby MS are moving
  - Signal strength in the receiver may change even tens of decibels within a very short time frame
  - Signal coherence distance = separation between locations where fast fading correlation is negligible. Signal coherence distance is half of the carrier wavelength
    - f = 2GHz => coherence distance = c/(2*f) =7.5 cm
  - Coherence time = time in which MS travels coherence distance
    - Coherence time depends on MS speed.
- In cell dimensioning/link budget fast fading is taken into account through a certain margin (=fast fading margin)

Fast Fading



Especially the changes in component signal phases create rapid variations in sum signal

Sum signal at time t $S(t) = a_1(t)e^{j\phi_1(t)} + \ldots + a_5(t)e^{j\phi_5(t)}$

Sum signal at time t+t0 $S(t+t_0) = a_1(t+t_0)e^{j\phi_1(t+t_0)} + \ldots + a_5(t+t_0)e^{j\phi_5(t+t_0)}$

Path loss models

Content

- We recall first two important path loss models for macro- and micro-cell environments
  - I Model: Classical Okumura-Hata
    - Okumura-Hata is based on only few parameters but it works well and is widely used to predict path loss in macro-cell environments
  - II Model: COST 231 or Walfisch – Ikegami
    - This model is suitable for both macro- and micro-cell environments and it is mode general than Okumura-Hata. Walfisch – Ikegami models propagation phenomena more accurately but in cost of increased complexity.
- Then we consider path loss in urban environment when both transmitter and receiver are below the rooftop (Berg model)
  - Outdoor to outdoor model
  - Path loss of RS – MS signal in street canyon II Model: BRT – BRT, NLOS (Berg model)
- Finally, we discuss shortly on outdoor-to-indoor modeling
- Terminology
  - ART= Above Roof Top
  - BRT = Below Roof Top
  - LOS = Line-of-Sight
  - NLOS = Non Line-of-Sight

General path loss model/outdoor

- Outdoor path loss models are usually given in the form

(*) $$L = A + 10 \cdot n \cdot \log_{10}(R)$$ (in decibels)

Here

- R is the distance between TX and RX
- A and n are constants. Values of these constant are depending on the various parameters such as carrier frequency, antenna heights etc

- An other form for formula (*)

$$\tilde{L} = 10^{L/10} = 10^{A/10} \cdot R^n = \tilde{A} \cdot R^n$$

Note that n defines the exponential attenuation of the signal. Typically its value is 3-4 in urban environment. In free space n=2.

Okumura-Hata

- Okumura-Hata propagation loss model
  - Based on measurements in Tokyo
  - May be the most widely used path loss model for attenuation of cellular transmissions in built up areas.
  - Most suitable for large macro-cells

$$L = A + B\log_{10} f_c - 13.82\log_{10} h_b - a\left(h_m\right) + \left(C - 6.55\log_{10} h_b\right)\log_{10} d$$

A and B constants

	150-1000 MHz	1500 – 2000 MHz
A	69.55	46.3
B	26.16	33.9
C	44 – 47, default 44.9	

f_c Carrier frequency (MHz)

h_b Base station antenna height

$30m \le h_b \le 200m$

h_m Mobile station antenna height

$h_m \approx 1.5m$

$a\left(h_m\right)$ Mobile antenna gain function

C constant gives distance dependency and should be fitted to local measurements

Okumura-Hata

- Mobile station antenna gain function
  - Small/Medium size city

$$a(h_m)=(1.1\log_{10} f_c-0.7)h_m-(1.56\log_{10} f_c-0.8)$$

  - Large city

$$a(h_m)=\begin{cases} 8.29(\log_{10}(1.54h_m))^2-1.1 & f\leq 200MHz \\ 3.2(\log_{10}(11.75h_m))^2-4.97 & 200MHz< f_c\leq 1500MHz \end{cases}$$

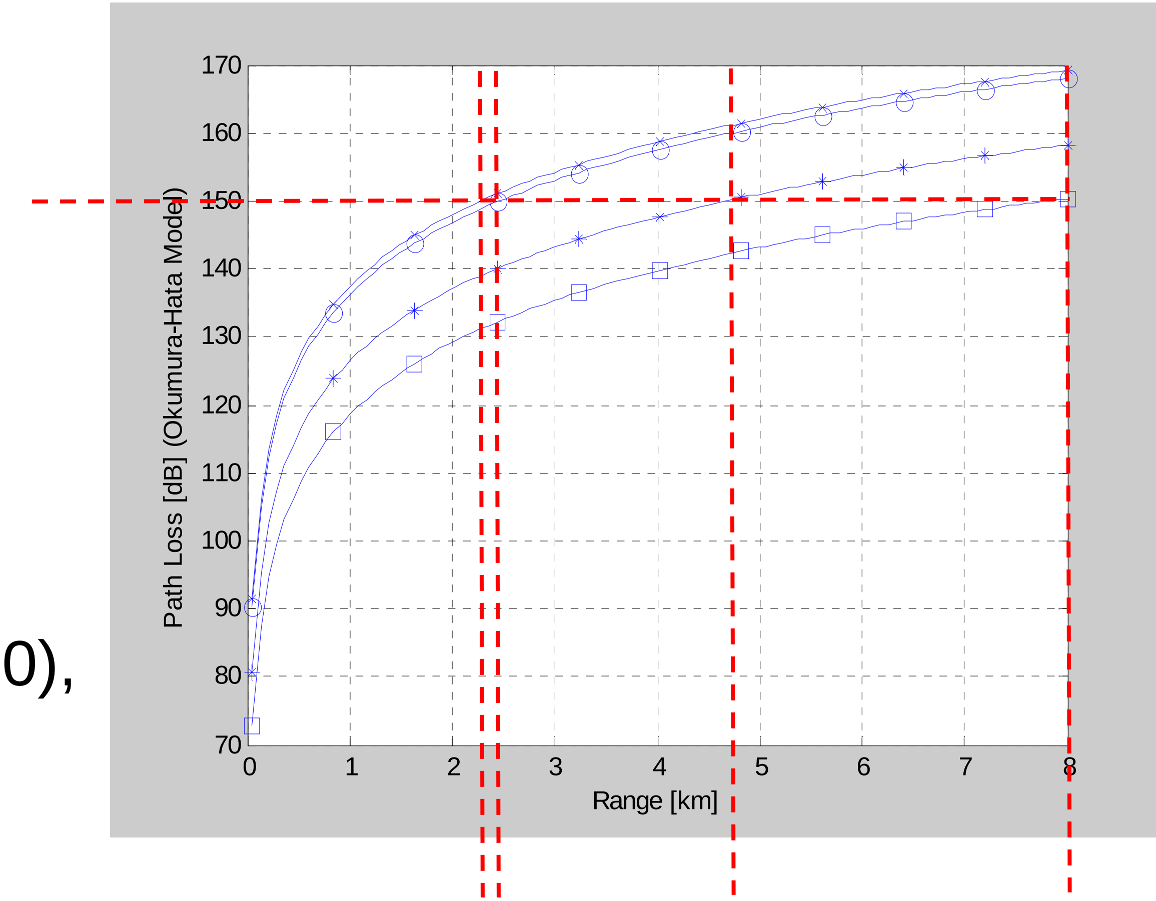
  - Antenna gain function can be in most cases be ignored!

$$a(h_m)=0, \quad f_c>1500 \ MHz$$

$$a(h_m)=0, \quad h_m=1.5m$$

Okumura-Hata: Example

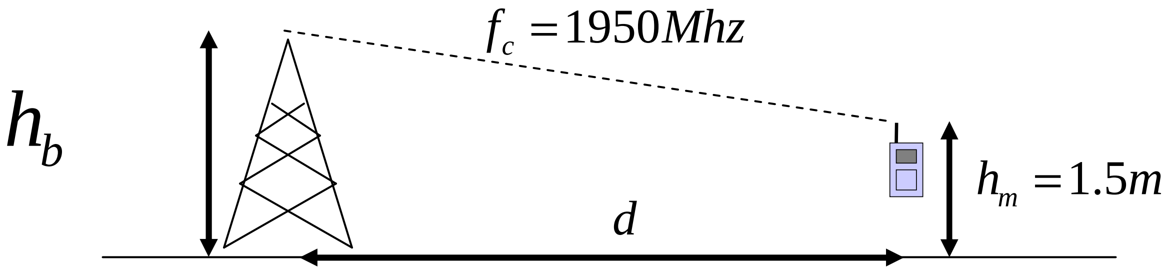
- Path loss according to Okumura-Hata model in large city when
  - f = 450 MHz (□)
  - f = 900 MHz (*)
  - f = 1800 MHz (o)
  - f = 1950 MHz (x)
- Flash-OFDMA (NMT-450), GSM900, GSM1800, WCDMA



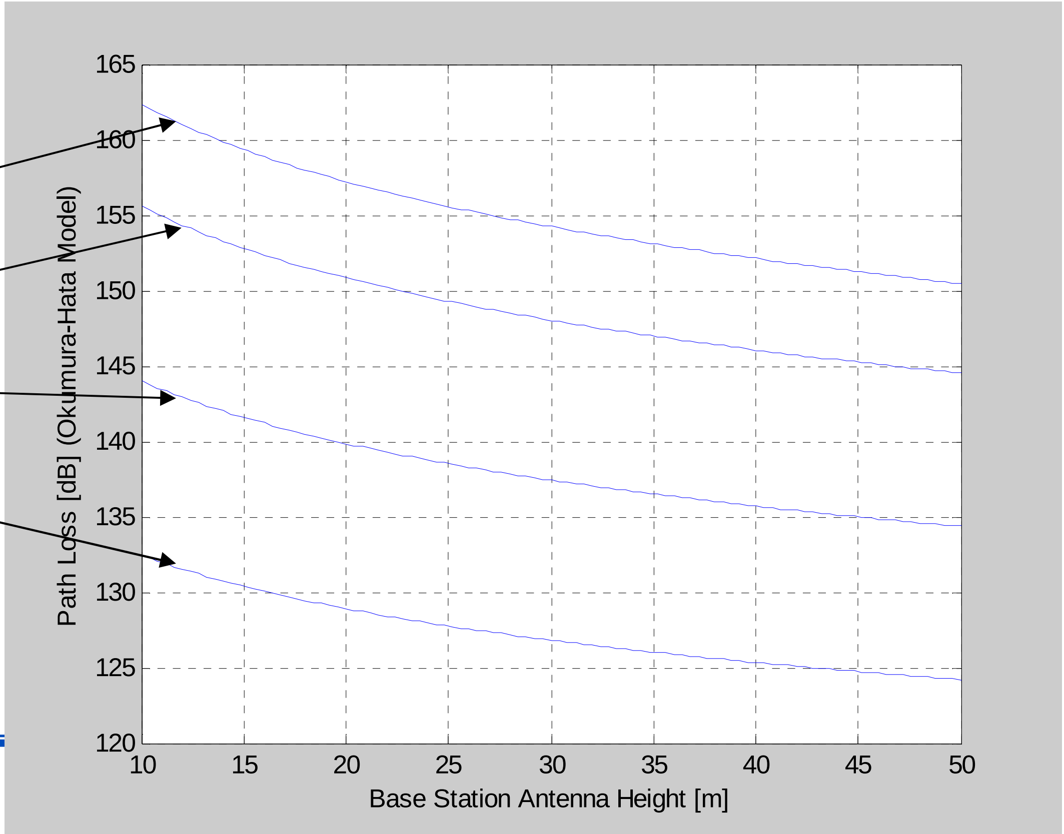
Note: There would be huge differences in coverage if allowed path losses would be the same for different systems

BS height = 30m, MS height = 1.5m

Okumura-Hata: Example



- Impact of base station antenna height:
  - Distance = 3.0 km
  - Distance = 2.0 km
  - Distance = 1.0 km
  - Distance = 0.5 km
- Distance measured between TX and RX



COST231-Walfisch-Ikegami path loss model

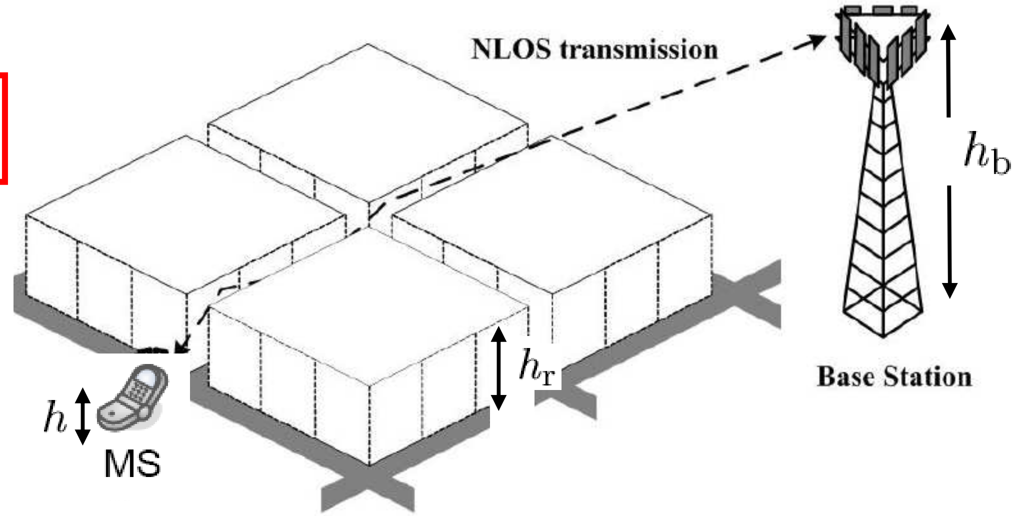
$$L = L_0 + L_{\mathrm{rts}} + L_{\mathrm{msd}} + a(h)$$

L_0 = Free space loss

L_{rts} = Roof top to street diffraction

L_{msd} = Multi-screen loss

$a(h)$ = correction factor that depends on mobile/relay station height



In the following we also use notations:

- R = Distance [km], limited to 0.02 - 5 km
- f = frequency [MHz], limited to 800 - 2000 MHz
- ϕ = Street orientation [deg]
- h_{r} = Roof top height [m]
- h = Mobile station/relay station height [m]
- h_{b} = Base station height [m], limited to 4 - 50 m
- w = Street width [m]
- b = Building spacing

Note: we consider only NLOS case

COST231-Walfisch-Ikegami path loss model

Free space loss:

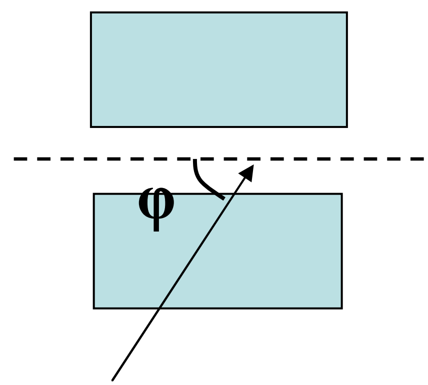
$$L_0 = 32.4 + 20 \cdot \log_{10}(R \cdot f)$$

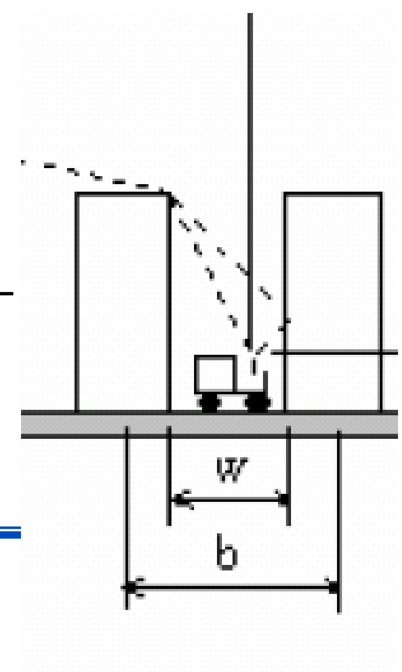
Roof top to street diffraction:

$$L_{\mathrm{rts}} = \max \left\{0, -16.9 + 10 \cdot \log_{10}(f/w) + 20 \cdot \log_{10}(h_{\mathrm{r}} - h) + L_{\mathrm{ori}}\right\},$$

$$L_{\mathrm{ori}} = \begin{cases} -10 + 0.354\phi & 0 \le \phi \le 35, \\ 2.5 + 0.075(\phi - 35), & 35 \le \phi \le 55, \\ 4.0 - 0.114(\phi - 55), & 55 \le \phi \le 90. \end{cases}$$

The rooftop-to-street diffraction loss term determines the loss which occurs on the wave coupling into the street where the receiver is located



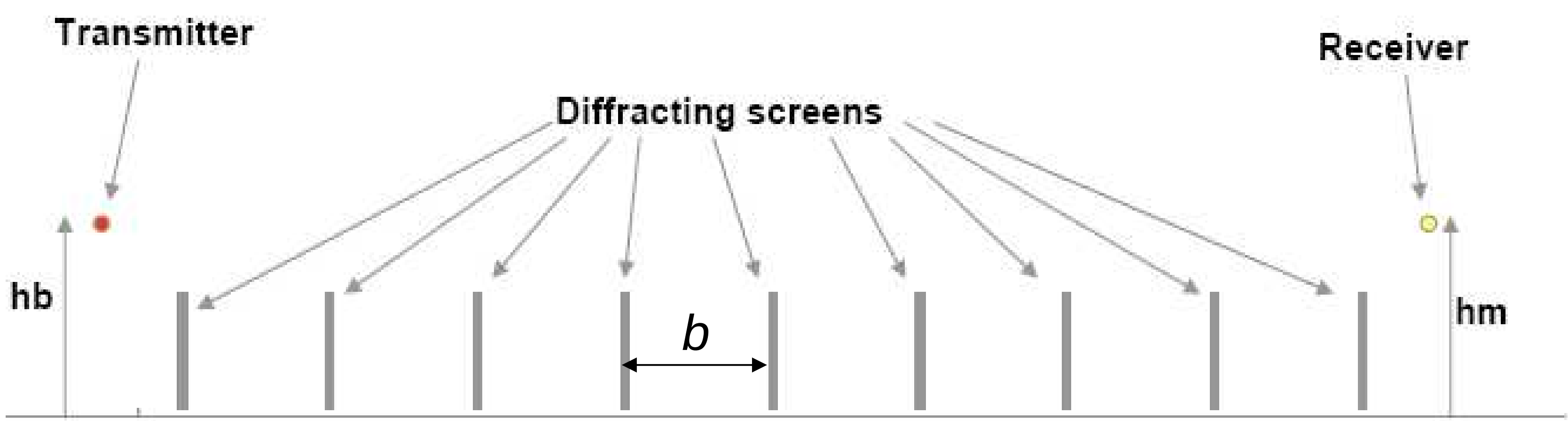


COST231-Walfisch-Ikegami path loss model

Multi-screen diffraction loss

$$L_{\mathrm{msd}} = \max\left\{0, -18\log_{10}(1+h_{\mathrm{b}}-h)+54 + 18\cdot\log_{10}(R)+k_r\cdot\log_{10}(f)-9\log_{10}(b)\right\},$$

$$k_r = \begin{cases} -4+0.7(f/925-1), & \text{medium size city/suburban centre} \\ -4+1.5(f/925-1), & \text{metropolitan centre.} \end{cases}$$



COST231-Walfisch-Ikegami path loss model

Correction factor related to BRT transceiver height

$$a(h) = -\Big\{(1.1\log_{10}(f) - 0.7)h - (1.56\log_{10}(f) - A) + 20\log_{10}(h_r - h) - 20\log_{10}(h_r - 3.5)\Big\},$$

$$A = 1.56\log_{10}(f) - 3.5(1.1\log_{10}(f) - 0.7).$$

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. This problem was solved by the above correction factor.

COST231-Walfisch-Ikegami path loss model: Impact of rooftop height

Parameters:

BS antenna height = 30m

Carrier frequency = 1950MHz

Street width = 12m

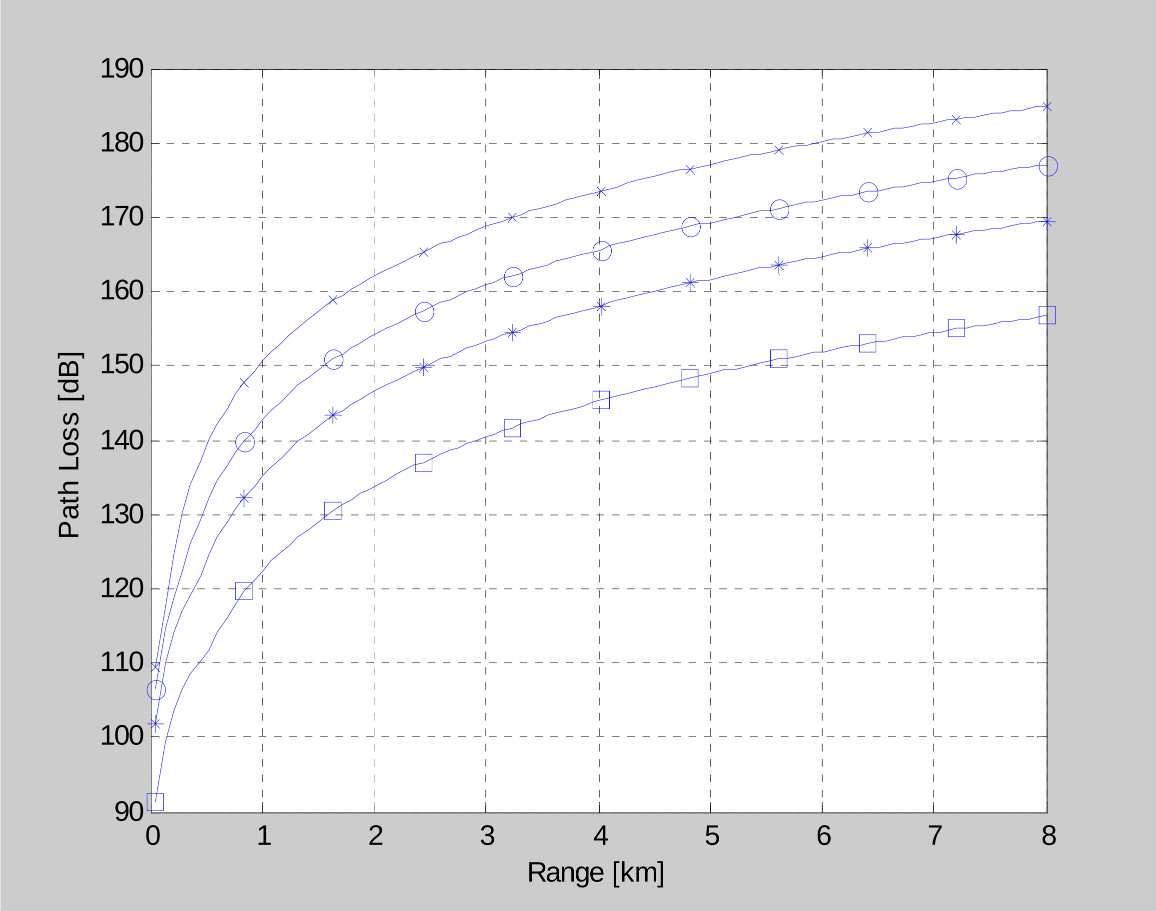
Building spacing = 60m

Street orientation = 90 degrees

Roof top heights:

6m (□), 12m (*)

18m (o), 24m (x)



Remarks:

- ❑ W-I and Okumura-Hata give approximately the same path loss curve when roof top height is 12m
- ❑ Impact for rooftop height is crucial for cell coverage

COST231-Walfisch-Ikegami path loss model: Impact of MS height

Parameters:

Roof top height = 12m

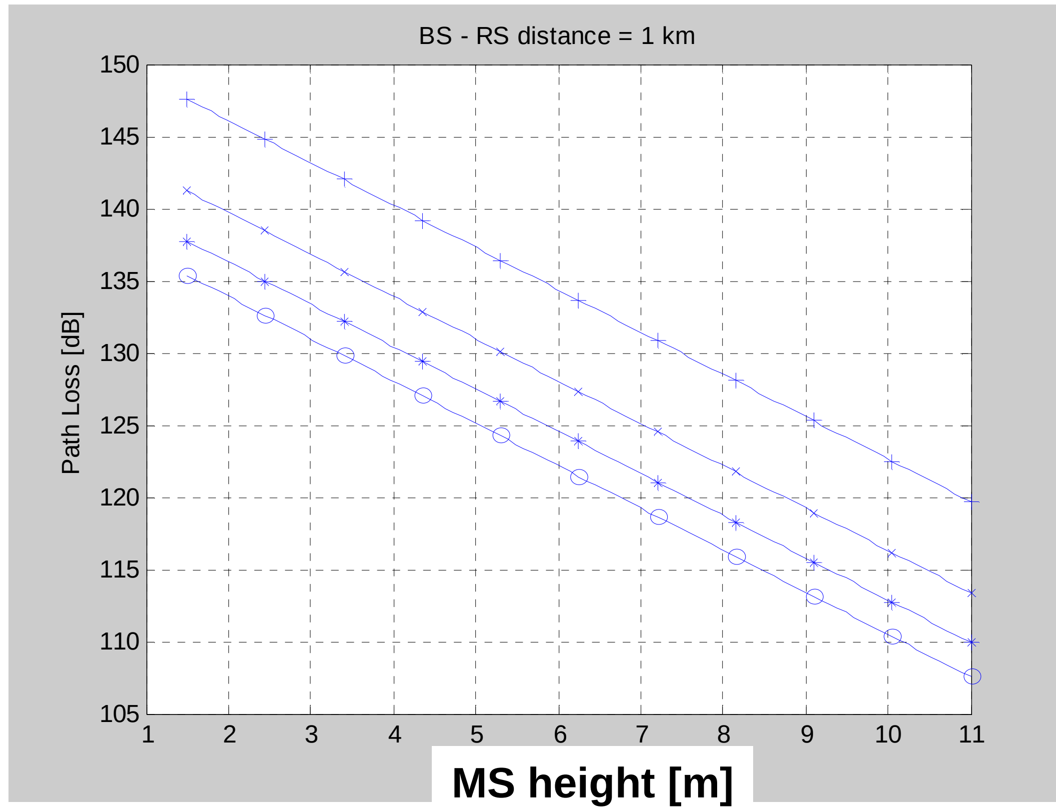
Carrier frequency = 1950MHz

Street width = 12m

Building spacing = 60m

Street orientation = 90 degrees

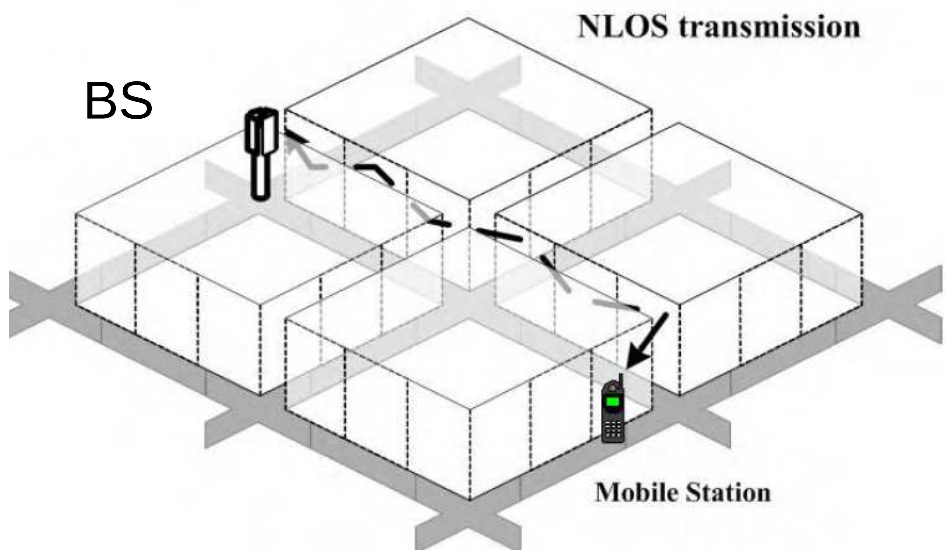
BS antenna height = 15m (o), 20m (*), 25m (x), 30m (+)



Notice:
- BS antenna 20m -> 30m => 10 dB gain
- MS antenna 1.5m -> 5m => 10 dB gain

Berg model

Scenario:
Both BS and MS antennas are below rooftop.
Model takes the minimum of an over-the-rooftop signal component and a round-the streets component.
This scenario will be increasingly important in future since density of network elements is increasing and macro-cell site costs are high



$$L_{\text{final}} = \max\{L, L_{\text{over roof top}}\}$$

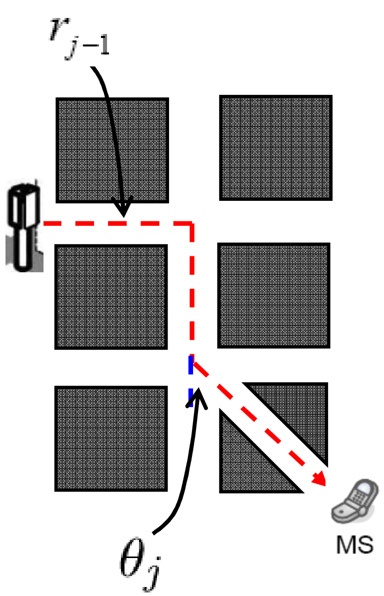
$$L = 20\log_{10}\left(\frac{1}{\lambda}4\pi d_n D(R)\prod_{j=1}^{n} e^{s \cdot r_{j-1}}\right)$$

$$L_{\text{over roof top}} = 24 + 45\log_{10}\left(d(\text{Euclidean})\right)$$

Berg model

$$R = \sum_{j=1}^{n} r_{j-1} = \text{Distance along streets between Tx and Rx}$$

$$r_j = \text{Length of the street between nodes } j \text{ and } j+1 \text{ (there are } n+1 \text{ nodes in total)}$$



$$D(R) = \begin{cases} 1 \text{ if } R \le r_{bp} \\ \dfrac{R}{r_{bp}} \text{ if } R > r_{bp} \end{cases}$$

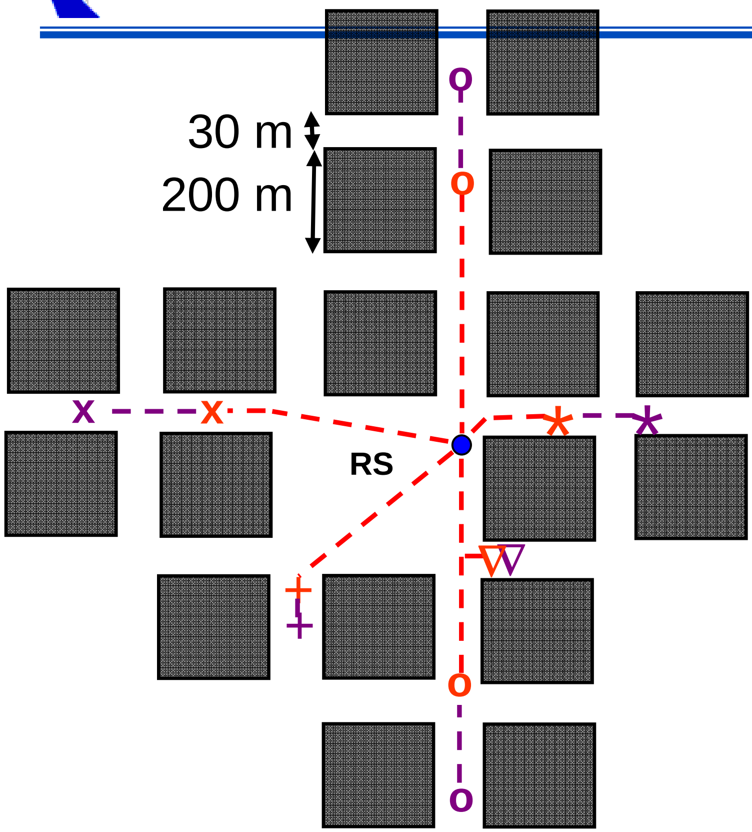
$$r_{bp} = \begin{cases} r_0 \text{ if } r_0 \le \dfrac{4(h_t - h_0)(h_r - h_0)}{\lambda} \\ \dfrac{4(h_t - h_0)(h_r - h_0)}{\lambda} \text{ if } r_0 > \dfrac{4(h_t - h_0)(h_r - h_0)}{\lambda} \end{cases}$$

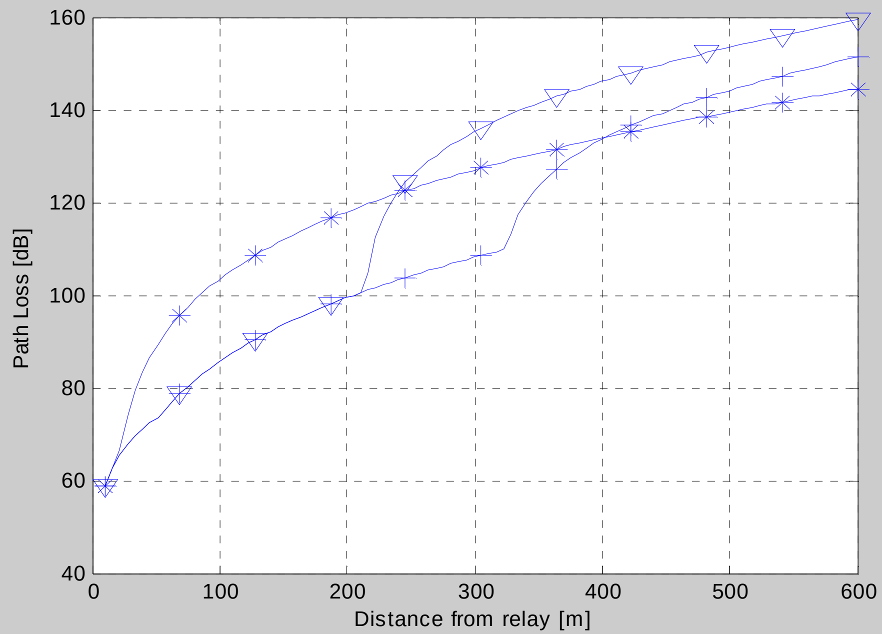
$$d_j = k_j r_{j-1} + d_{j-1} \qquad q_j = \left(\frac{\theta_j}{180}\right)^{1.5}$$

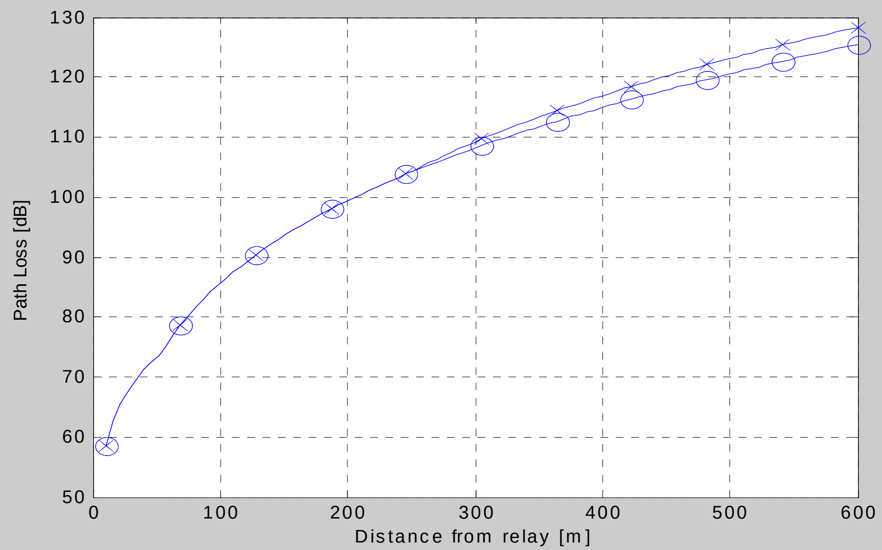
$$k_j = k_{j-1} + d_{j-1} q_{j-1} \qquad k_0 = 1 \text{ and } d_0 = 0$$

Check how to use this model
Note: Path loss depends heavily on corners (how many, how sharp)

Berg model: Example





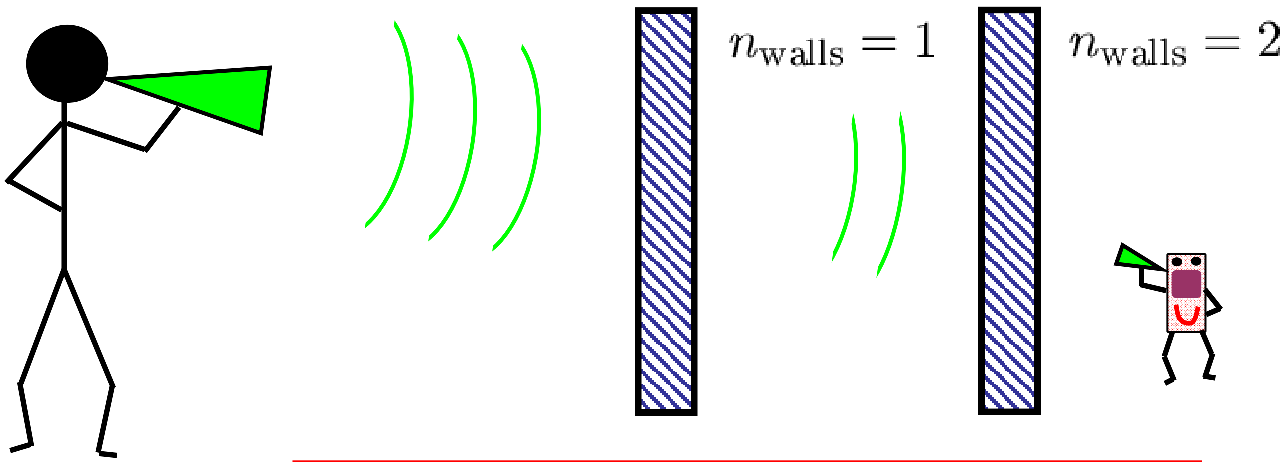


Red marks = range along the dashed route
Violet marks = range without penetration loss

Remarks:

- **This model is quite pessimistic (high path loss)**
- **Signal is dying soon round the corner**
- **BS location planning is important**

Outdoor-to-indoor modeling: Example



$$L = L_{\text{outdoor to outdoor}} + L_{\text{excess}}$$

where $L_{\text{outdoor to outdoor}}$ is the path loss in outdoors and L_{excess} is normally distributed variable with mean

$$L_{\text{excess}} = 18 + 3 \cdot n_{\text{walls}}, \qquad [dB]$$

and standard deviation 8dB.

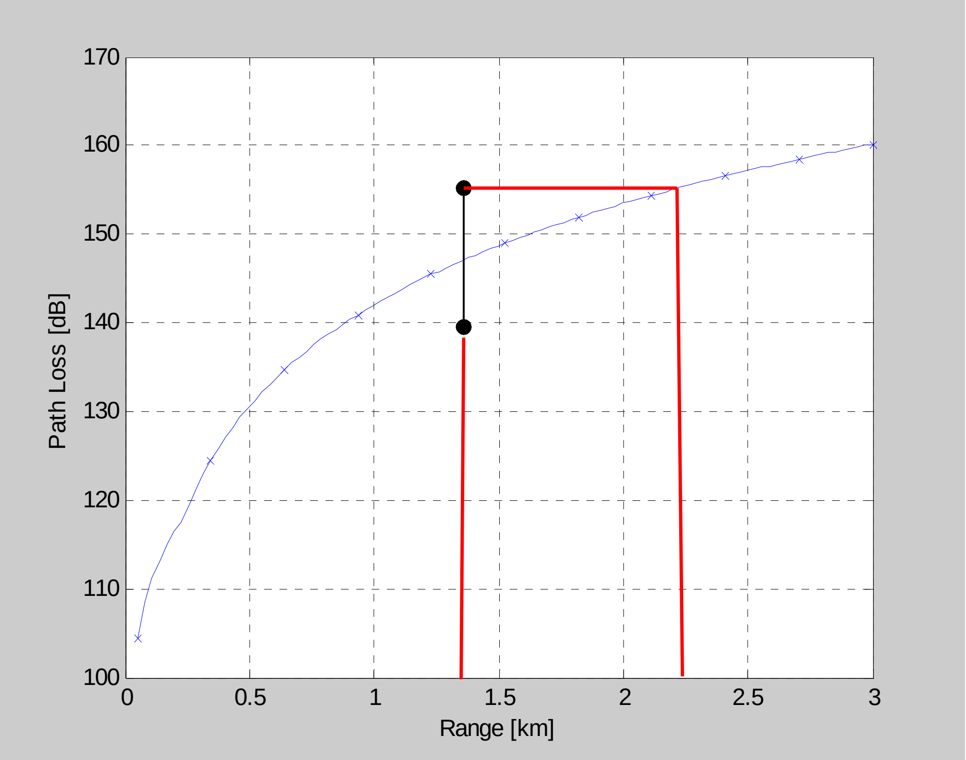
Remark:
- Path loss depends on number of walls

Shadow fading

General remarks

- In urban areas macro-cell ranges are from few hundred meters up to few kilometers
- Shadowing by big buildings etc can be critical on cell edge. It may create large coverage holes
- Example: Allowed total signal fading in system is 155dB and shadow fading margin is 8dB. How much larger (in %) would the coverage be without shadow fading margin? Use figure of the slide for range comparison.
- Answer: Cell range would increase from 1.35 km up to 2.2 km which leads to 267% increase in coverage
- Remark: the impact of shadow fading can be really large

W-I with parameters:
BS antenna height = 25m
Roof top height = 15m
Carrier frequency = 1950MHz
Street width = 12m
Building spacing = 60m
Street orientation = 90 degrees



Shadow fading model

- Shadow fading is modeled by log-normal distribution, i.e. signal strength <u>in decibels</u> is of the form

  (1) $$L = \overline{L} + X$$

  where first term is the mean path loss and latter term follows the normal distribution,

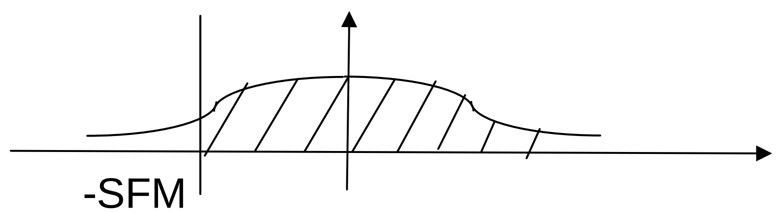
  (2) $$X \sim \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{x^2}{2\sigma^2}} = f(x)$$

  with zero mean and standard deviation σ.

Cell edge coverage probability

- In link budget shadow fading is taken into account through a certain shadow fading margin (SFM). In cell border we require that the signal strength plus SFM is larger than mean signal level by a certain probability, denoted by P_{cov}. Then we compute the corresponding SFM. Hence, we require that

$$
\begin{aligned}
P_{\text{cov}} &= P\left\{L + SFM > \overline{L}\right\} \\
&= P\left\{\overline{L} + X + SFM > \overline{L}\right\} \\
&= P\left\{X > -SFM\right\}
\end{aligned}
$$



$L = A + 10 \cdot n \cdot \log_{10}(R)$

$L = A + 10 \cdot n \cdot \log_{10}(R)$

Cell edge coverage probability

- Using the distribution (2) we find that

$$P_{\mathrm{cov}} = P\{X > -SFM\} = \frac{1}{\sqrt{2\pi}\sigma}\int_{-SFM}^{\infty} e^{-\frac{x^2}{2\sigma^2}}dx$$

$$= \frac{1}{\sqrt{2\pi}}\int_{-SFM/\sigma}^{\infty} e^{-\frac{t^2}{2}}dt = Q(-SFM/\sigma) = 1 - Q(SFM/\sigma)$$

From this equation we can solve SFM for given P_{cov} and σ:

$$SFM = \sigma \cdot Q^{-1}(1 - P_{\mathrm{cov}})$$

Cell edge coverage probability

- Function 1-Q is the cumulative density function (CDF) of normal distribution with zero mean and standard deviation 1. Moreover,

$$Q(\infty) = 0, \quad Q(-\infty) = 1,$$

$$Q(-x) = \frac{1}{\sqrt{2\pi}} \int_{-x}^{\infty} e^{-\frac{t^2}{2}} dt = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{t^2}{2}} dt - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-x} e^{-\frac{t^2}{2}} dt$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{t^2}{2}} dt - \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{t^2}{2}} dt = 1 - Q(x)$$

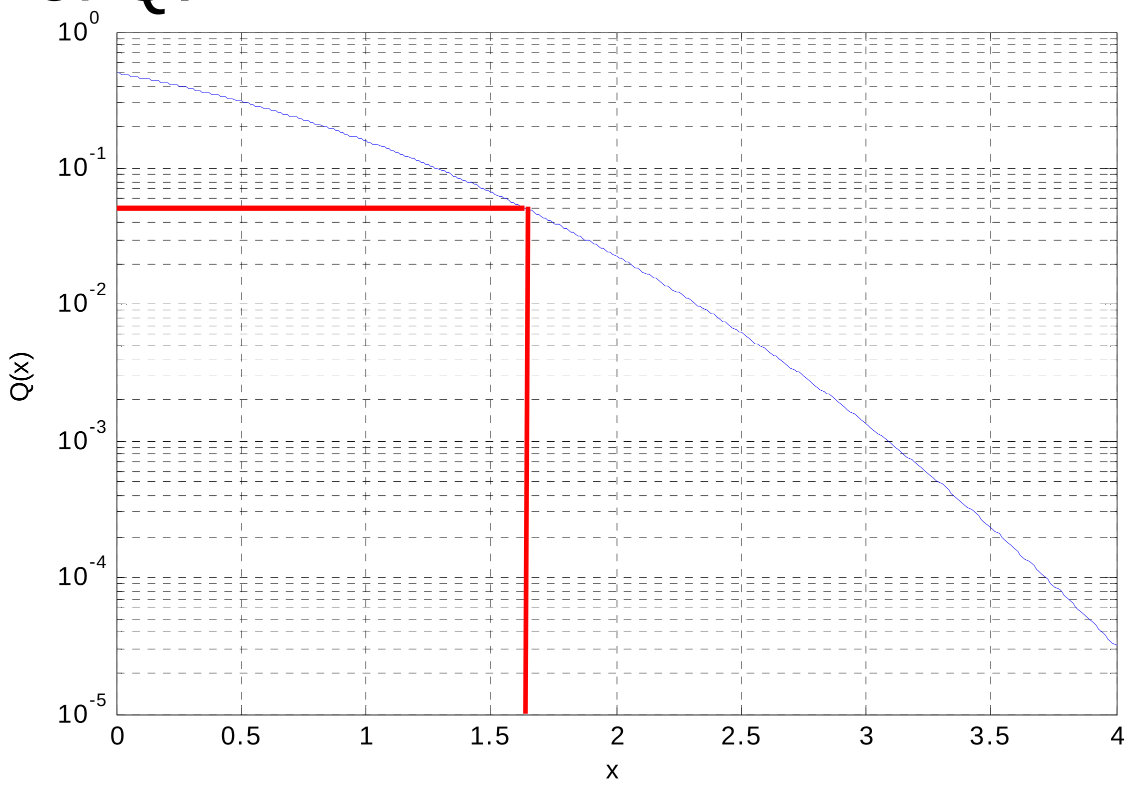
Cell edge coverage probability

- We can estimate the value of SFM by using the inversion curve of Q.

Example: Let P_{cov}=0.95 and let σ=6dB. Then we find from the curve that

$$Q^{-1}\left(1-\Pr_{\mathrm{cov}}\right)\approx 1.6449$$

and hence, SFM=11.6dB



Outdoors: σ=5-8dB. Indoors: σ=10-12dB.

Single cell coverage probability

- Next we compute the cell coverage probability in case of a single cell.
- Analytical computation is pretty technical but result shows the relation between path loss exponent n, standard deviation σ of shadow fading and the required cell coverage probability

Single cell coverage probability

- Let us compute the single cell coverage probability. We use assumptions:
  - Mean path loss follows the general formula, i.e.

$$\overline{L}(r) = A + 10 \cdot n \cdot \log_{10}(r)$$

  - Cell radius is R
  - Users are uniformly distributed in the cell, i.e.

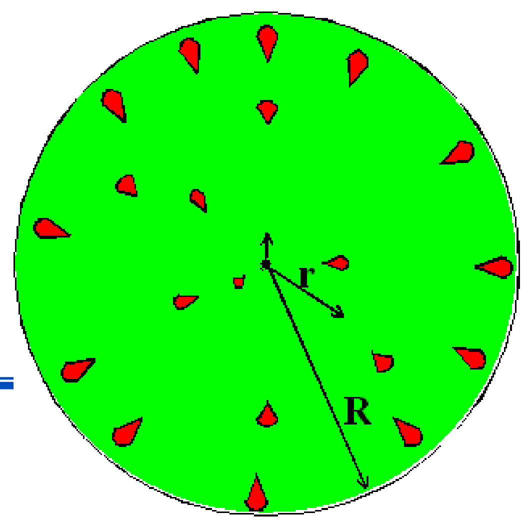
$$p(r,\varphi) = \frac{r}{\pi R^2}, 0 \le r \le R, \quad 0 \le \varphi \le 2\pi$$

Single cell coverage probability

- The cell coverage probability is obtained by averaging the local coverage probability over all possible mobile positions. Hence, we must compute the integral

$$F_u = \int_0^{2\pi}\int_0^{R} P_{\mathrm{cov}}(r)\, p(r,\varphi)\, dr\, d\varphi$$

First we need to find formula for coverage probability within a certain distance r.



Single cell coverage probability

- The coverage probability at distance r is given by

$$P_{\mathrm{cov}}(r) = P\left\{\overline{L}(r) + X > \overline{L}(R) - SFM \,|\, r\right\}$$

where lower bound is defined by the maximum allowed path loss. We use now the equations:

$$\overline{L}(R) - \overline{L}(r) = A + 10n\log_{10}(R) - (A + 10n\log_{10}(r))$$

$$= 10n\log_{10}\left(\frac{R}{r}\right)$$

$$L(r) = \overline{L}(r) + X$$

Single cell coverage probability

- We obtain a form

$$P_{\mathrm{cov}}(r) = P\left\{X > -SFM - 10n\log_{10}\left(\tfrac{r}{R}\right) \mid r\right\}$$
$$= Q\left(-\left(SFM + 10n\log_{10}\left(\tfrac{r}{R}\right)\right)/\sigma\right)$$

and thus, there holds

$$F_u = \frac{2}{R^2}\int_0^R Q\left(-\left(SFM + 10\cdot n\log_{10}\left(\tfrac{r}{R}\right)\right)/\sigma\right) r\,dr$$

Next task is to compute this integral

Single cell coverage probability

- By using the substitution

$$a = -\frac{SFM}{\sigma}, b = -\frac{1}{\sigma} 10 n \log_{10} e \qquad x = a + b \ln\left(\frac{r}{R}\right)$$

we obtain

$$r = R \exp\left(\frac{x-a}{b}\right) \qquad r = 0 \Rightarrow x \to -\infty$$

$$dr = \frac{1}{b} R \exp\left(\frac{x-a}{b}\right) dx \qquad r = R \Rightarrow a$$

and

$$F_u = \frac{2}{b} \int_{-\infty}^{a} Q(x) \exp\left(\frac{2(x-a)}{b}\right) dx$$

Single cell coverage probability

- We proceed using integration by parts

$$\int uv'dx = uv - \int u'vdx$$

now $u = Q(x)$ $\qquad v' = \exp\left(\frac{2(x-a)}{b}\right)$

$$u' = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{1}{2}x^2\right) \qquad v = \frac{b}{2}\exp\left(\frac{2(x-a)}{b}\right)$$

and we get

$$F_u = \frac{2}{b}\left[Q(x)\frac{b}{2}\exp\left(\frac{2(x-a)}{b}\right)\Bigg|_{x=-\infty}^{x=a} + \frac{b}{2}\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{a}\exp\left(-\frac{x^2}{2}+\frac{2(x-a)}{b}\right)dx\right]$$

$$= Q(a) + \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{a}\exp\left(-\frac{x^2}{2}+\frac{2(x-a)}{b}\right)dx$$

Single cell coverage probability

- We can still go forward by completing the squares:

$$-\frac{x^2}{2}+\frac{2(x-a)}{b}=-\frac{1}{2}\left(x^2-\frac{4}{b}x\right)-\frac{2a}{b}=-\frac{1}{2}\left(x^2-2\frac{2}{b}x+\left(\frac{2}{b}\right)^2-\left(\frac{2}{b}\right)^2\right)-\frac{2a}{b}$$

$$=-\frac{1}{2}\left(x-\frac{2}{b}\right)^2+\frac{1}{2}\left(\frac{2}{b}\right)^2-\frac{2a}{b}$$

$$=-\frac{1}{2}\left(x-\frac{2}{b}\right)^2+\frac{2(1-ab)}{b^2}$$

Then cell coverage probability admit the form

$$F_u=Q(a)+\exp\left(\frac{2(1-ab)}{b^2}\right)\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{a}\exp\left(-\frac{1}{2}\left(x-\frac{2}{b}\right)^2\right)dx$$

Single cell coverage probability

- We still need to substitute $t = x - \frac{2}{b}$ Then

$$F_u = Q(a) + \exp\left(\frac{2(1-ab)}{b^2}\right)\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{a-\frac{2}{b}} \exp\left(-\frac{1}{2}t^2\right)dx = Q(a) + \exp\left(\frac{2(1-ab)}{b^2}\right)\left(1 - Q\left(a - \frac{2}{b}\right)\right)$$

and finally we are able to write the

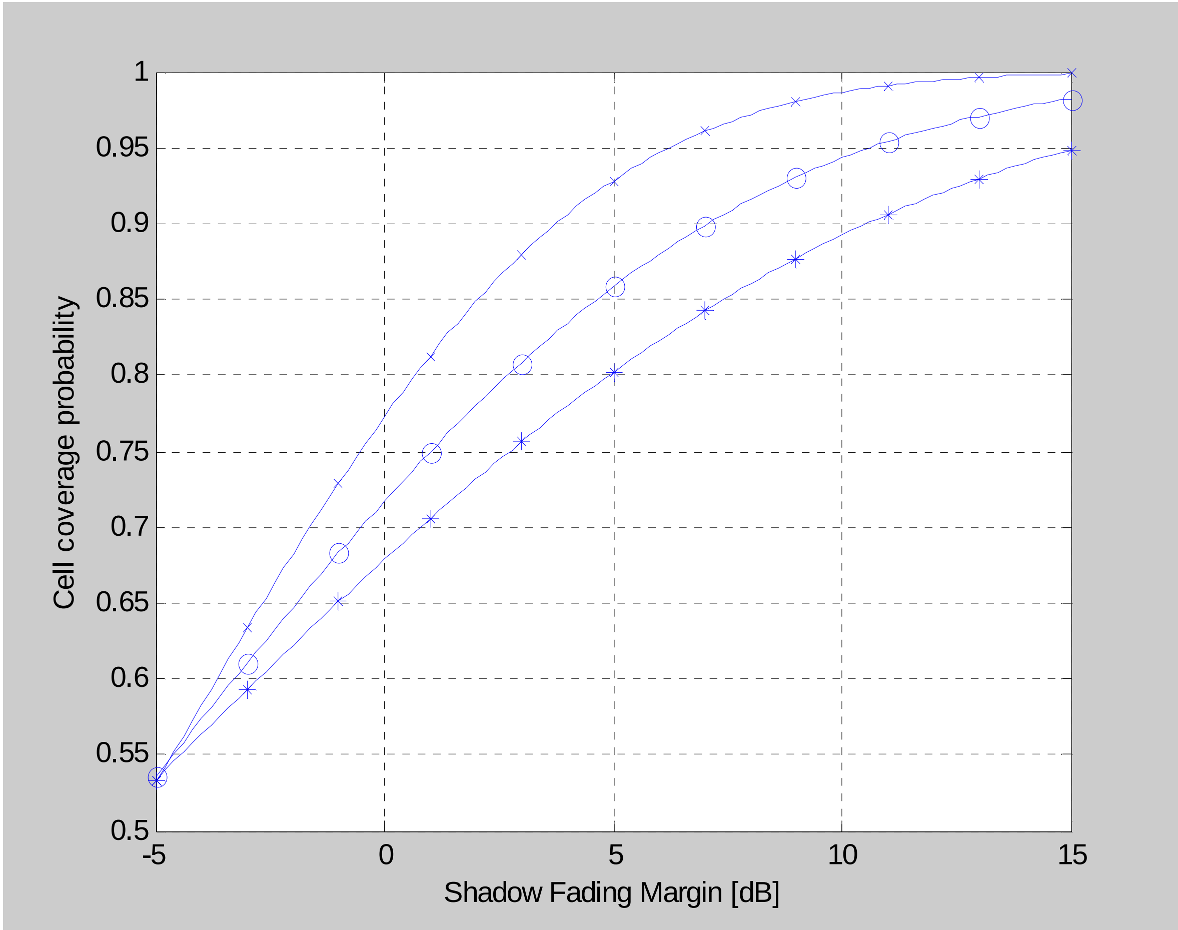
$$F_u = Q(a) + \exp\left(\frac{2(1-ab)}{b^2}\right)\left(1 - Q\left(a - \frac{2}{b}\right)\right)$$

$$a = -\frac{SFM}{\sigma}, b = -\frac{1}{\sigma}10n\log_{10} e$$

Coverage probability on the edge of the cell

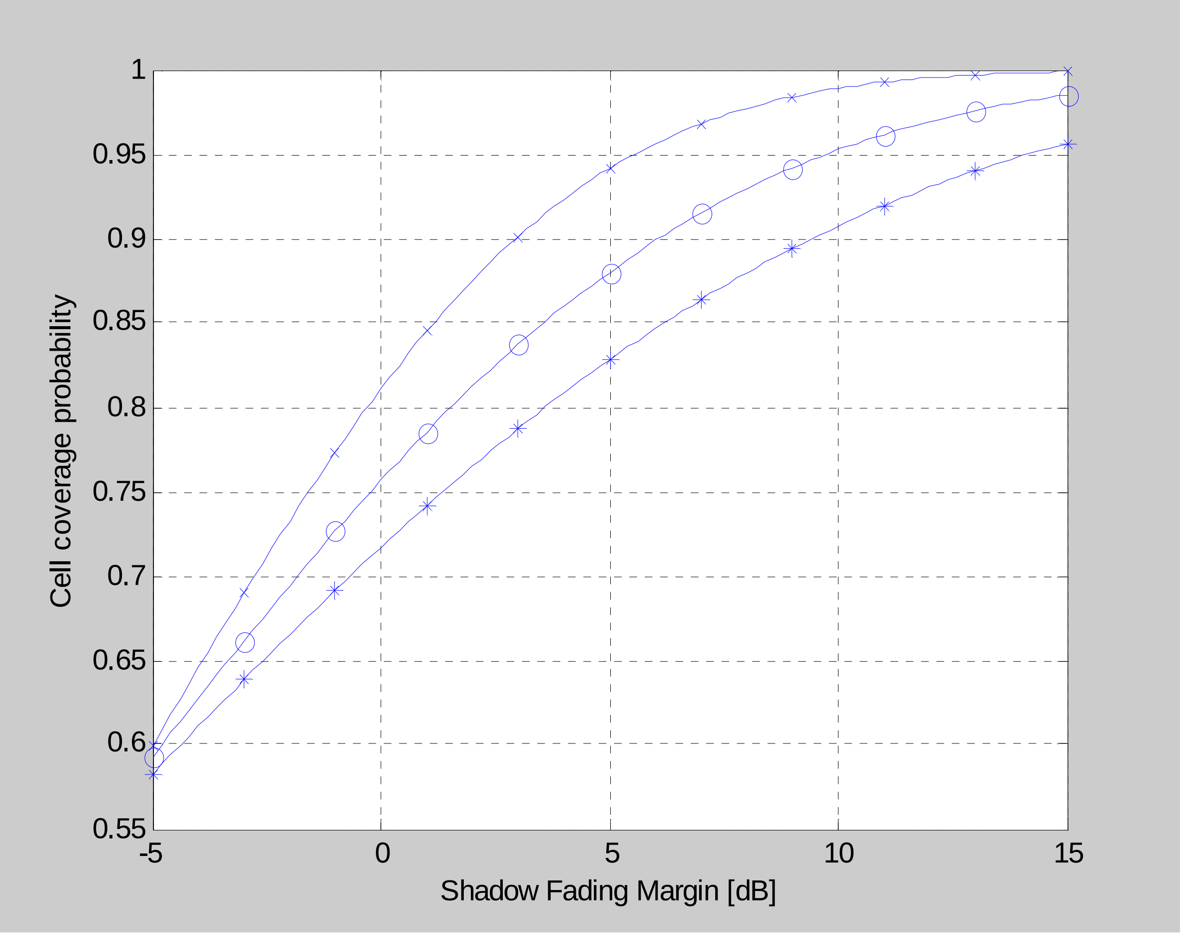
Single cell coverage probability

- Path loss exponent n=3
- Shadow fading margin is
  - 6dB (x)
  - 9dB (o)
  - 12dB (*)
- Remark: The SFM difference between 95% and 80% coverage requirements large



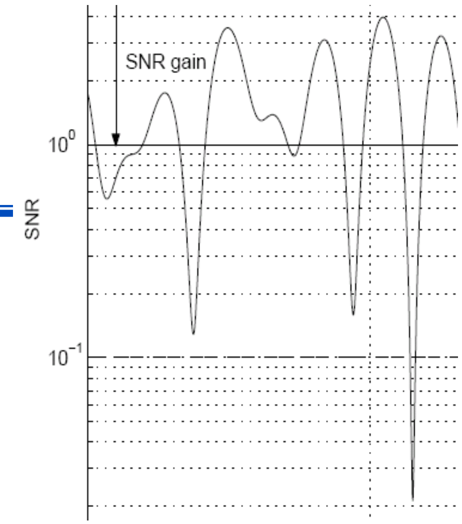
Single cell coverage probability

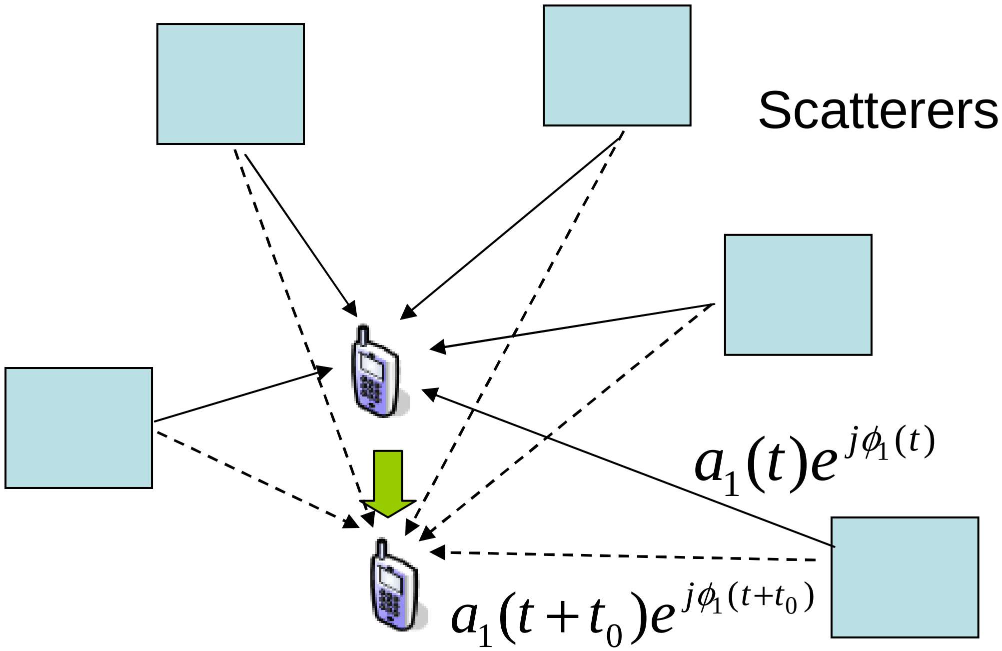
- Path loss exponent n=4
- Shadow fading margin is
  - 6dB (x)
  - 9dB (o)
  - 12dB (*)
- Remark: The SFM difference between 95% and 80% coverage requirements is even larger than in case n=3.



Fast Fading

Recall: Fast Fading





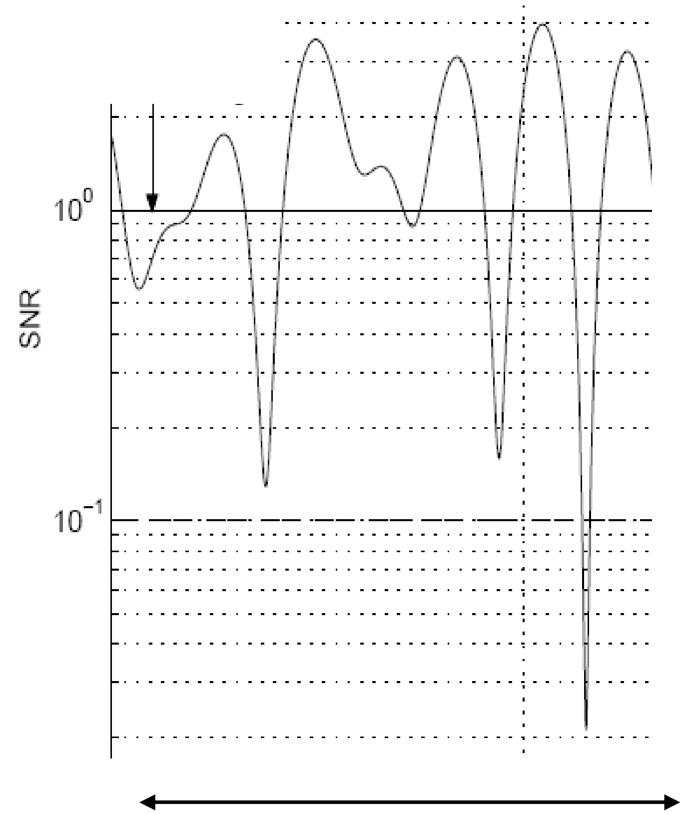
Especially the changes in component signal phases create rapid variations in sum signal

Sum signal at time t $\quad S(t) = a_1(t)e^{j\phi_1(t)} + ... + a_5(t)e^{j\phi_5(t)}$

Sum signal at time t+t0 $\quad S(t+t_0) = a_1(t+t_0)e^{j\phi_1(t+t_0)} + ... + a_5(t+t_0)e^{j\phi_5(t+t_0)}$

Fast fading

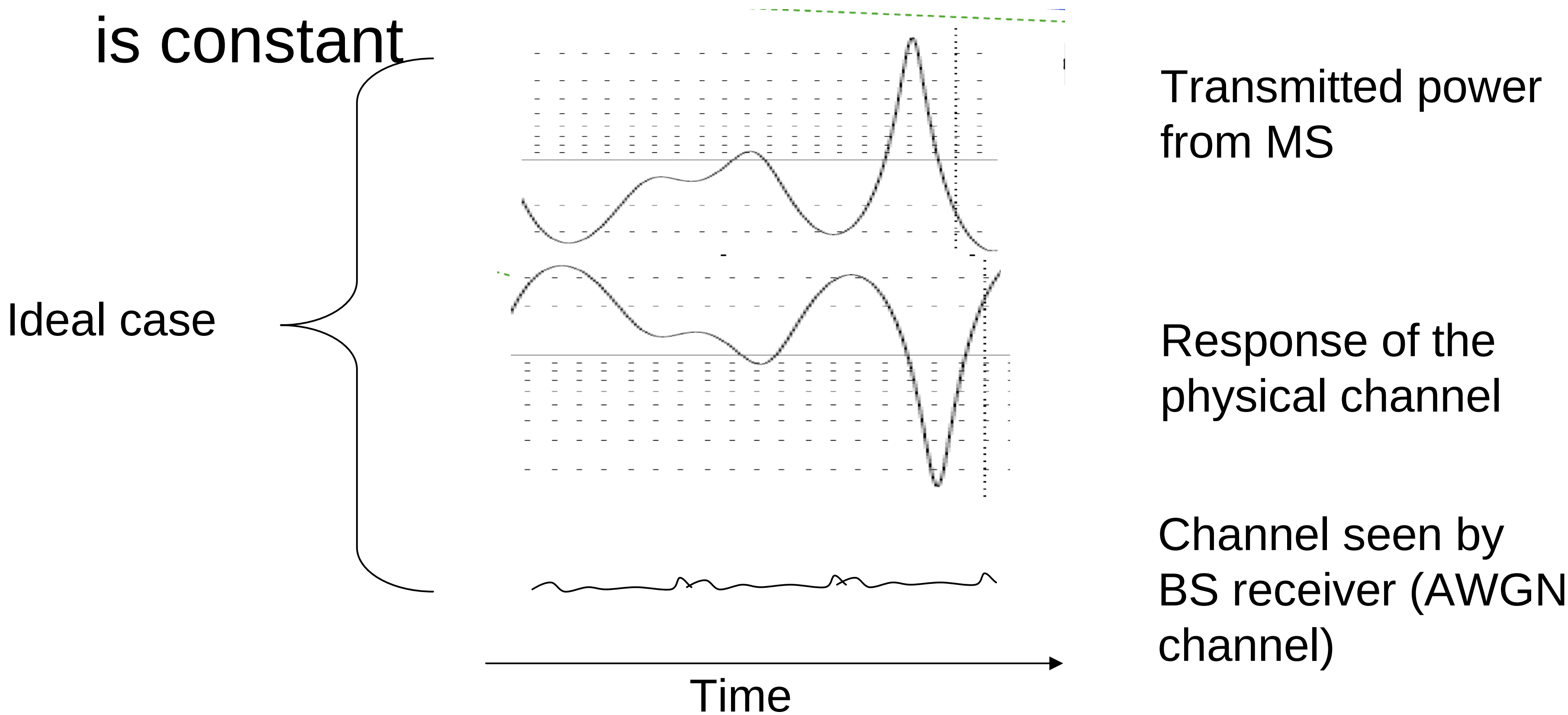
- In link budget a fast fading margin is needed because
  - If fast power control is applied, then some headroom is needed especially in uplink since MS power reservations are limited. If power control fails, the whole uplink may beak down
  - Although link adaptation (=adaptation of channel coding and modulation) would be used instead of fast power control, there can be need for fast fading margin; fast fading can be crucial for slowly moving users



Fading time scale depends on the user speed.

Ideal fast power control

- Fast power control aims to convert the channel so that mean power of the signal in the receiver is constant



Limited power control dynamics

- At the cell edge MS power control starts to hit its maximum value.

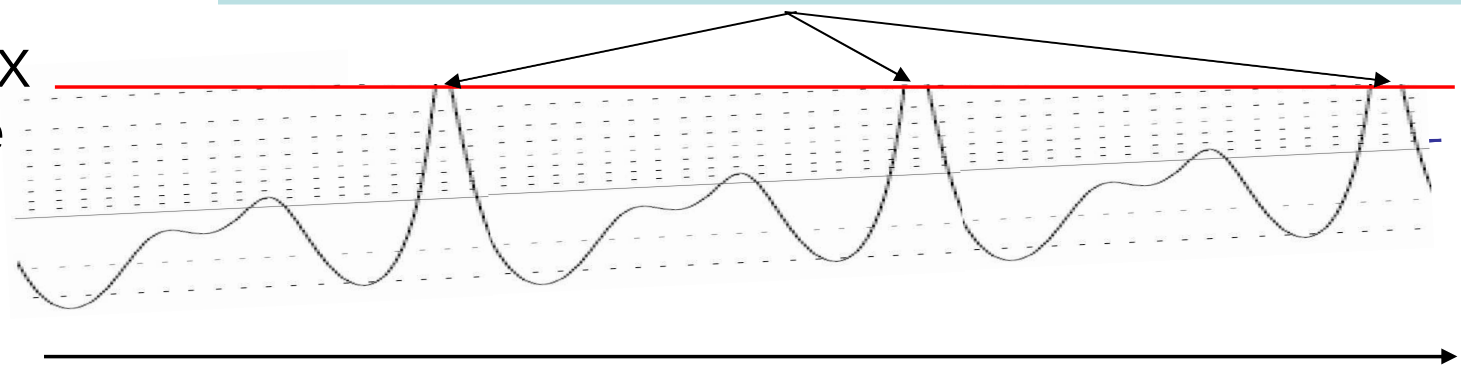
  => Number of erroneous frames is increasing

  => Data rate is decreased when QoS degrades

  => in the worst case connection breaks down

Longer and longer times with ‘bad connection’ temporal length of the fades depends on the user speed

Maximum TX power value



MS travels towards cell edge/coverage hole => mean transmission power needs to be increased