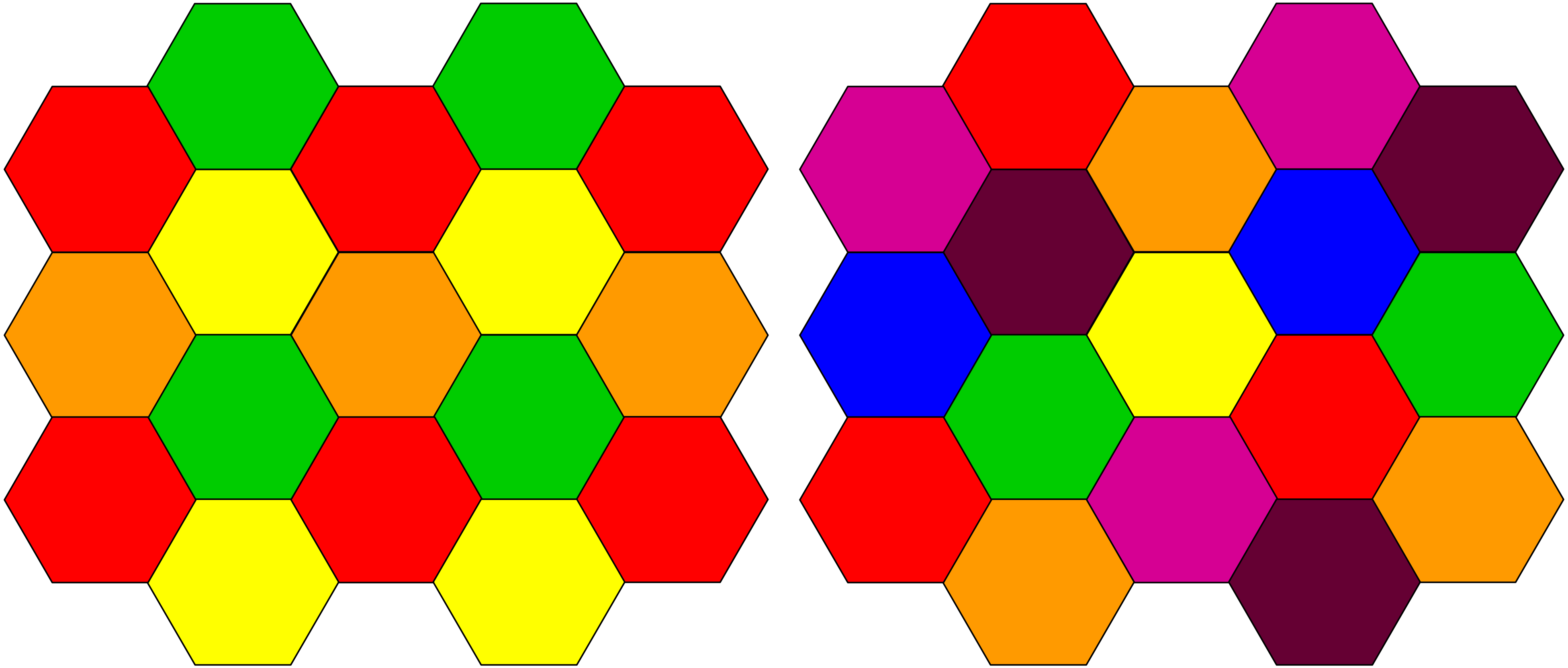
Mobile Systems



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Plan

- In this section we will look in particular at the effects of propagation on systems in the mobile
  - We have covered the mechanisms already, after a brief review of mobile system configurations we will focus on channel effects and models to predict them.

Terrestrial mobile

Meaning the base station and the mobile are on the ground

Aim of mobile systems

- Provide coverage and mobility
  - Coverage needed to all areas where system will be used
  - Indoor coverage frequently needed as well

- Provide capacity
  - May be a large number of users
  - Quality of service - avoiding call blocking and dropped calls
  - An increasing demand for higher data rates

Distinction against fixed services

Mobile systems differ from fixed services in that:

- Antennas are typically low and non-directional
  - The terminals are immersed in clutter and multipath is highly likely
- Ranges are not usually high
  - There are exceptions
- The path changes with time
  - Models need to be statistical with respect to location as well as time
  - Doppler shift, delay spread and similar phenomena are important
- Lower availability specification
  - We would like mobiles to work 99.99% of the time but we don’t expect it

Frequency Bands

Almost exclusively VHF/UHF

- 30MHz - 3 GHz

- Business Radio
  - PMR type services, Emergency services etc.
    - Range of 10km or more
  - Coverage over a large area, a town or a county
    - Range of 1-5km in town, 10-20km out of town
  - Long range services operate at VHF, shorter range at UHF
    - Maritime mobile for example uses VHF

- Mobile telephones
  - Cellular radio 2G, 3G 800MHz to 2 GHz
    - 100m - 15km range

Frequency Bands

Why VHF/UHF

- Favourable propagation
  - links are not limited to line of sight (coverage)
  - do not propagate too far (excessive range = interference)
  - relatively low propagation loss (battery power)
  - good penetration into buildings at UHF
  - low background noise
  - Doppler etc. within reasonable limits

- Inexpensive hardware
  - Efficient amplifiers, cheap antennas, mass market

Frequency sharing

Spectrum is limited - Broadcasting takes a large chunk below 1 GHz

- Extensive frequency reuse
  - Shared channels in the same area
  - Need good interference models to enable sharing
  - There are many millions of terminals in the UK
    - GSM capacity is practically interference limited in cities
- Economically significant
  - Cellular mobile revenue is large
  - Ability to sell a few 100MHz for £20 billion

Cellular concept

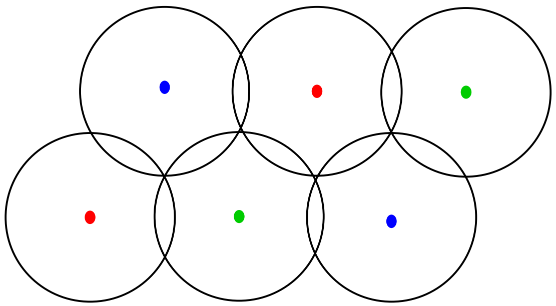
A quick reminder of cellular system topology

Cell types

- **Macro-cell**
  - regional coverage, outdoor medium traffic density, tall masts above rooftops, coverage defined by terrain 1 - 30km
- **Small Macro-cell**
  - as above but with lower antennas though still above most rooftops, coverage up to 3km
- **Micro-cell**
  - town coverage, high traffic density, low masts below rooftops so coverage defined by buildings, up to 1km
- **Pico-cell**
  - street or building coverage, very high traffic density, can be indoor, coverage strongly influenced by buildings, vehicles, people etc. up to 500m

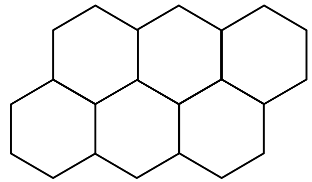
The theory behind cellular

We can cover an area will an array of overlapping coverage cells



Ideally the coverage from a base station is circular

Choosing always the closest base gives us an array of hexagons



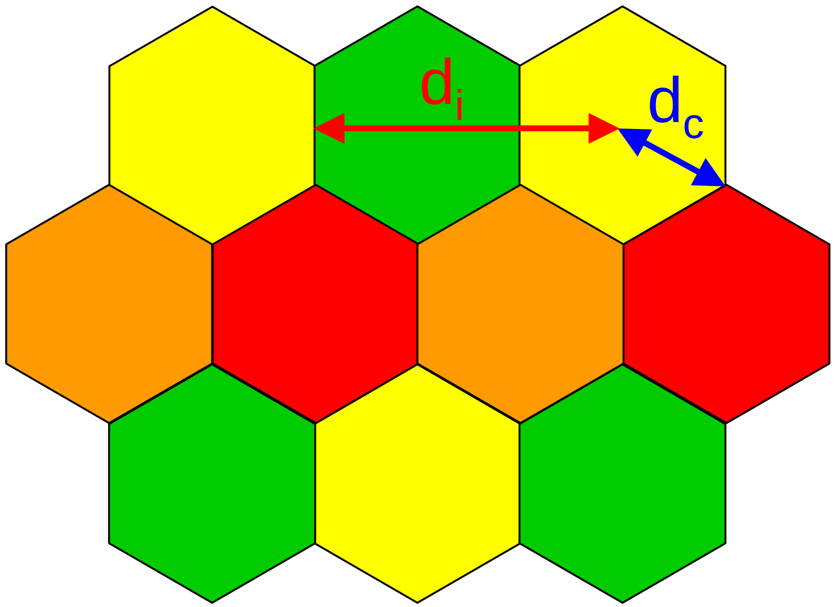
Spectrum is scarce & expensive

- So is is important to reuse spectrum
- Propagation theory indicates frequencies can be re-used by base stations if they are far enough apart
  - Path loss is at least square law
  - To get 12 dB C/I an interferer needs to be 4x further away

The theory behind cellular

So we chose a frequency reuse plan to maximise separation

- For no adjacent cells to be of the same frequency needs 4 channels



Maximum distance path loss difference from furthest in cell to the closest interferer

$L = 20\log(d_i/d_c)$

from geometry $d_i/d_c = 2.6$

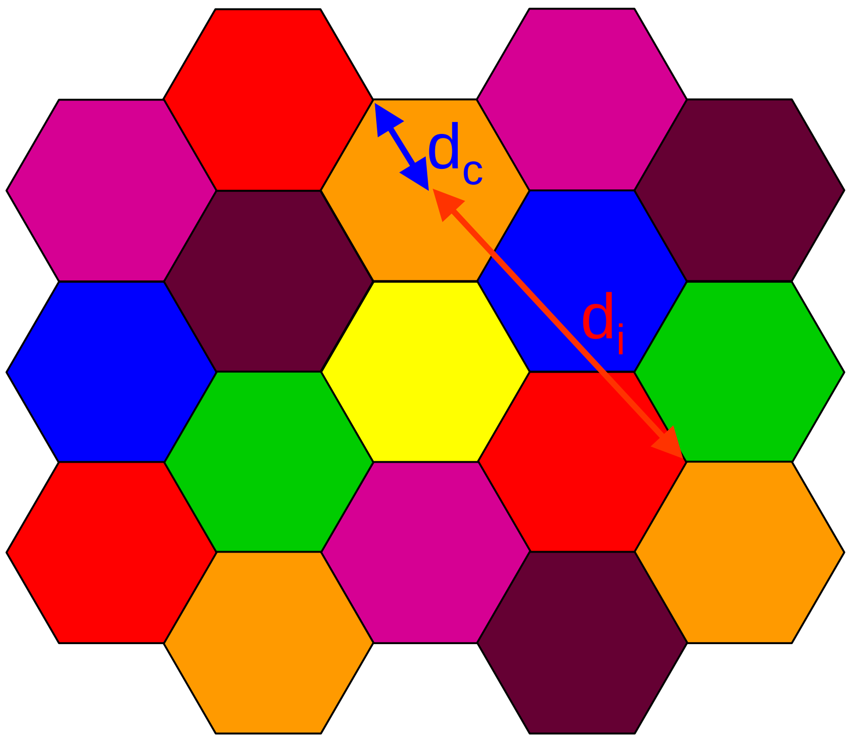
$L = 8.3$ dB

but note this is worst case and that there are 6 surrounding cells contributing interference (+8 dB)

7 channel frequency reuse

A better performing system uses 7 channels

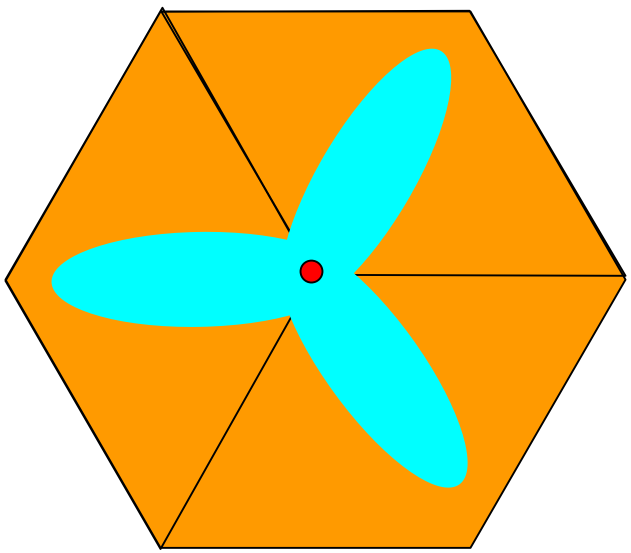
– This increases the distance



Now the distance ratio is much greater ~ 3.6 giving us a worst case C/I of 11 dB - but again, there are 6 surrounding cells.

Sectorisation

To overcome the interference from surrounding cells sectored antennas patterns are used



This example splits the cell into 3 segments and means the antenna discrimination will eliminate 4 out of the 6 adjacent interferers for each sector

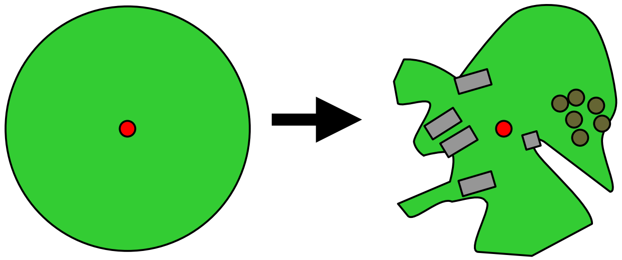
That is interference is reduced by a factor of 3.

Cellular coverage

In practice, unless we live somewhere flat without any buildings or vegetation we do not get nice circular cells

Typically mobile antennas are low

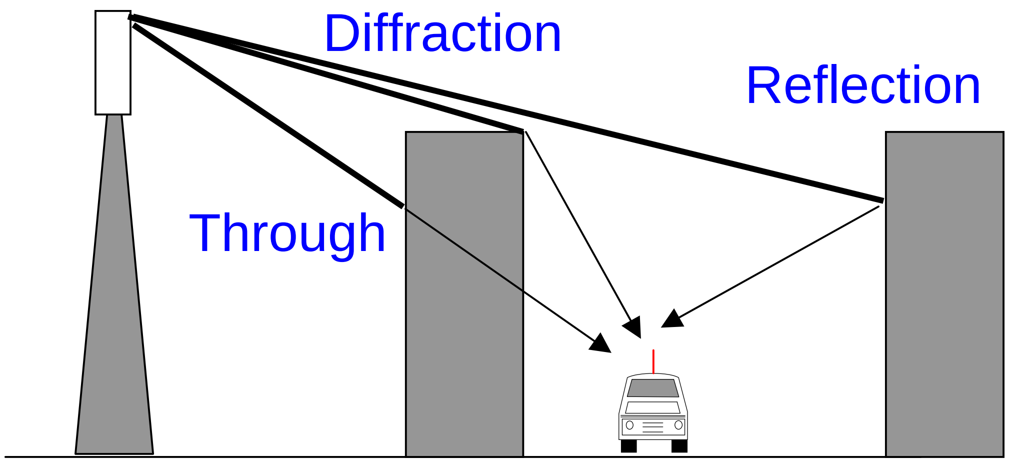
- The propagation path is frequently not line of sight
- Blockage by buildings
- Blockage by vegetation
- Blockage by other mobiles
- Lots of multipath

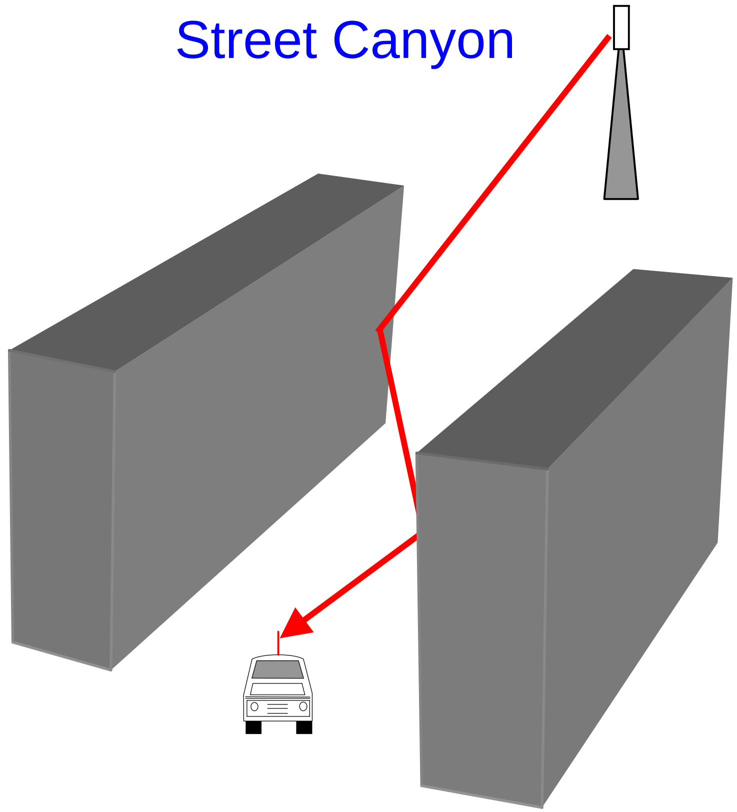


Firstly we will consider models that predict the mean signal level ignoring multipath effects - I.e. coverage models

Coverage modes

Signals arrive by combination of line of sight, diffracted, reflected and scattered modes and by penetration through buildings

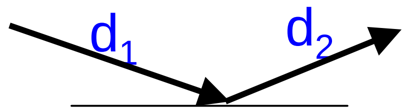




Some rules of thumb

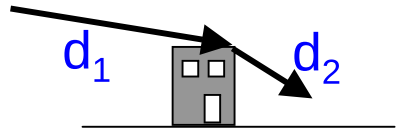
Field strength versus mechanism

- Specular reflection



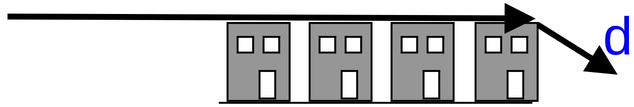
$$E \propto \frac{1}{d_1 + d_2}$$

- Single diffraction



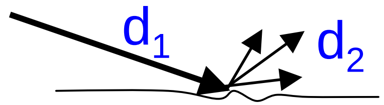
$$E \propto \sqrt{\frac{d_2(d_1 + d_2)}{d_1}}$$

- Multiple diffraction



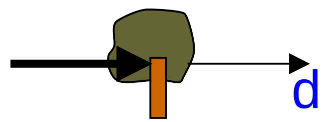
$$E \propto d^{-1.9}$$

- Rough surface scatter



$$E \propto \frac{1}{d_1 \cdot d_2}$$

- Penetration/absorption



$$E \propto \frac{1}{d} \times \text{constant}$$

Measurements & models

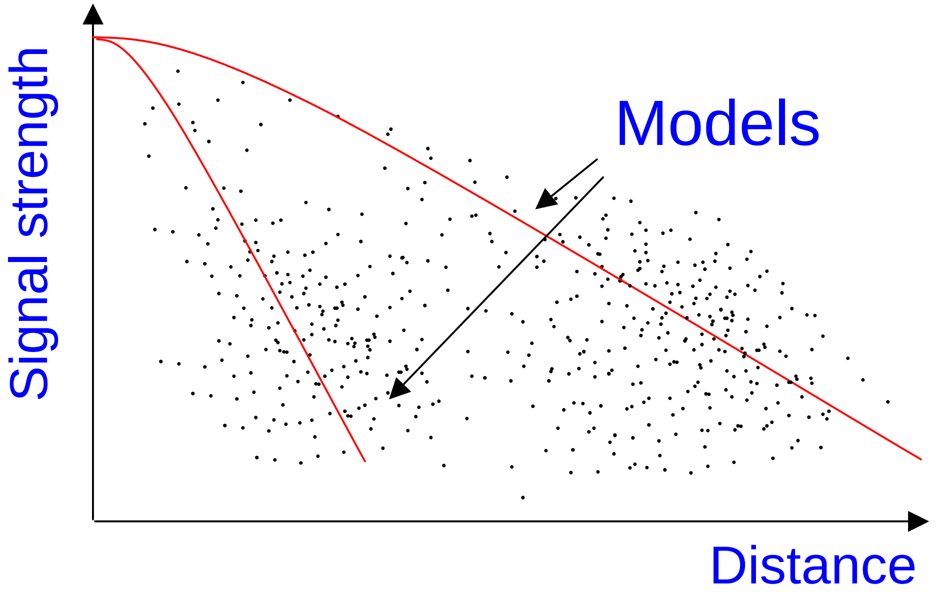
When we come to model measurements simple distance models don't tend to work well

Tend to find there is considerable spread because distance is not the only factor

- e.g. we need to account for the buildings

There is also fast fading from multipath

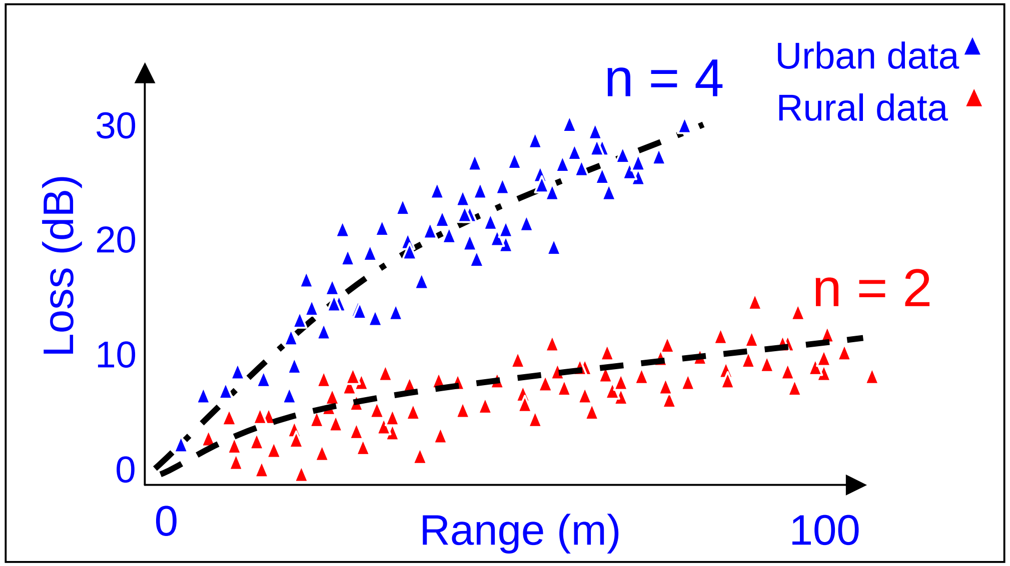
- to remove this from measurements filter the data over ~40 wavelengths (Lee criterion)



Empirical models

Single power law models

We may find we have measurements that look like this



We can fit a power law

a constant

$$\frac{P_r}{P_t} = \frac{1}{L} = \frac{k}{d^n}$$

path loss exponent

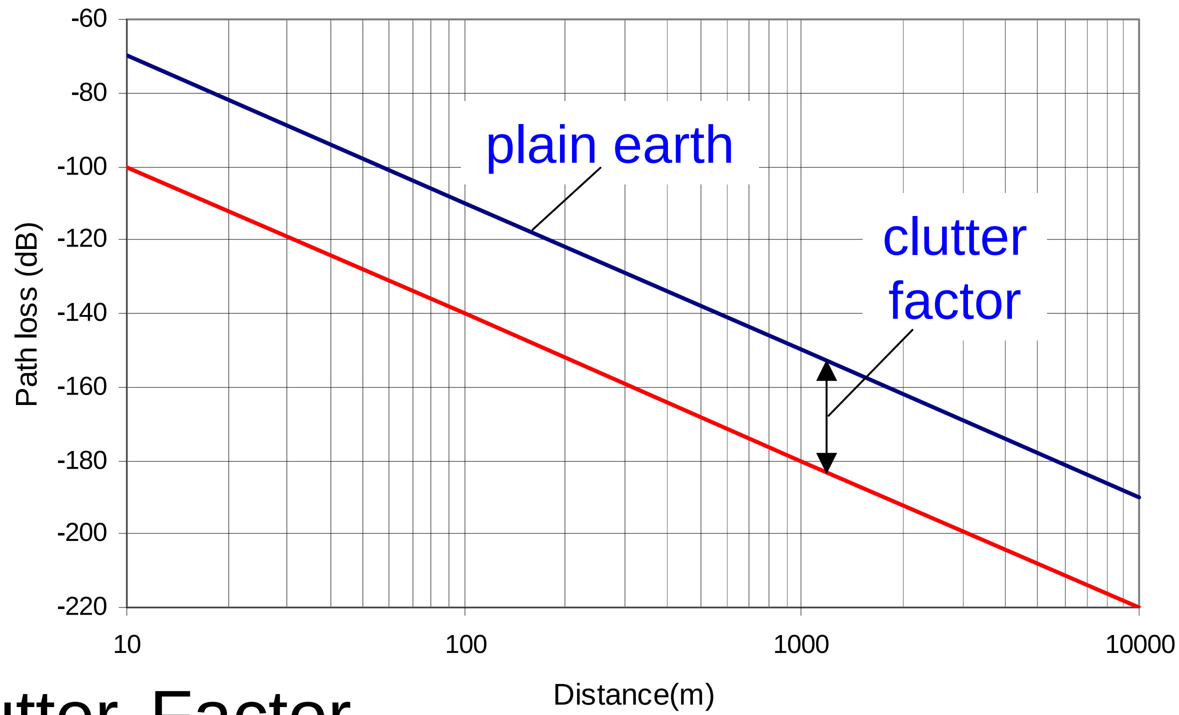
n - is the power law exponent, k is a constant. Both depend on factors of antenna height, frequency and environment

In dB $$L = 10n\log\left(\frac{d}{d_{ref}}\right) + L_{ref} \text{ dB}$$

reference distance loss at reference distance

Single power law models

Measurements in suburban and urban areas tend to show that the power law is 4 plus there is an additional "clutter factor" which does not depend on range



$$L = \text{Plane Earth Loss} + \text{Clutter Factor}$$

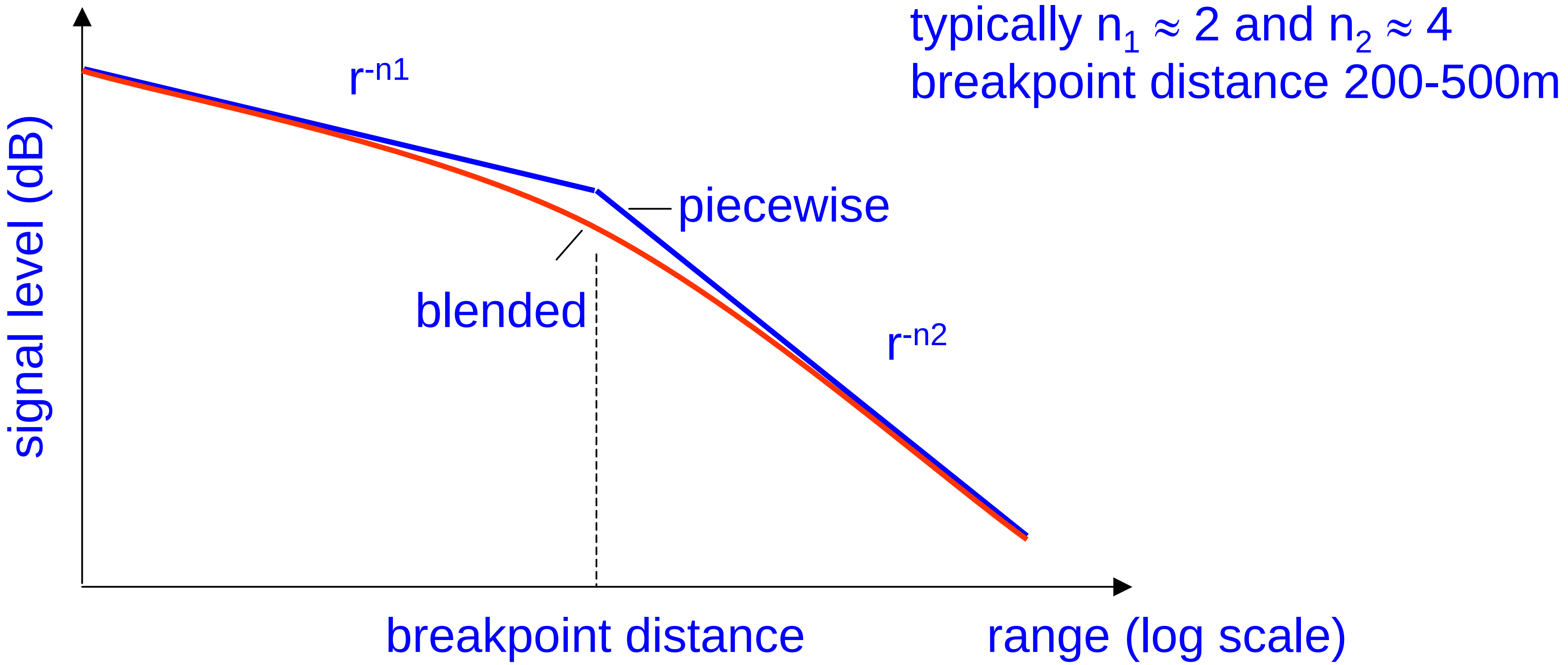
$$L = 40\log(d) + L_{ref} + L_{clutter} \text{ dB}$$

The clutter factor depends on location, mobile height, frequency etc.

Dual slope empirical model

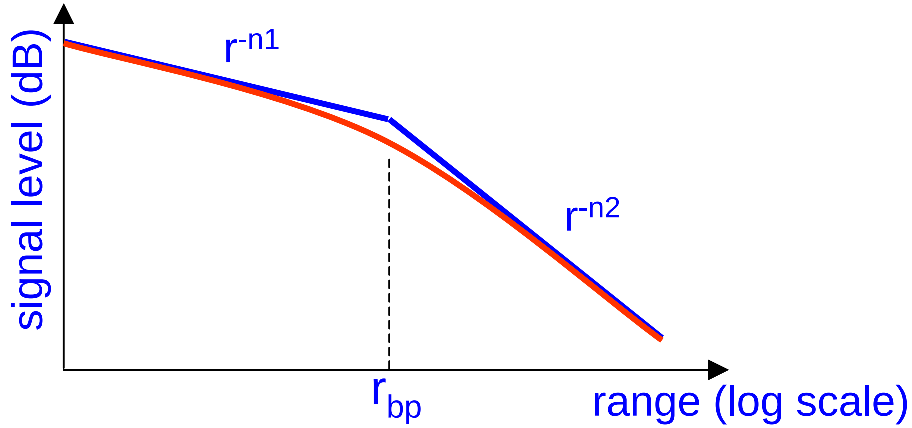
Very simple - a piecewise approximation

- Model follows one power law out to a breakpoint distance, then swaps to another power law



Dual slope empirical model

Formulae



Piecewise

$$L = \begin{cases} L_1 + 10 n_1 \log(r) & \text{for } r \le r_{bp} \\ L_1 + 10 n_2 \log\left(\dfrac{r}{r_{bp}}\right) + 10 n_1 \log(r_{bp}) & \text{for } r > r_{bp} \end{cases} \quad [\text{dB}]$$

Continuous

$$L = L_1 + 10 n_1 \log(r) + 10(n_2 - n_1)\log\left(1 + \frac{r}{r_{bp}}\right) \quad [\text{dB}]$$

Where L_1 is the reference path loss at r = 1m

Okumura-Hata model

A widely used empirical model based on measurements from 150MHz to 1.5 GHz made in Tokyo in 1968

- Okumura produced a set of curves and Hata produced formulae to match the curves
- Based on 3 classes of environment
  - Open area
    - open space, no tall trees or buildings in path
  - Suburban area
    - village, highway scattered with trees and houses, some obstacles near the mobile but not congested
  - Urban area
    - built up city or large town with large buildings and houses

Okumura-Hata model

General formula

$$L = A + B \log(d) - C_{env} \quad dB$$

Where

$A = 69.55 + 26.16 \log(f_{MHz}) = 13.82 \log(h_{base})$

$B = 44.9 - 6.55 \log(h_{base})$

and $C_{env} = 4.78 \log(f_{MHz})^2 + 18.33 \log(f_{MHz}) + 40.94$ for an open area

$= 2 \log(f_{MHz}/28)^2 + 5.4$ for

$= 3.2 \log(11.75 h_{mobile})^2 - 4.97$ for a large

$= 8.29 \log(1.54 h_{mobile})^2 - 1.1$ for

$=(1.1 \log(f_{MHz} - 0.7) h_{mobile} - 1.56 \log(f_{MHz}-0.8)$ for a small/medium city

Very easy to use

Valid 150MHz to 1.5 GHz for base stations 30m - 200m and ranges 1km-20km

COST 231-Hata model

This is a 1999 extension of the Okumura-Hata model to 2 GHz for small/medium cities (3G Mobile)

$$L = D + B \log(d) - C_{env} + E \qquad \text{dB}$$

Where:

$$B = 44.9 - 6.55 \log(h_{base})$$

$$C_{env} =(1.1 \log(f_{MHz} - 0.7)\ h_{mobile} - 1.56 \log(f_{MHz}-0.8)$$

$$D = 46.3 + 33.9 \log(f_{MHz}) - 13.82 \log(h_{base})$$

E = 0 dB in medium sized cities and suburban areas

E = 3 dB in metropolitan areas

COST 231-Hata model accuracy

The COST231 model has been extensively tested

- Measurements give a standard deviation of error of 5-7 dB between 150MHz and 2 GHz

- Model works best at 900MHz in urban areas
  - Measurements in Brazil claim 3 dB standard deviation!

- In rural areas, standard deviations of 15 dB were found

Frequently see various models of this type with slightly different parameters - there are many of them

Problems with empirical models

- The empirical models can only be used for cases within the parameter range
  - Limited to measurement set and however much extra the author thought reasonable
- Classifying environments is also subjective
    - London, New York are clearly cities
    - Los Angeles is a city but not remotely like New York
    - Guildford is not a city but it has a Cathedral
    - St David's Wales is a city - with only 2000 inhabitants
- Physical models attempt to overcome this
  - We covered some in the introductory section
  - These models consider reflection, diffraction and street canyon propagation mechanisms

Physical models

Semi-empirical
(some physics, some curve fitting)

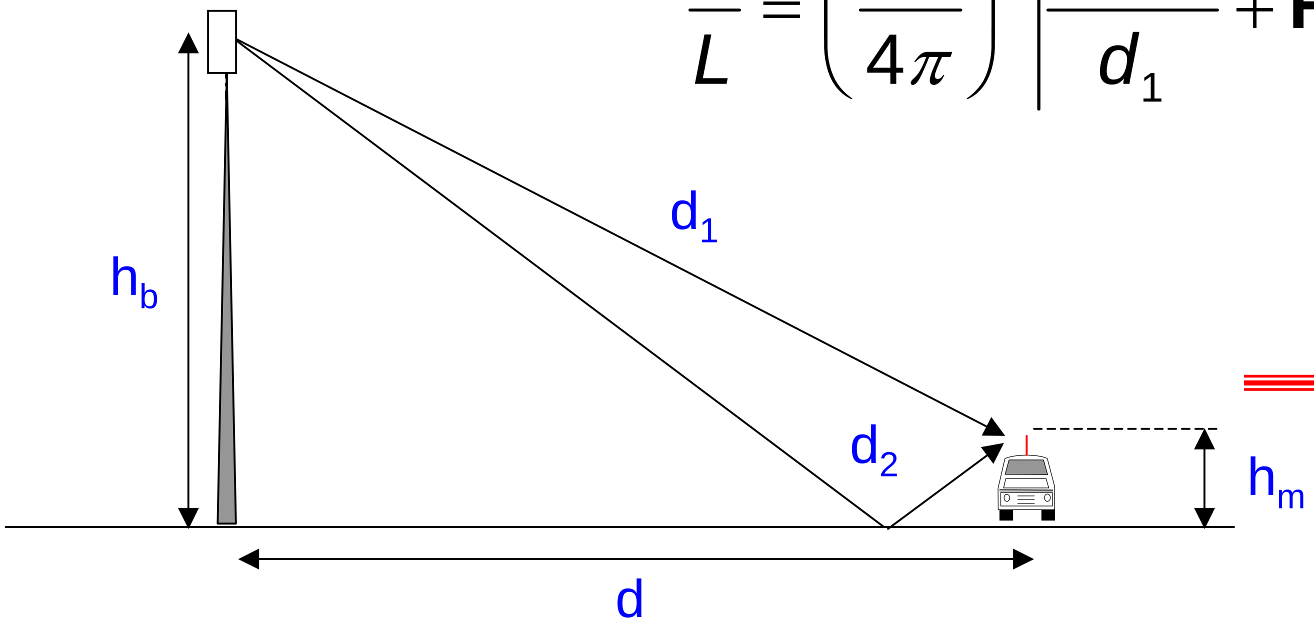
Line of sight plus reflection

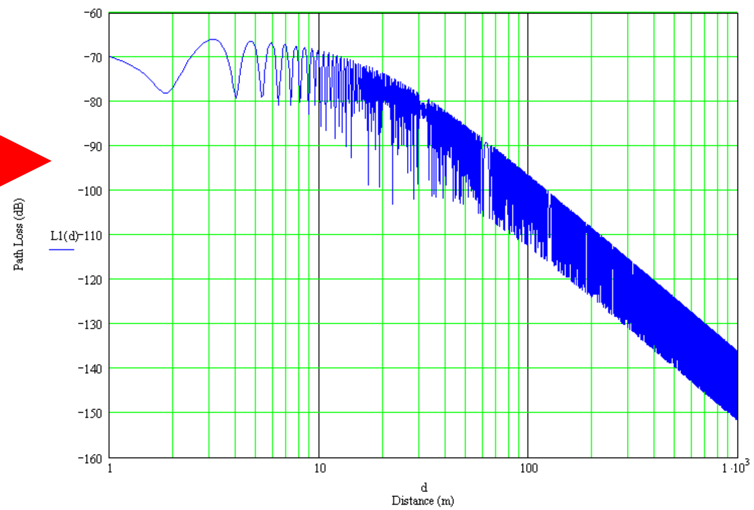
Assumes two rays one direct path and a dominant reflection - usually from the ground

Constructive and destructive interference

reflection coefficient

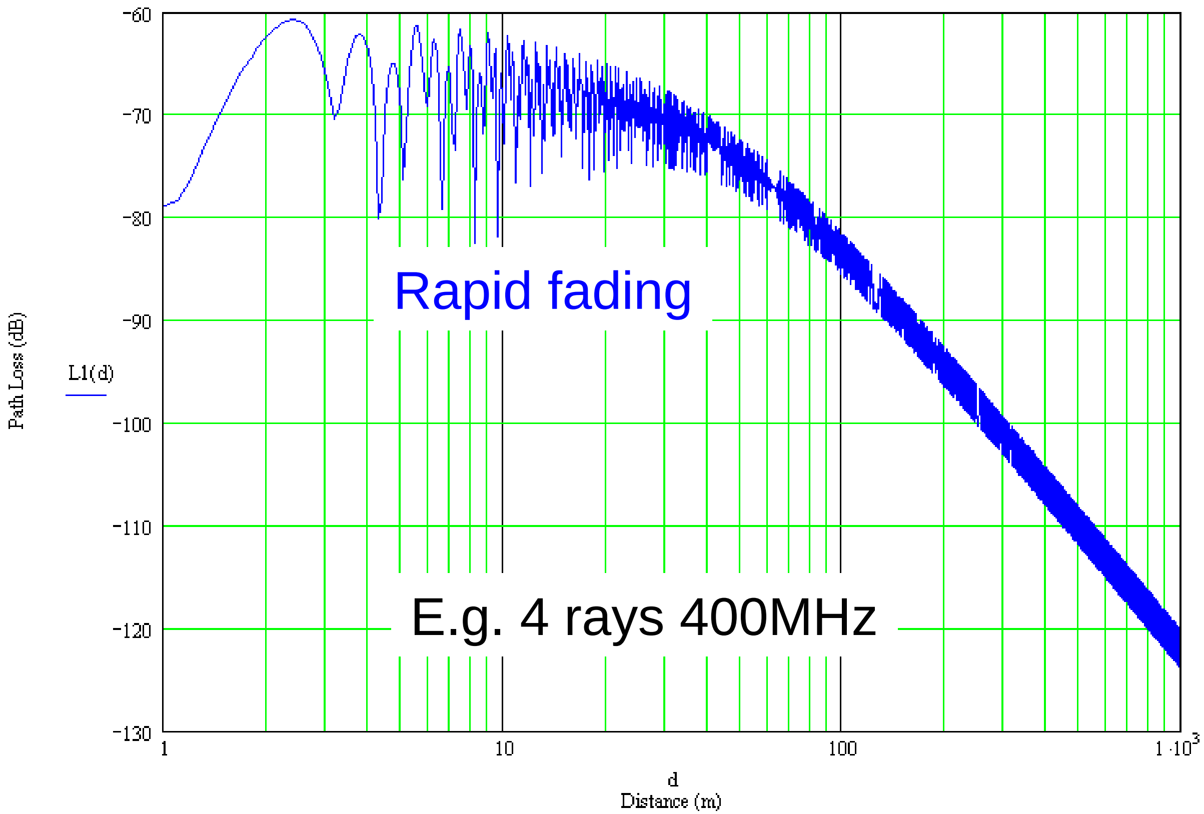
$$\frac{1}{L} = \left(\frac{\lambda}{4\pi}\right)^2 \left| \frac{e^{-jkd_1}}{d_1} + \mathbf{R}\frac{e^{-jkd_2}}{d_2} \right|^2$$

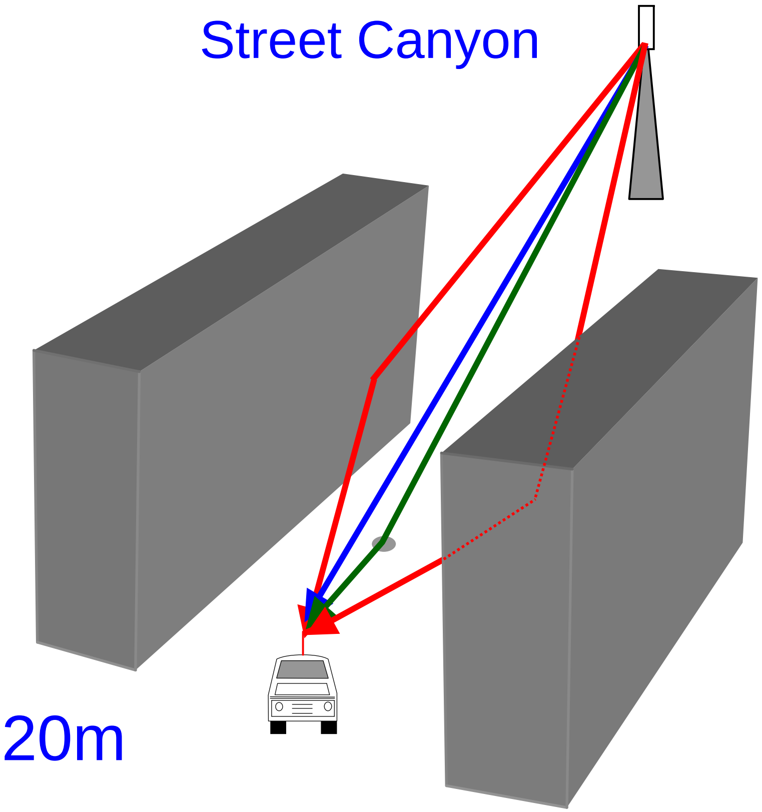




Street canyon

Extension of the two ray model



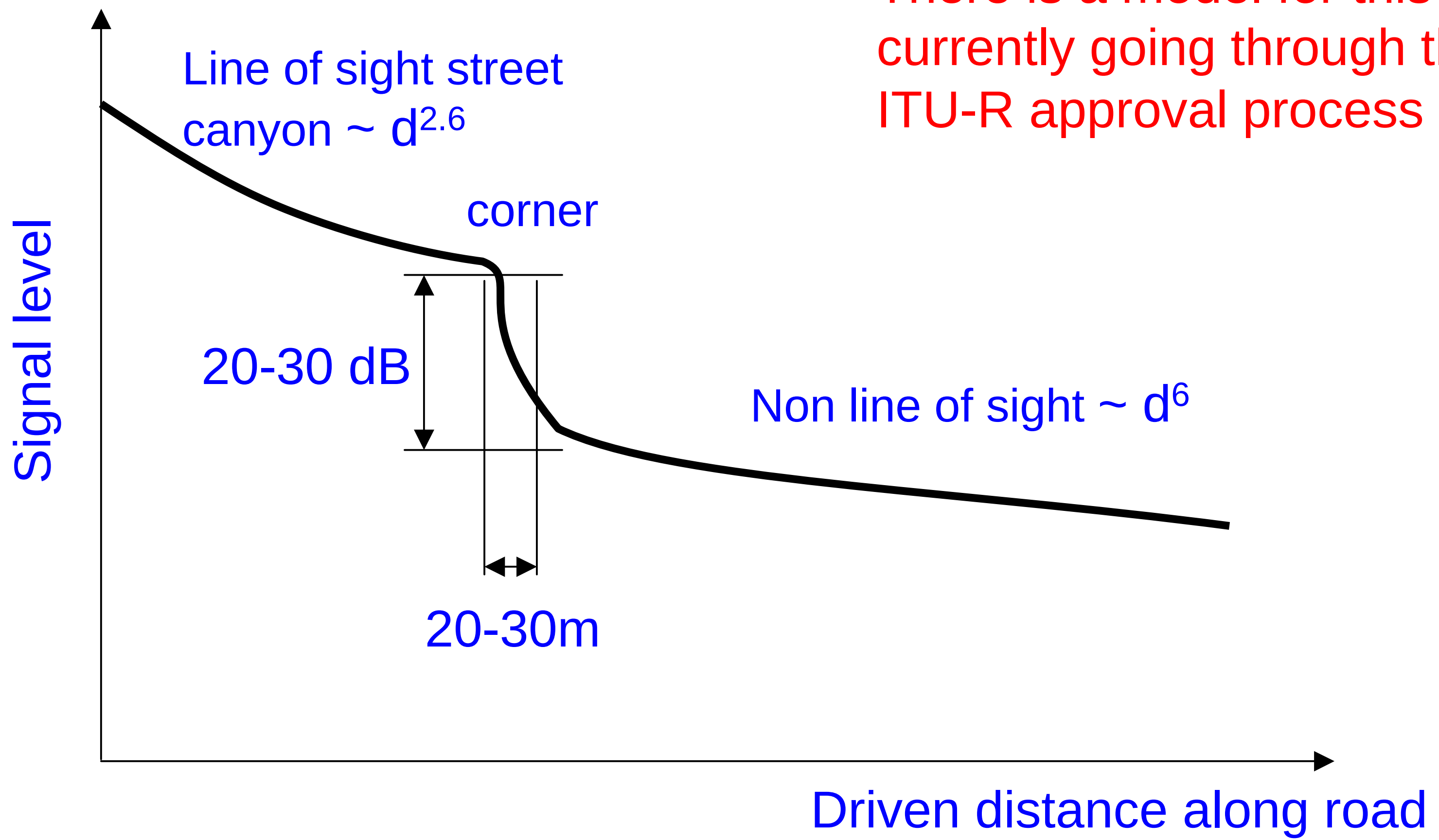


$$L = 42.6 + 26\log(d_{km}) + 20\log(f_{MHz}) \text{ for } d > 20\text{m}$$

Corner losses

In built up areas as mobile transits away from line of sight around a corner there is a rapid drop in signal level as the dominant mode transits from line of sight street canyon to diffraction over and around buildings

There is a model for this currently going through the ITU-R approval process

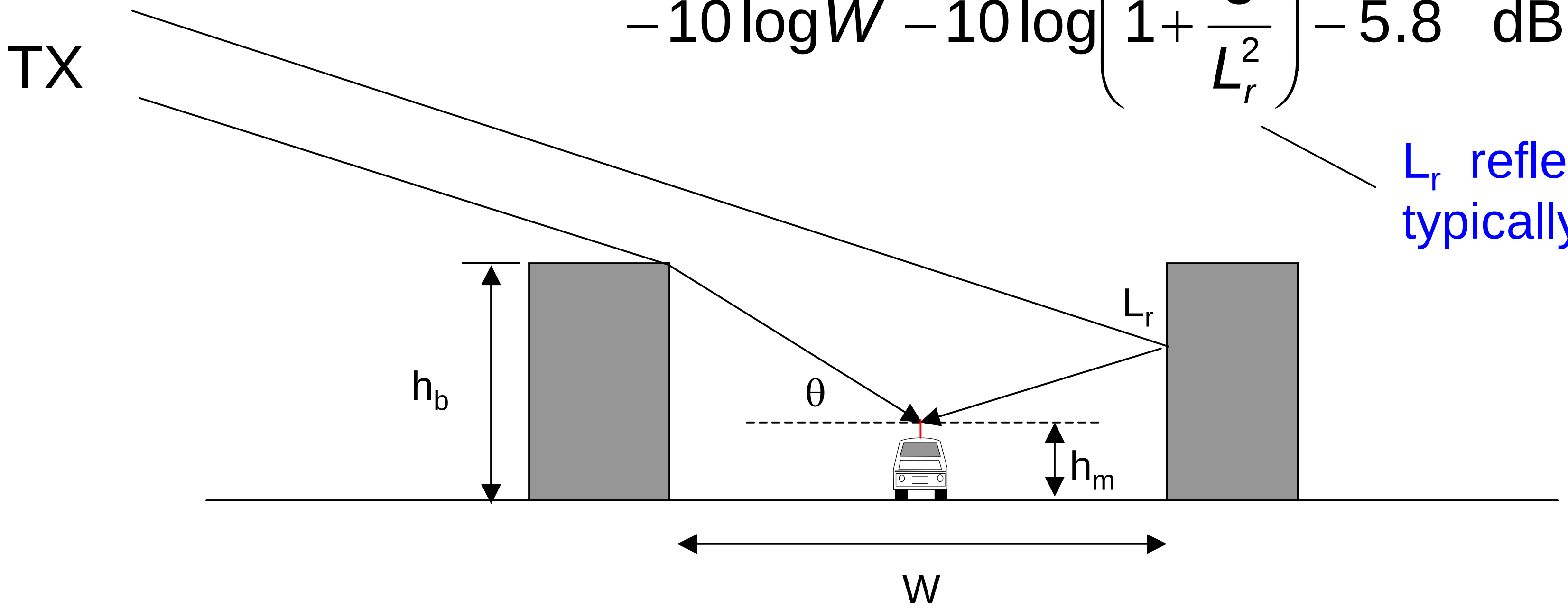


Non line of sight models

Ikegami model

- Based on a single diffraction edge plus a reflection
- Uses ray tracing and a detailed map of building locations (entirely deterministic)
- Power sums the diffracted and reflected ray - free space plus extra loss

$$\text{Extra Loss } L = 10\log f + 10\log(\sin\theta) + 20\log(h_b - h_m)$$
$$- 10\log W - 10\log\left(1 + \frac{3}{L_r^2}\right) - 5.8 \quad \text{dB}$$



L_r reflection loss typically ~0.25

Walfisch/Ikegami model

This is a 2 state model

Development of Ikegami model (800MHz to 2 GHz)

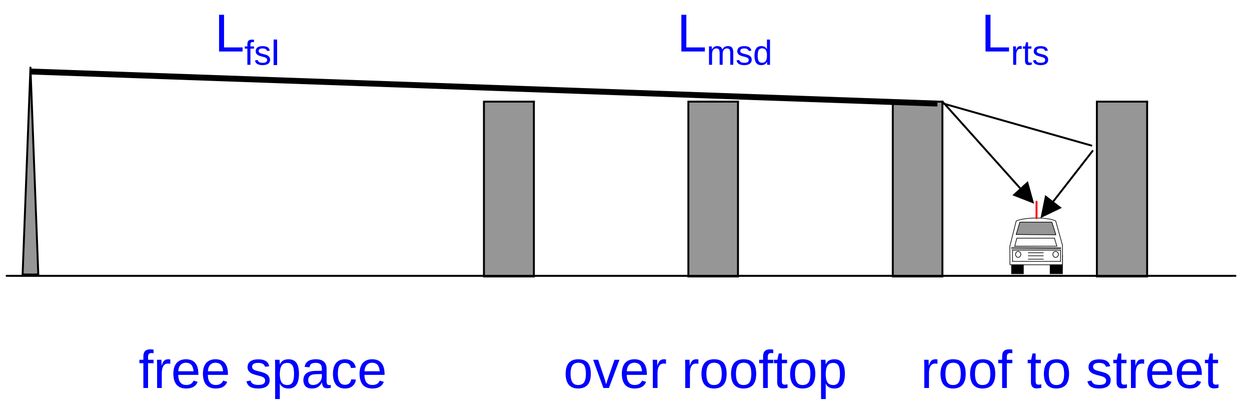
using:

- Two ray LOS model $L = 42.6 + 26\log(d_{km}) + 20\log(f_{MHz})$

or:

- Free space + Rooftop to street + multiple screen diffraction

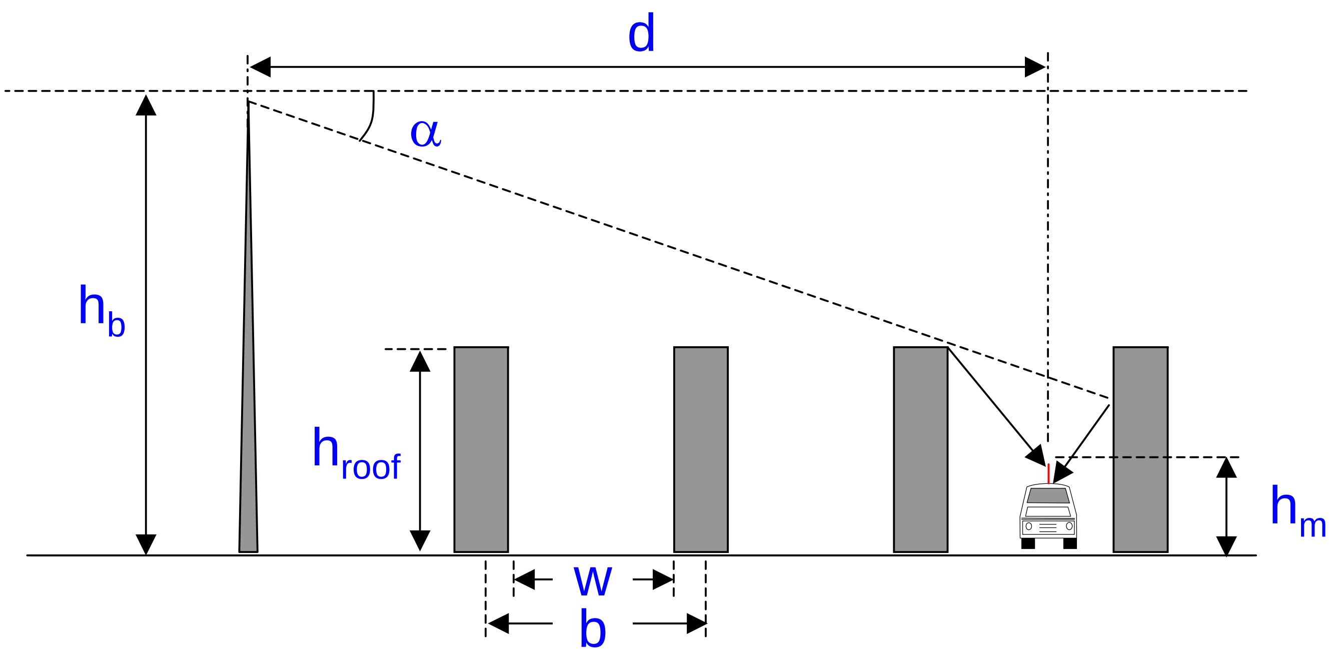
$$L = L_{fsl} + L_{rts} + L_{msd}$$



Over rooftop model

Energy comes over the rooftops via multiple screen diffraction mechanism and into the street by a combination of reflection and diffraction

- This is a complex calculation that can be approximated well

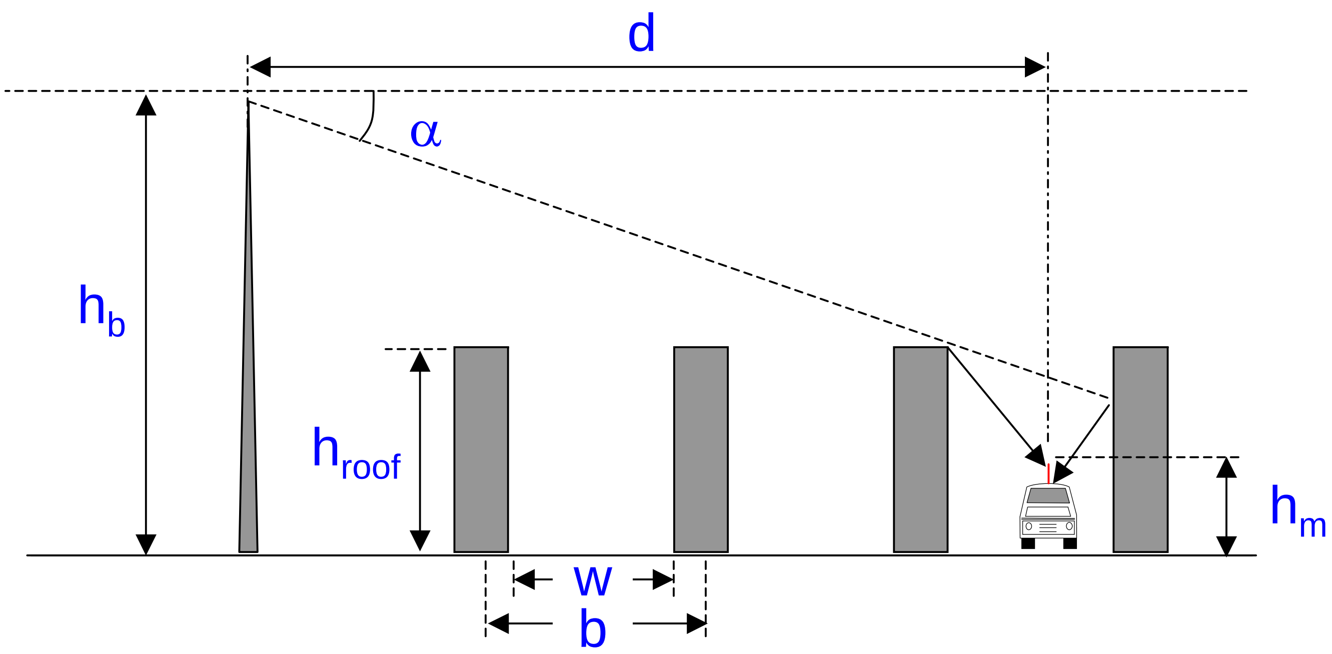


Rooftop to street loss

Roof to street (only applies if mobile is below roof height)

$$L_{rts} = \begin{cases} -16.9 + 10\log(w) + 10\log(f) + 2 - \log(h_{roof} - h_m) + L_{ori} & h_{roof} > h_m \\ 0 \quad \text{otherwise} \end{cases}$$

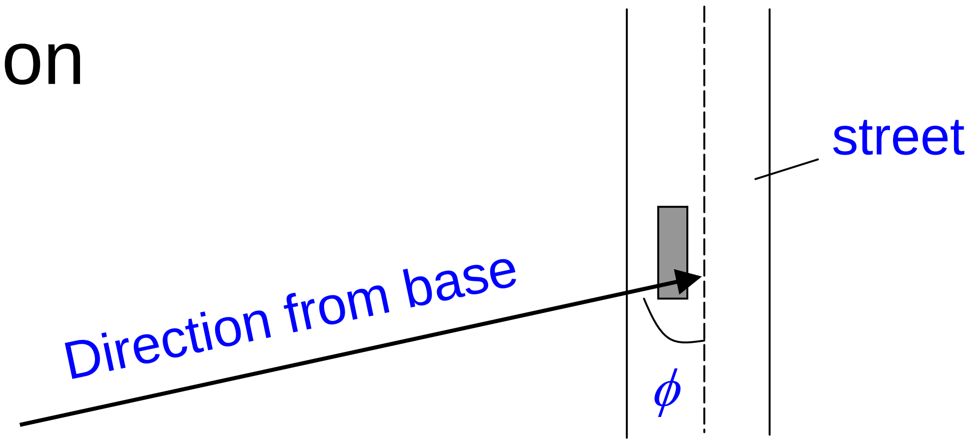
street orientation



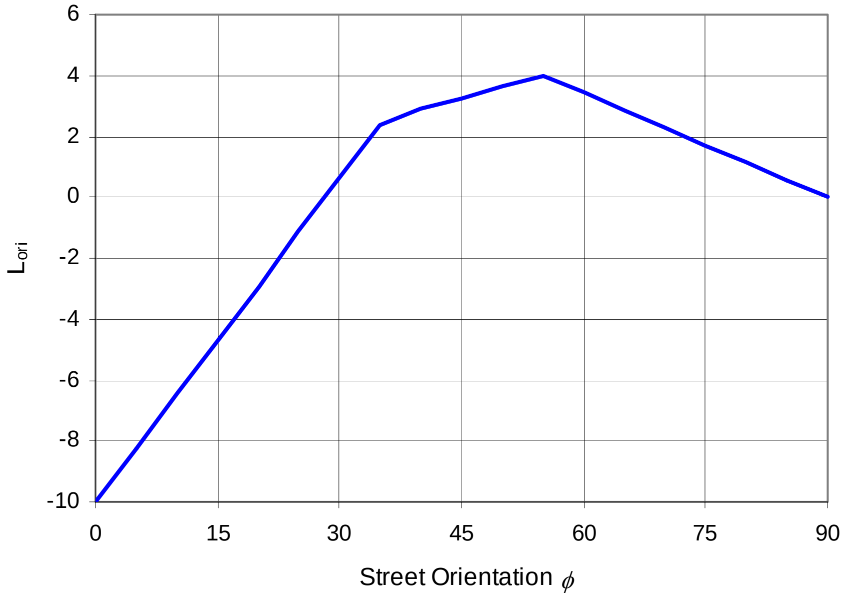
Rooftop to street loss

Street orientation correction

Range -10 to +4 dB
Correction = 0 at 90^0



$$L_{ori} = \begin{cases} -10 + 0.354\phi & \text{for } 0 \le \phi < 35 \\ 2.5 + 0.075(\phi - 35) & \text{for } 35 \le \phi < 55 \\ 4 - 0.114(\phi - 55) & \text{for } 55 \le \phi \le 90 \end{cases}$$



Multi-screen diffraction

The multi-screen diffraction is a fit to the theoretical result

$$L_{msd} = L_{bsh} + k_a + k_d \log(d_{km}) + k_f \log(f_{MHz}) - 9\log(b_m)$$

Where:

$$L_{bsh} = \begin{cases} -18 \log(1 + h_b - h_{roof}) & \text{for } h_b > h_{roof} \\ 0 & \text{for } h_b \le h_{roof} \end{cases}$$

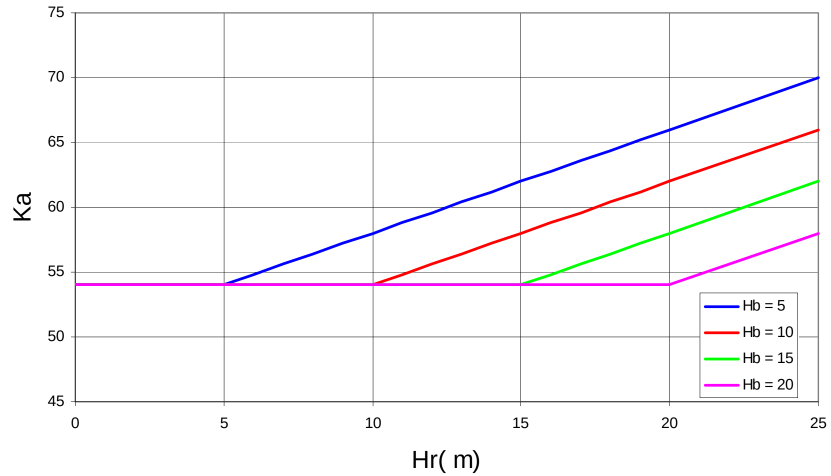
A base station height gain function

$$k_a = \begin{cases} 54 & \text{for } h_b > h_{roof} \\ 54 - 0.8\Delta h_b & \text{for d} \ge 0.5\text{km and } h_b \le h_{roof} \\ 54 - 1.6\Delta h_b d & \text{for d} < 0.5\text{km and } h_b \le h_{roof} \end{cases}$$

$$\Delta h_b = h_b - h_{roof}$$

A term for increased loss if base below rooftop

K_a



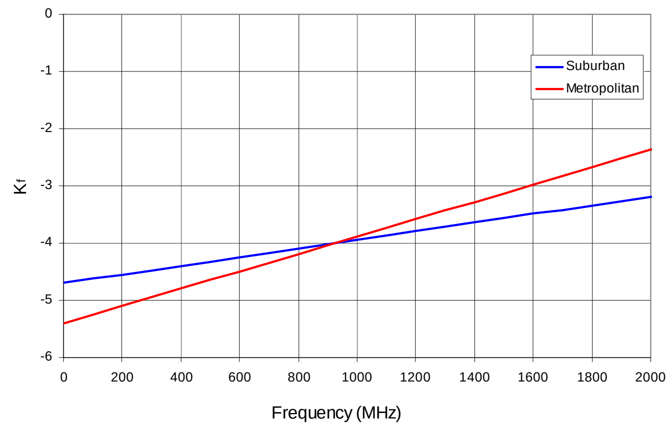
Multi-screen diffraction

The frequency and distance dependencies

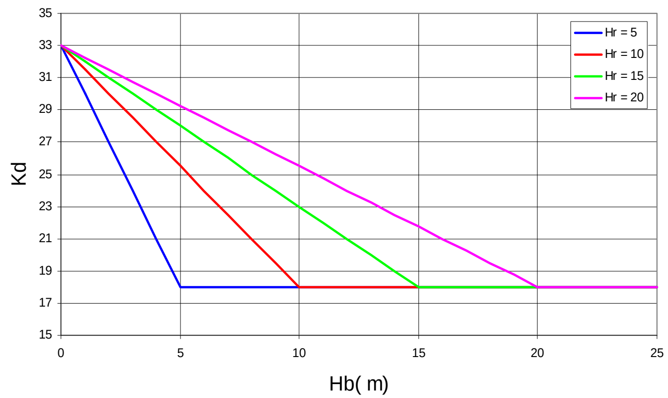
$$L_{msd} = L_{bsh} + k_a + k_d \log(d_{km}) \; + \; k_f \log(f_{MHz}) - 9\log(b_m)$$

and:

$$k_f = -4 + \begin{cases} 0.7\left(\dfrac{f}{925} - 1\right) & \text{for medium cities} \\ 1.5\left(\dfrac{f}{925} - 1\right) & \text{for dense urban areas} \end{cases}$$



$$k_d = \begin{cases} 18 & \text{for } h_b > h_{roof} \\ 18 - 15\left[\dfrac{\Delta h_b}{h_{roof}}\right] & \text{for } h_b \le h_{roof} \end{cases}$$



loads of equations - tedious by hand but it is fairly simple to write a program to do this

Other effects

Buildings

Building shadowing

Some measurement data

- The shadowing effect depends on the building material
- Metal - either metal walls or foil used for insulation makes the external walls of many buildings effectively opaque to radio signals
- Transmission tends to come through the windows
- with significant diffraction around and over the building

Building Shadowing Loss (Terrestrial Paths)		
Building type	Attenuation (dB) 880 MHz	Attenuation (dB) 1922 MHz
Office complex	7.9	9.5
Shopping arcade	12.9	10.8
Two floor shopping arcade	12.3	8.3
Hotel	11.3	11.2
Average	**11.1**	**10.0**

Building penetration

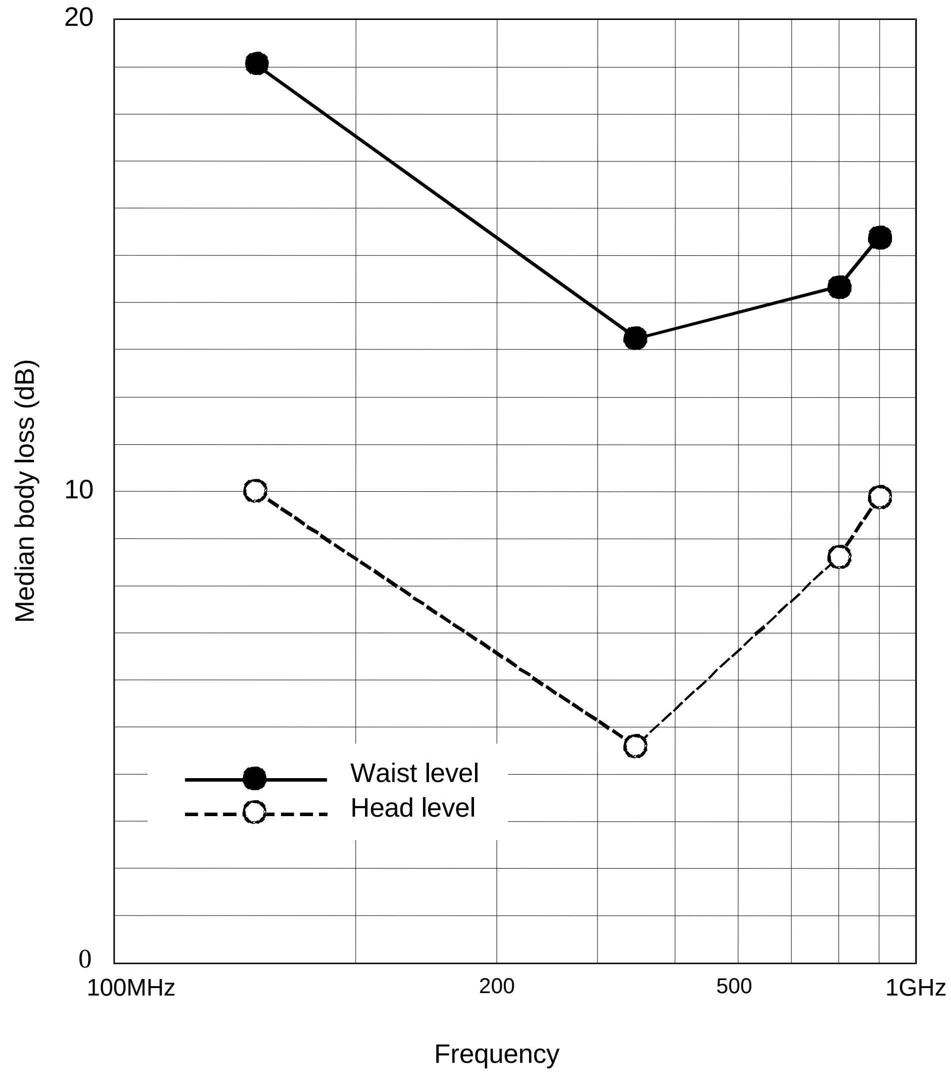
The amount of energy that passes into a building

- Wooden shed typically a few dB loss at UHF
- Metal warehouse practically nothing gets through
- Office block, typically 10 dB loss per wall
- Unless we know the building construction, it is not easy to estimate

- Often signals come in through the windows
  - 5.6 GHz WLAN - e.g. typically 5-15 dB down inside an office vs outside
  - Consider the size of the opening compared to the wavelength
    - higher frequencies penetrate better
    - Not good for VHF, UHF better
      - one of the reasons UHF is a sweet spot for mobile systems

Body losses

Assuming a person is in the line of the signal holding a handset we can expect 5-15 dB of attenuation

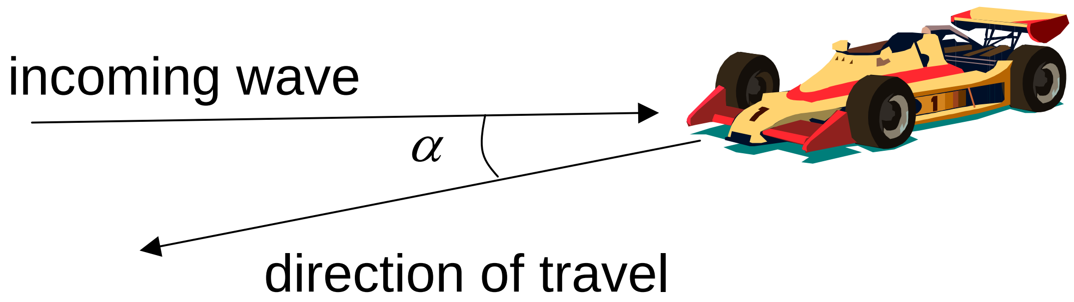


Dynamics

Fast fading & Multipath effects

Doppler

The Doppler effect results in a change in the apparent frequency of a received wave at a mobile receiver compared to a stationary receiver



$$\text{Doppler shift } f_d = f_0 \frac{v}{c} \cos(\alpha)$$

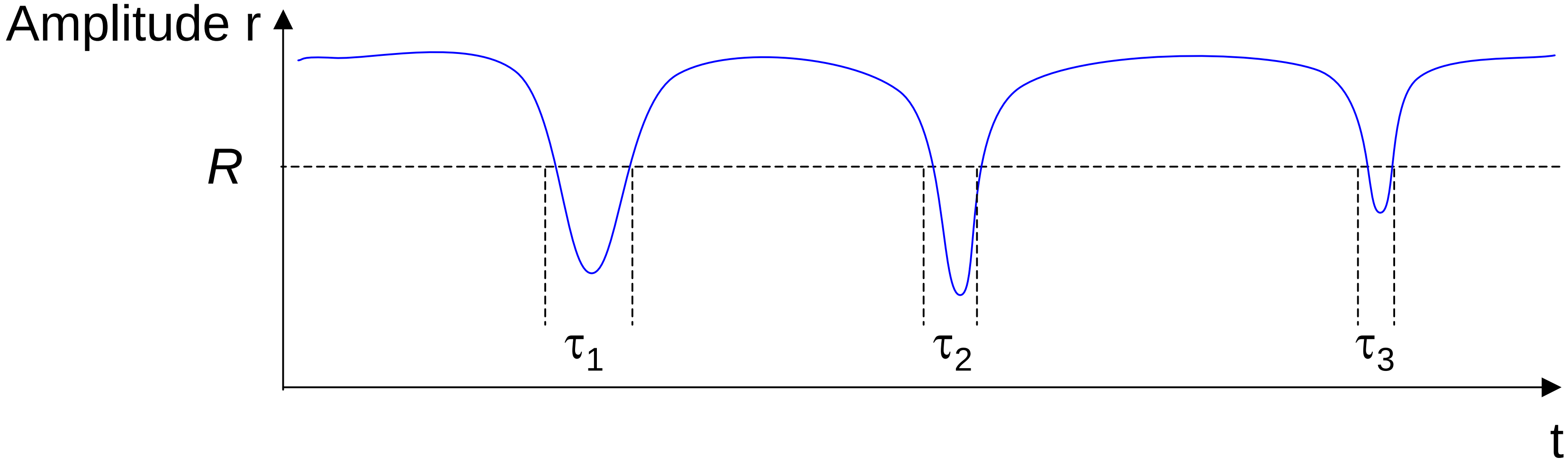
Slow/Fast fading

Signals vary with time and location and may combine direct and indirect paths

- Slow fading comes from the mobility, changes in shadowing or changes in the path e.g. passing a tree or building
  - does not vary quickly with frequency
- Fast fading comes from moving through the constructive and destructive interference patterns caused by multipath
  - varies quickly with frequency

Mobile fading duration

We are interested in the time a signal amplitude falls below some threshold *R*



When the signal falls below the threshold – the receiver fails to decode the signal properly and we lose data

We need to know the average fade rate duration below R

Mobile fading duration

We know the fading follows a Rayleigh distribution

Rayleigh Distribution

$$P(r) = \frac{r}{\sigma^2} e^{\left(-r^2/2\sigma^2\right)}$$

$2\sigma^2$ is the mean square value of a Rayleigh distribution

The probability of a fade below threshold R is

$$P(r \le R) = \int_0^R P(r).dr = 1 - e^{-(R^2/2\sigma^2)}$$

Mobile fading duration

The average threshold crossing rate is

$$N_R = \frac{\sqrt{\pi}}{\sigma^2} R f_m e^{-R^2/2\sigma^2}$$

The Doppler shift ($f_m = \upsilon/\lambda$) governs how quickly we go through half wavelength nulls

We have skipped a lot of maths here – it is enough to know this comes from the Rayleigh distribution

The expected (mean) value of the fade duration is

$$E\{\tau_R\} = \frac{P(r \leq R)}{N_R} = \frac{1 - e^{\left(R^2/2\sigma^2\right)}}{N_R}$$

Mobile fading duration

Substituting for N_R

$$E\{\tau_R\} = \sqrt{\frac{\sigma^2}{\pi}}\frac{e^{-R^2/2\sigma^2} - 1}{Rf_m}$$

This is inversely proportional to the velocity – so fade durations are much longer for portables compared to mobiles

Multiplying by $f_m = \upsilon/\lambda$ gives the fade duration in terms of wavelengths

$$L_R = \sqrt{\frac{\sigma^2}{\pi}}\frac{e^{-R^2/2\sigma^2} - 1}{R}$$

Location variability

Rural area

- For paths of equal length the standard deviation, of the location variability distribution is:

$$\sigma_L = \begin{cases} 6 + 0.69\left(\frac{\Delta h}{\lambda}\right)^{1/2} - 0.0063\left(\frac{\Delta h}{\lambda}\right) & \text{dB} \quad \text{for } \Delta h/\lambda \leq 3000 \\ 25 & \text{dB} \quad \text{for } \Delta h/\lambda > 3000 \end{cases}$$

Where Δh is the inter-decile (10% to 90%) height variation in m

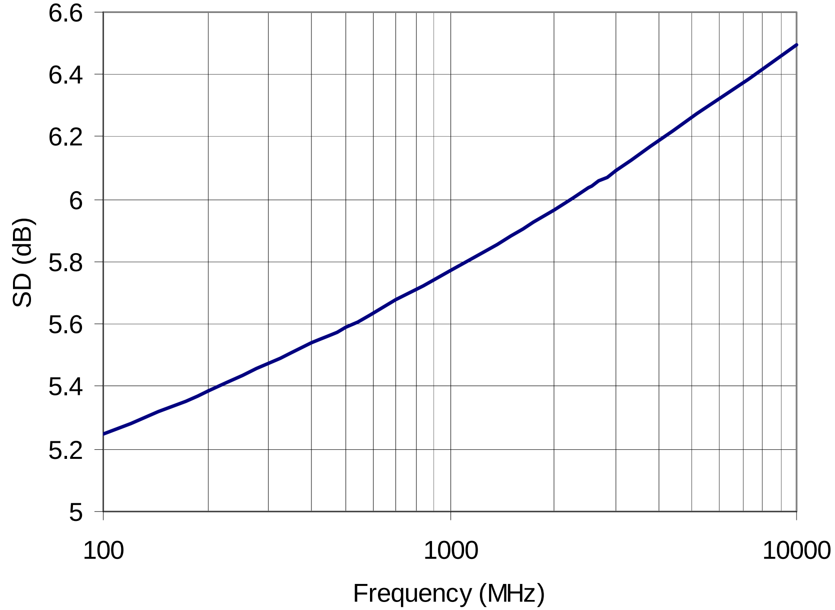
Location variability

Flat urban areas

– For paths of equal length the standard deviation, of the location variability distribution is:

$$\sigma_L = 5.25 + 0.42\log\left(\frac{f}{100}\right) + 1.01\log^2\left(\frac{f}{100}\right) \qquad \text{dB}$$

Where *f* is in MHz.



Number of multipath components

Typical values from measurements

Frequency (GHz)	Antenna height (m)		Range (m)	Maximum number of signal components					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.35	4	1.6	0-200	2	3	2	4	5	6
			0-1 000	2	3	2	4	5	9
8.45	4	1.6	0-200	1	3	2	3	4	6
			0-1 000	1	2	2	4	4	8
15.75	4	1.6	0-200	1	3	2	3	4	5
			0-1 000	2	3	2	4	6	10

Urban area – low base station

Note 2 – 9 components

Number of multipath components

Typical values from measurements

Frequency (GHz)	Antenna height (m)		Range (m)	Maximum number of signal components					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.67	40	2.7	0-5 000	1	2	1	3	3	5

Urban area – high base station

Note 1 – 5 components

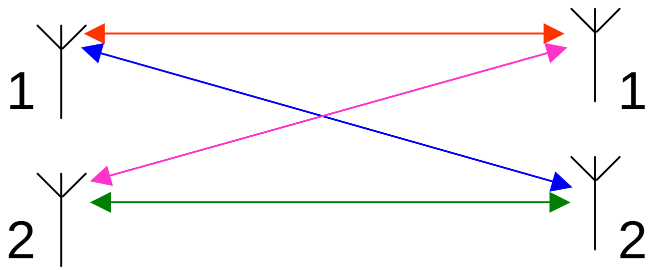
Frequency (GHz)	Antenna height (m)		Range (m)	Maximum number of signal components					
	h_b	h_m		A = 3 dB		A = 5 dB		A = 10 dB	
				80%	95%	80%	95%	80%	95%
3.35	4	2.7	0-480	2	2	2	2	2	3

Residential area – low base station

Aside - MIMO

MIMO stands for Multiple Input - Multiple Output

- This is a new technology that takes advantage of multipath to increase channel capacity
- the throughput for a MIMO system increases as the number of antennas is increased
- Patented by Bell Labs in 1984



$$\mathbf{H} = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix}$$

Transfer matrix – ***a*** are the complex channel coefficients between each TX/RX antenna pair

(There can be many antennas)

MIMO Capacity

Ideally….

The Shannon limit for a single channel is

$$\text{Capacity} = \log_2(1 + SNR) \quad \text{bits/sec per Hz}$$

For a MIMO system with n_t transmit and n_r receive antennas

$$\text{Capacity} = \log_2\left\{\det\left|\mathbf{I}_{\mathbf{nr}} + SNR \cdot \mathbf{HH}^{\mathbf{H}}\right|\right\}$$

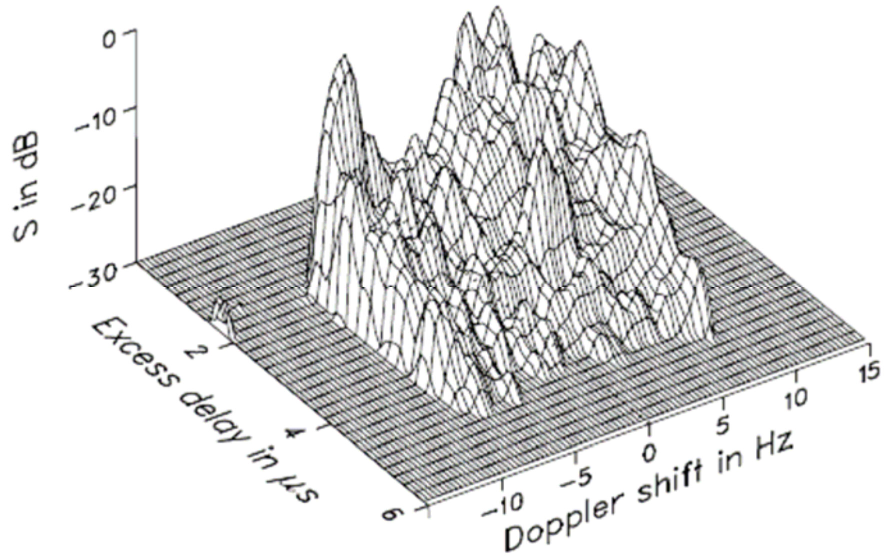
$$= \sum_{i=1}^{n_r} \log_2\left(1 + \frac{SNR}{n_t}\sigma_i^2\right)$$

Where σ_i are the Eigenvalues of $\mathbf{HH}^{\mathbf{H}}$ which depend on the multipath, larger values give higher capacity.

Delay spread measurements

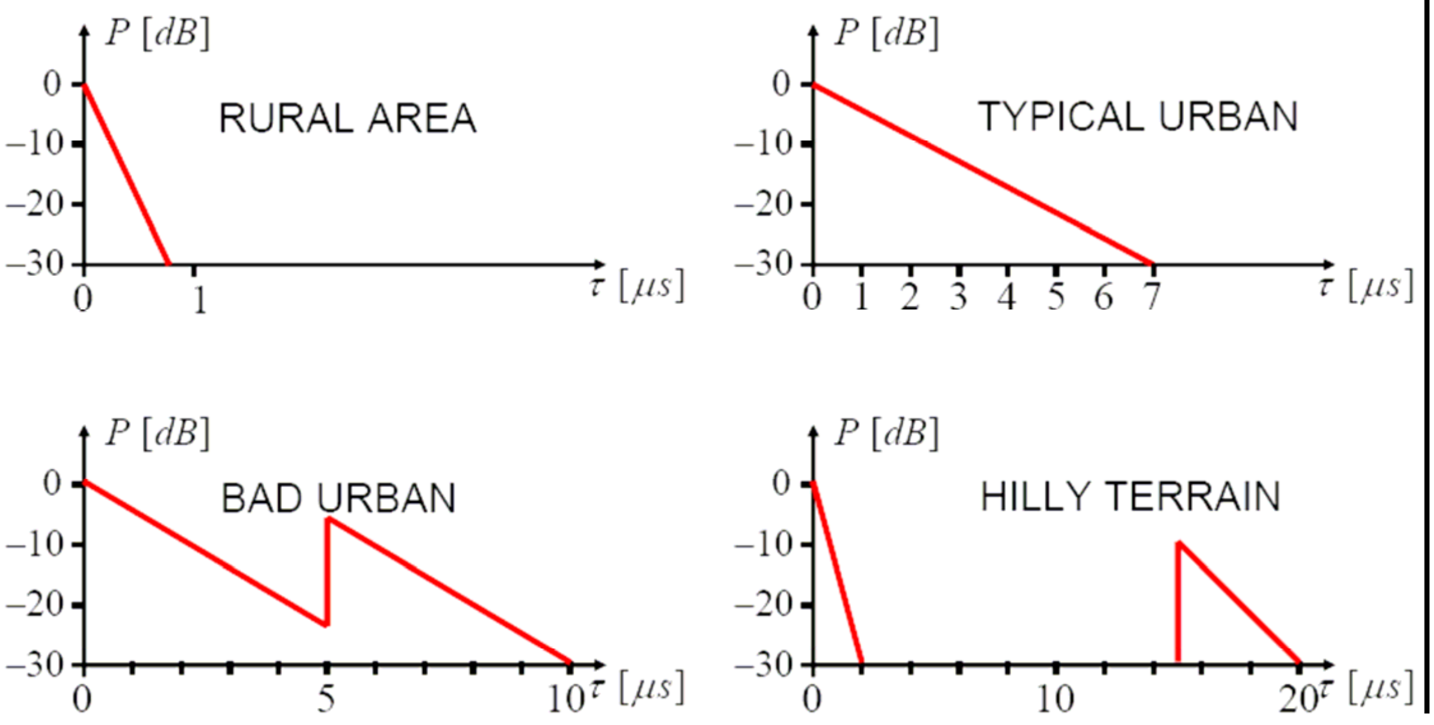
These come from the COST 231 report – a 2μS to 5μS excess delay is equivalent to 600m to 1.5km of excess path

Delay Doppler spreading function for a non line of sight microcell at 900MHz



Delay spread model

COST 207 specifies 4 delay spread models for simulations
(but not the path losses)

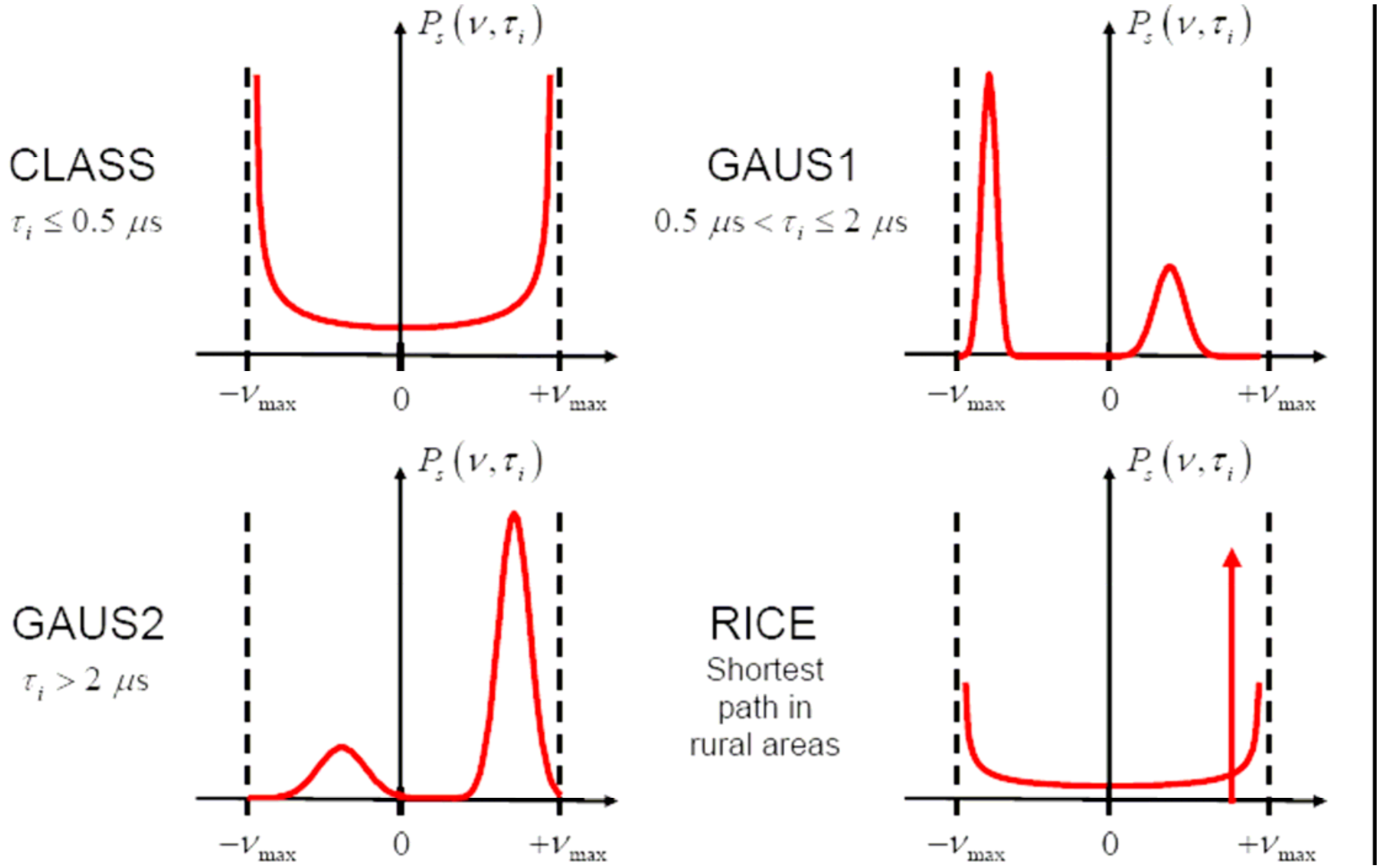


The GSM Bit period is 3.69 μs – so one might think this a problem, but

The standard uses adaptive equalization to tolerate up to 15 μs of delay spread through a 26-bit Viterbi equalizer training sequence

Doppler spread models

COST 207 also specifies four Doppler spread models



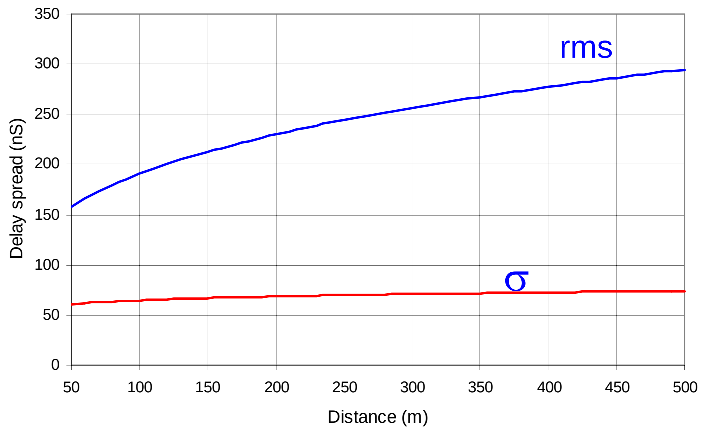
Delay spread

Power law fit to measured data 2-15GHz

r.m.s delay spread, $a_s = C_a d^{\gamma_a}$ nS

standard deviation, $\sigma_s = C_\sigma d^{\gamma_\sigma}$ nS

Measurement conditions				a_s		σ_s	
Area	f (GHz)	h_b (m)	h_m (m)	C_a	γ_a	C_σ	γ_σ
Urban	2.5	6.0	3.0	55	0.27	12	0.32
	3.35-15.75	4.0	2.7	23	0.26	5.5	0.35
			1.6	10	0.51	6.1	0.39
	3.35-8.45		0.5				
Residential	3.35	4.0	2.7	2.1	0.53	0.54	0.77
	3.35-15.75		1.6	5.9	0.32	2.0	0.48



E.g. 2.4 GHz

NB - At 300m at 2.4 GHz 250nS rms delay spread would be a problem for a link operating at above 4Msymbols/sec - hence OFDM etc in Wireless LANs

Terrestrial mobile summary

We have covered the main propagation modes important for mobile systems

- Unlike terrestrial fixed links mobiles tend to be immersed in clutter
  - Blockage and multipath have most influence
  - The environment of the mobile must be considered
    - We can do this Empirically based on a class of environment
    - Or we can do it deterministically, using physical parameters associated with the specific location

Further resources

ITU-R P.1411

“Propagation data and prediction methods for the planning of short range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz”

- This is the main recommendation containing models for short range outdoor propagation
  - Predicts path loss using a modification of the Walfisch Ikegami model
  - Predicts the fading distribution
  - Predicts the properties of the multipath
  - Predicts building entry loss

Indoor propagation

Indoor propagation

This has become especially important now wireless LANs are widespread

- Many of the mechanisms we have covered apply
- There are important differences between indoor and outdoor links
- Paths are shorter
  - High pass loss through walls, floors and furniture
  - Results in less delay spread
- Movement tends to be slower (1m/s vs 30m/s)
- It never rains

Additional propagation impairments

Caused mainly by:

- reflection from walls and floors
- diffraction around objects
- transmission loss through walls, floors, people, furniture and other objects in the room
- Waveguide effects especially in corridors at high frequencies
- people and equipment moving around

A room at the ITU

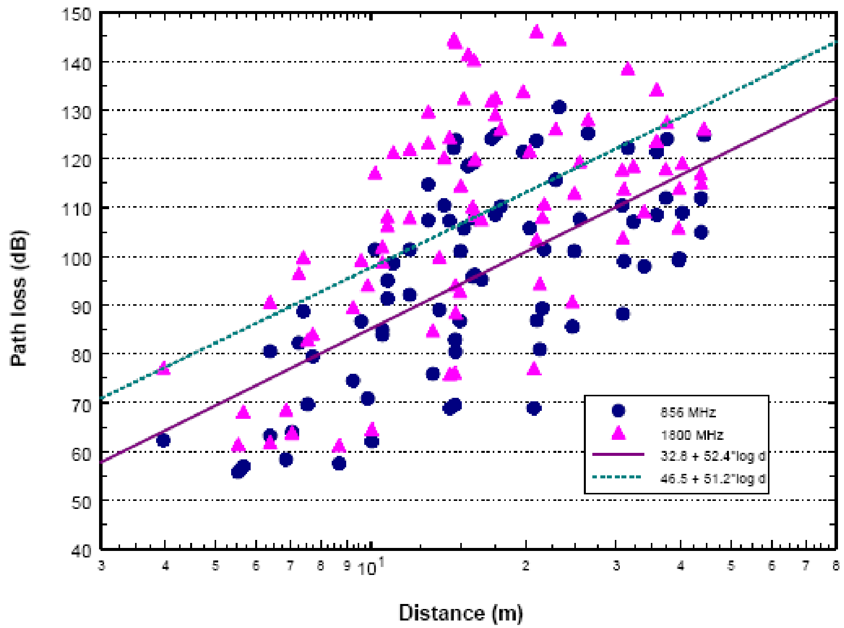
Indoor propagation observations

Some general observations from measurements

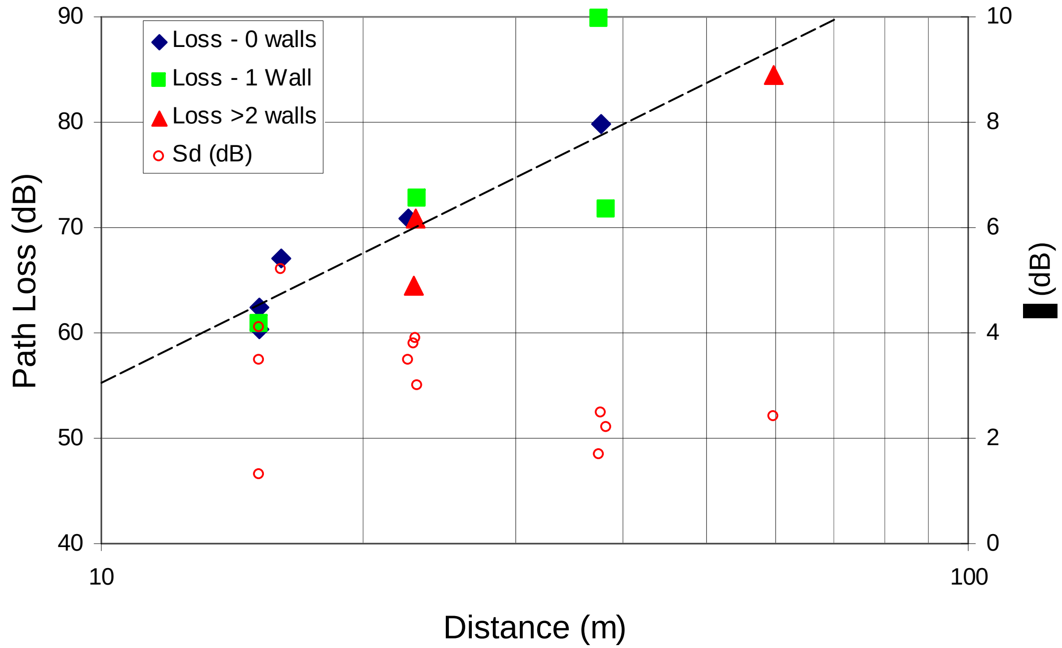
- Paths with line-of-sight exhibit free-space loss 20log(d)
- Large open rooms also follow the free space law 20log(d)
- Corridors may have path losses less than free-space E.g. 18log(d) because of a beam wave guiding effect
- Obstacles and partition walls can cause path loss to rise to 40log(d)
- Long unobstructed paths may show dual slope characteristics 20log(d) and 40log(d) – like outdoors
- Path loss versus frequency is not monotonic – higher frequencies suffer larger losses through walls etc. but can pass more easily through smaller apertures

Measurements

These show the results of some measurements



COST 231 Result - path loss with distance between the 4th floor of an office building and the 4th to 0th floor



Some 2.4 GHz measurements made on a single floor. These lie on a 40log(d) line

Paths through floors and walls

The Motley-Keenan model

– based on free space + losses for floor and walls

$$L = L_1 + 20\log(d) + n_f\alpha_f + n_w\alpha_w$$

Where

L_1 = reference loss at 1m
n_f = number of floors along path, α_f = loss per floor
n_w = number of walls along path, α_w = loss per wall

Typical figures

4 dB	Wooden wall/floor
7 dB	Concrete wall with non-metalised windows
10-20 dB	Concrete wall no windows, concrete floor

ITU-R P.1238

"Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz"

$$L_{total} = 20 \log_{10} f_{(MHz)} + N \log_{10} d + L_f(n) - 28 \quad \text{dB}$$

where:

- N = distance power loss coefficient
- d = separation distance (m) base to mobile (where $d > 1$ m)
- L_f = floor penetration loss factor (dB)
- n = number of floors between base station and portable terminal ($n \geq 1$)

Frequency	Residential	Office	Commercial
900 MHz	–	33	20
1.2-1.3 GHz	–	32	22
1.8-2 GHz	28	30	22
4 GHz	–	28	22
5.2 GHz	–	31	–

Values for N

Frequency	Residential	Office	Commercial
900 MHz	–	9 (1 floor) 19 (2 floors) 24 (3 floors)	–
1.8-2 GHz	$4n$	$15 + 4(n-1)$	$6 + 3(n-1)$
5.2 GHz	–	16 (1 floor)	–

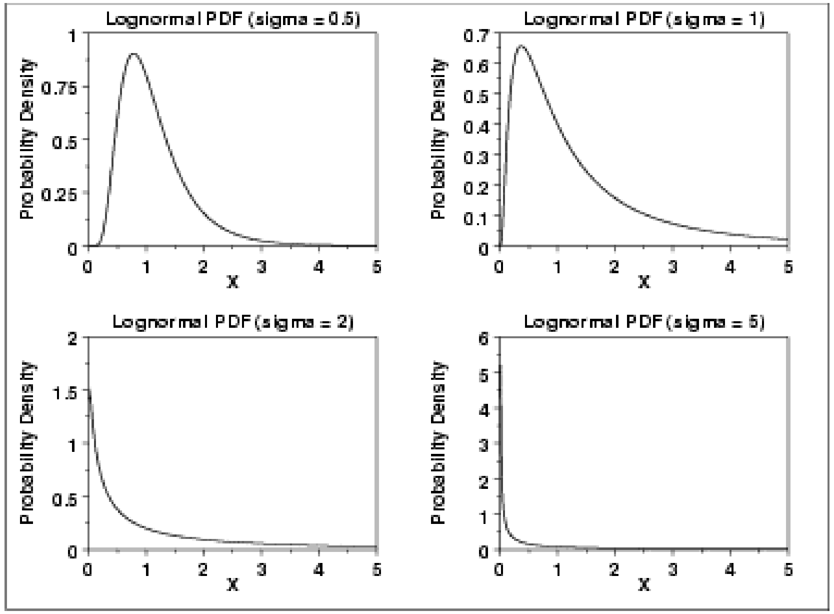
Values for $L_f(n)$

ITU-R P.1238

Variability

– The indoor shadow fading statistics follow a log normal distribution

$$f(x) = \frac{e^{-\ln(x)^2/2\sigma^2}}{x\sigma\sqrt{2\pi}}$$



Shadow fading statistics, standard deviation (dB) for indoor transmission loss			
Frequency (GHz)	**Residential**	**Office**	**Commercial**
1.8-2	8	10	10
5.2	–	12	–

Delay spread

Measured rms delay spread for omni antennas

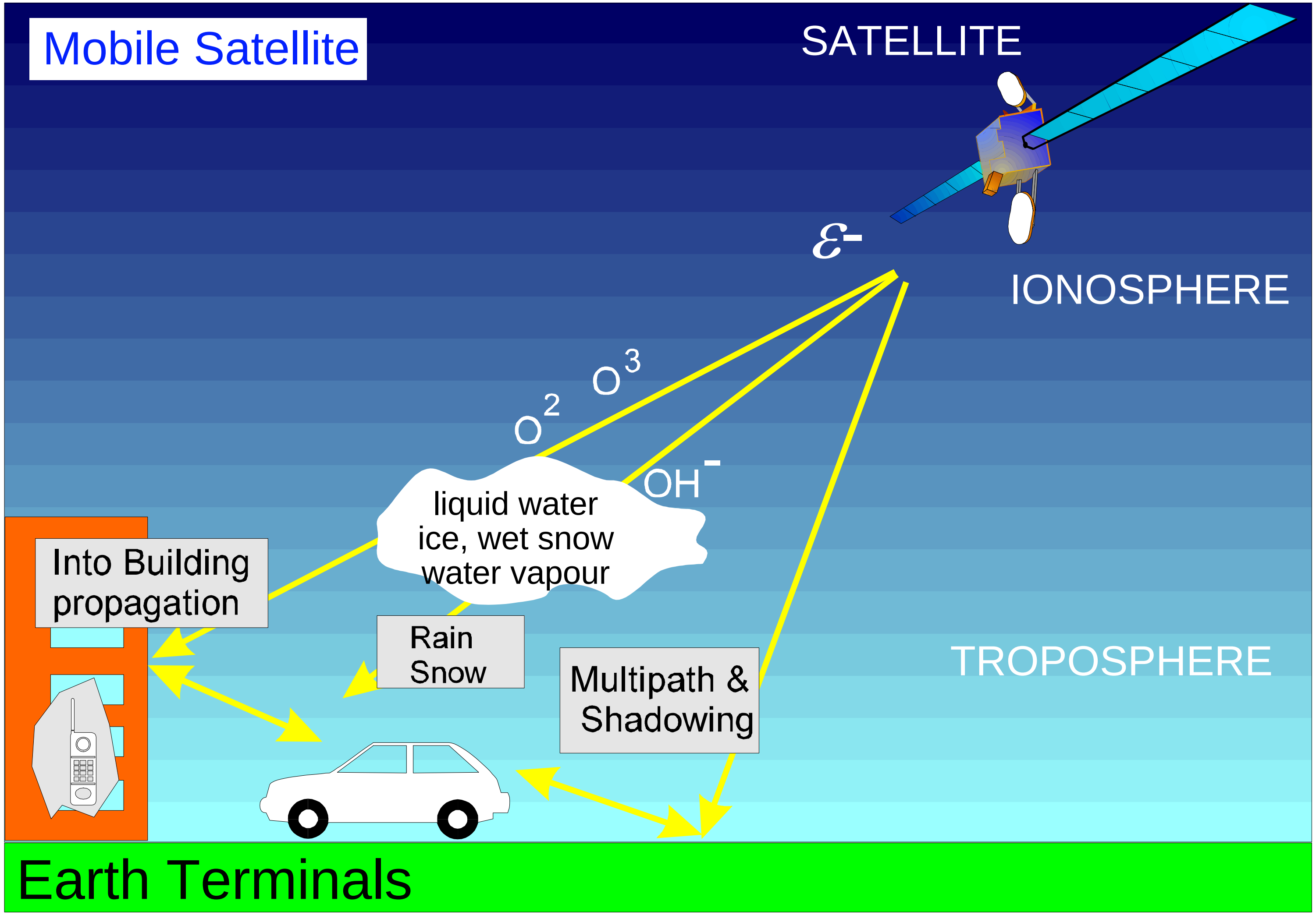
Frequency	Environment	Low (ns)	Median (ns)	High (ns)
1 900 MHz	Indoor residential	20	70	150
1 900 MHz	Indoor office	35	100	460
1 900 MHz	Indoor commercial	55	150	500
5.2 GHz	Indoor office	45	75	150

The r.m.s. delay spread is roughly proportional to the floor space

$$10 \log(\tau) = 2.3 \log(FS) + 11.0$$

FS in m^2, t in nS

Satellite mobile



Differences compared to terrestrial

The satellite acts like a very tall mast a long way away

- excellent regional coverage – "Mega cell"
- limits to the power budget
    - lower data rates
- likely to be line of sight except in urban areas
- possibly significant propagation delay
- Except for GEOs, the base station is moving rapidly
    - The path can change rapidly even if the earth terminal is stationary

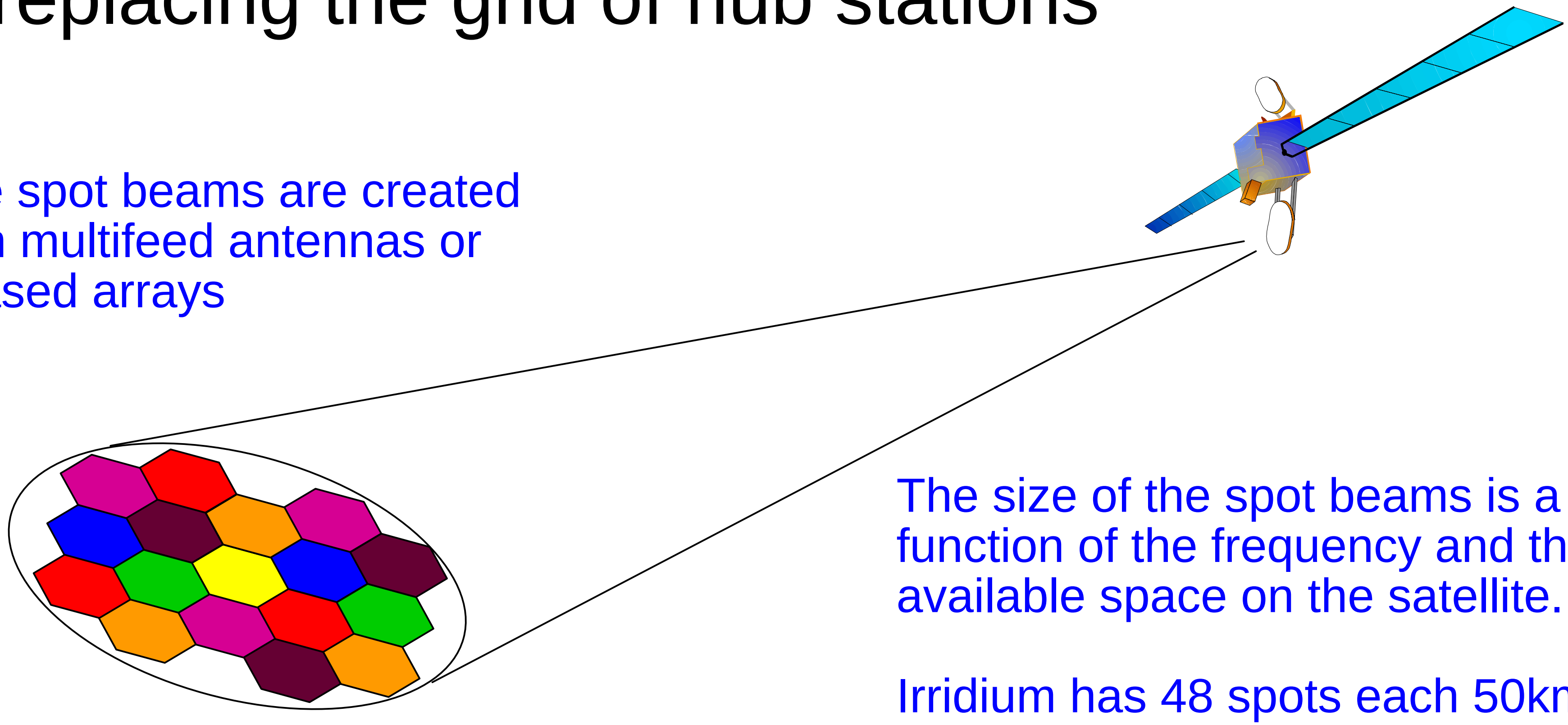
Some satellite systems

	GEO	ICO	MEO	Big LEO		
	INMARSAT B,C & M	P	Odyssey	Iridium	Global star	Aries
Orbit (km above ground)	36 k	10 k	10 k	780	1. 4 k	1 k
Number of Active Satellites	4	10	12	66	48	48
Min. Single Hop Delay (ms)	240	69	69	5.2	9	6.8
Downlink GHz	1.5	2.0	2.5	1.6	2.5	2.5
Uplink GHz	1.6	2.2	1.6	1.6	1.6	1.6

Cellular in satellite mobile

The spectrum available means frequencies need to be re-used – in a similar way to the terrestrial cellular concept with spot beams replacing the grid of hub stations

The spot beams are created with multifeed antennas or phased arrays



The size of the spot beams is a function of the frequency and the available space on the satellite.

Irridium has 48 spots each 50km across

Free space loss

The free space loss varies enormously

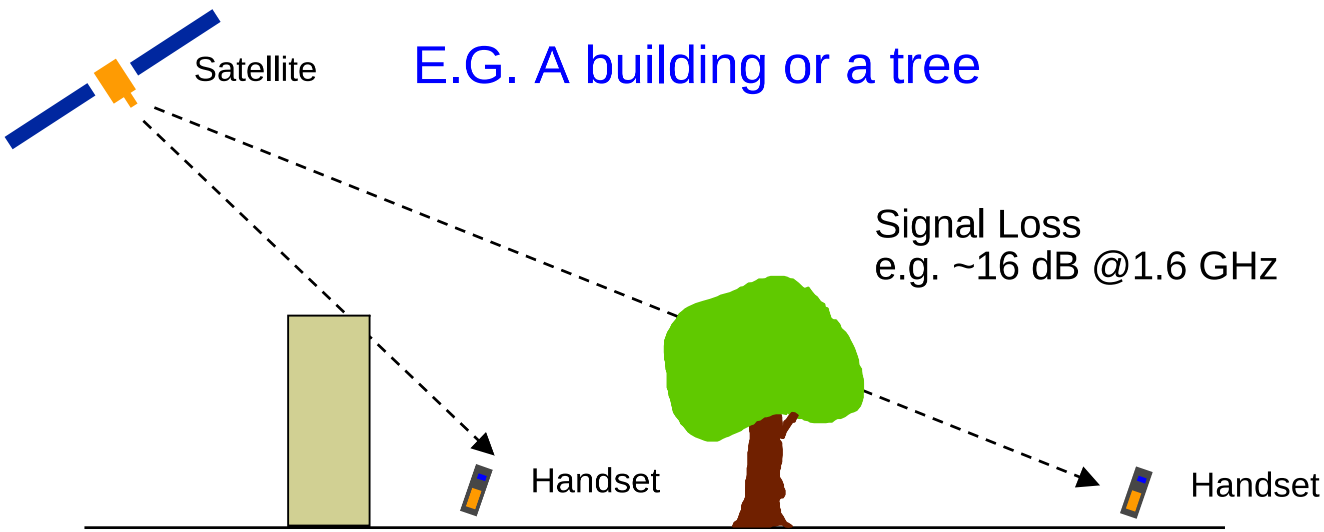
- For a LEO system like Iridium path loss varies between 154dB and 167 dB at 1.6 GHz
  - It does this over 5-10 minutes
  - With a Doppler shift of up to 37 kHz
  - And needs 66 satellites to provide global coverage

- For a GEO system at 36 000km the path loss is around 186 dB
  - But this does not vary
  - Has virtually no Doppler shift
  - Does not move – so a fixed antenna could be used
  - Only needs 3 satellites for near global coverage

Satellite mobile propagation modes

Shadowing

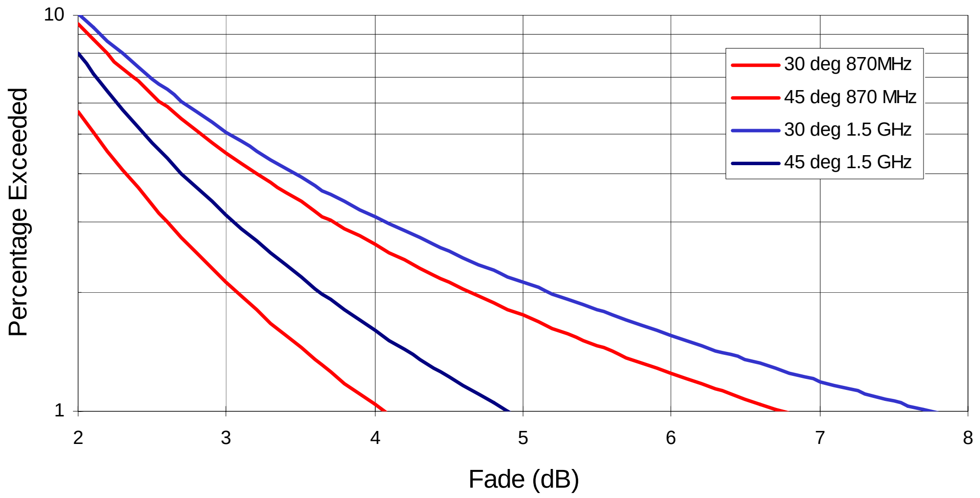
– Pure attenuation where an object is blocking the path

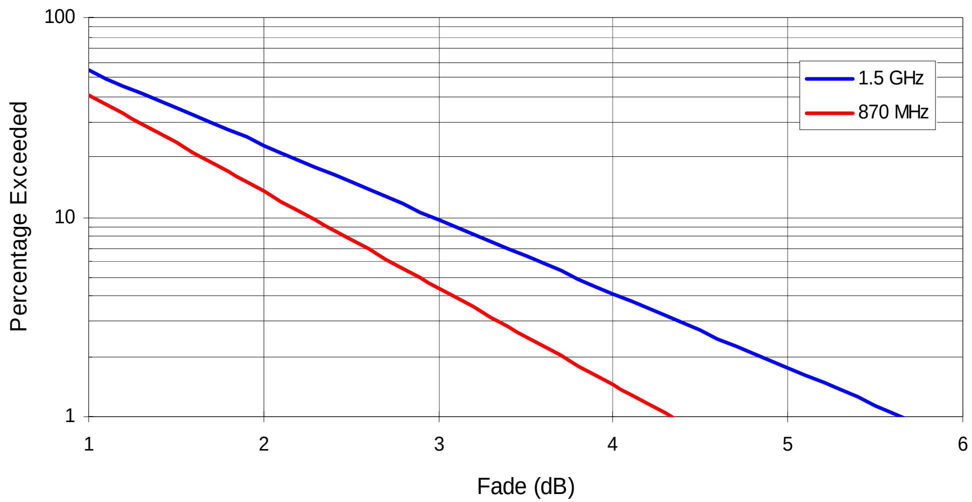


The degree of loss depends on the shadowing material and the path length through the obstruction. 10-15 dB at 1.5 GHz through buildings - highly dependent on construction.

Shadowing distributions

Some measured sample fade distributions for a mountain environment and a tree lined road





Mountain environment
(terrain shadowing)

Tree lined road
(vegetation shadowing)

Vegetation shadowing loss

Shadowing attenuation – various tree types

Single Tree Attenuation at 870 MHz				
Tree type	Attenuation (dB)		Attenuation coefficient (dB/m)	
Burr Oak	13.9	11.1	1.0	0.8
Pear	18.4	10.6	1.7	1.0
Holly	19.9	12.1	2.3	1.2
Pine Grove	17.2	15.4	1.3	1.1
Scotch Pine	7.7	6.6	0.9	0.7
Maple	10.8	10.0	3.5	3.2

Also a ~ 24% difference between winter and summer

Empirical shadowing model

From ITU-R P.681 a fit to measurements, mainly effect of trees

- Fade depth exceeded for P% of distances

$$L(P,\theta) = N(\theta) - M(\theta)\ln(P) \qquad \text{dB}$$

Where

$$N(\theta) = -0.443\theta + 34.76$$

$$M(\theta) = 3.44 + 0.0975\theta - 0.002\theta^2$$

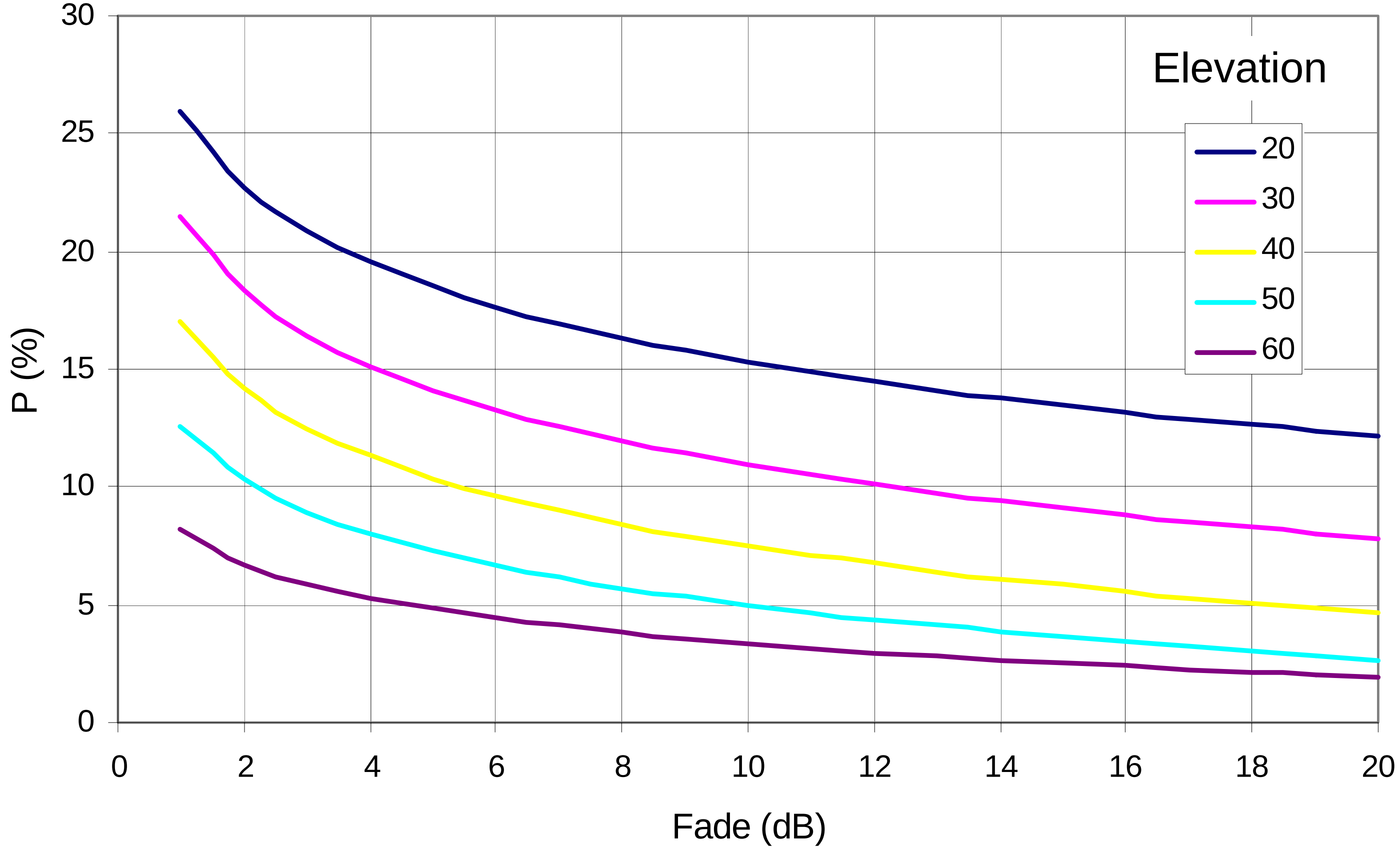
θ is the elevation angle in degrees

Only applies at L-Band ~1.5 GHz, for 20^0 to 60^0 and 1% to 20%

Example and extension on next slides

Empirical shadowing model

ITU-R P.681 Model

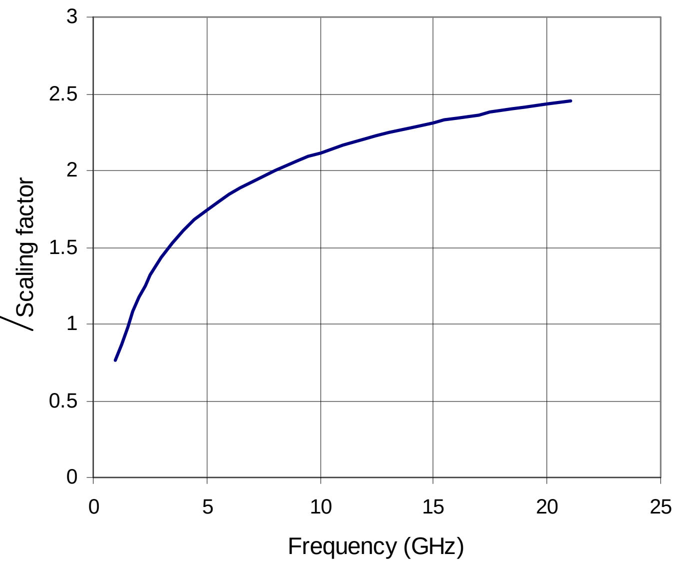


Fade Model for 1.5 GHz

Extension of shadowing model

For frequencies between 800MHz and 20GHz

$$A_{20}(p,\theta,f) = A(p,\theta)\,\exp\left\{1.5\left[\frac{1}{\sqrt{f_{1,5}}} - \frac{1}{\sqrt{f}}\right]\right\}$$



For percentages 1% to 80%

$$A(P,\theta,f) = \begin{cases} A_{20}(20\%,\theta,f) & \text{for } 1\% \le P < 20\% \\ A_{20}(20\%,\theta,f)\,\dfrac{1}{\ln 4}\ln\left(\dfrac{80}{P}\right) & \text{for } 60\% < P \le 80\% \end{cases}$$

Extension of shadowing model

For Elevation angles 7^0 to 80^0

- For angles below 20^0 use the value for 20^0
- For angles above 60^0 linearly interpolate from the value at to the value at 80^0 given in the table below

***p* (%)**	**Tree-shadowed**	
	1.6 GHz	**2.6 GHz**
1	4.1	9.0
5	2.0	5.2
10	1.5	3.8
15	1.4	3.2
20	1.3	2.8
30	1.2	2.5

Fades exceeded (dB) at 80° elevation

Shadow fade duration

Fade Duration - From Australian Measurements

- Speed of mobile = 25 m/s = 90 kph
- L-band (1545 MHz)
- Omni directional antenna
- 50º satellite elevation
- Moderate road - 50%-75% tree shadowing
- Extreme - total overhanging tree canopy

Followed a Log-Normal distribution

- Expressed in terms of duration distance d (so vehicle speed is accounted) and an attenuation threshold $A_{threshold}$.

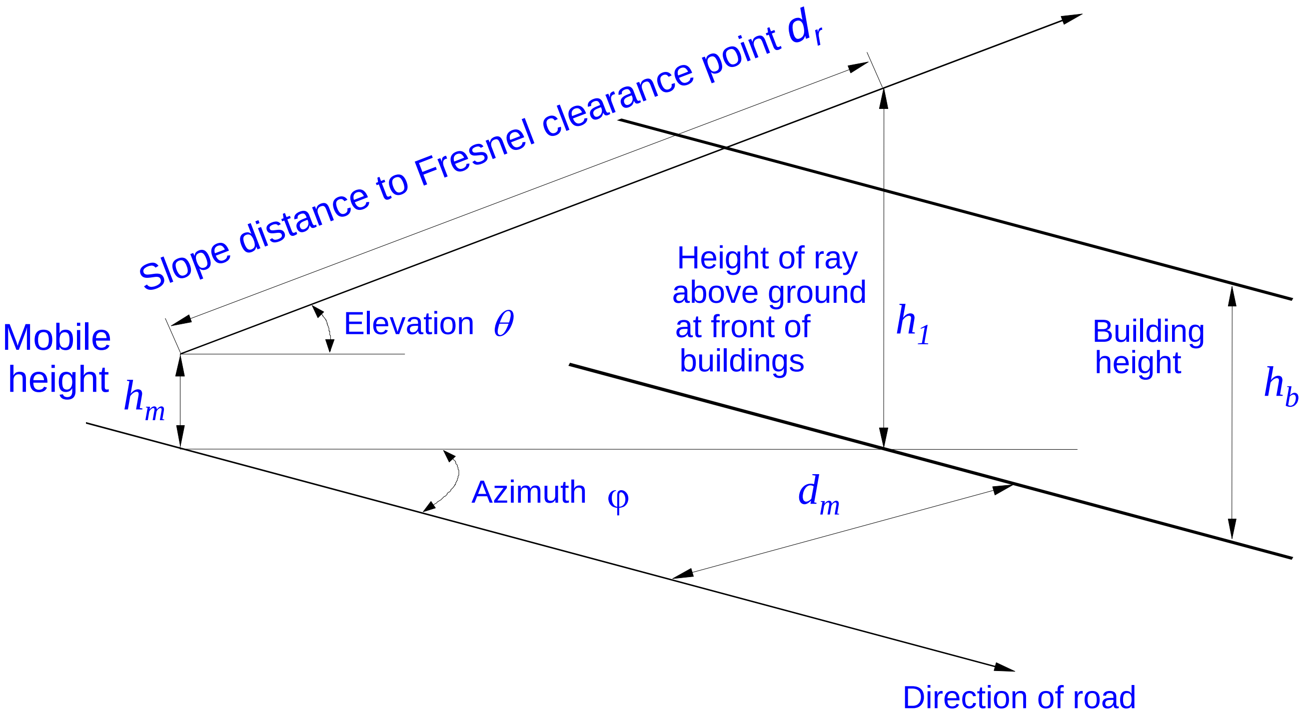
$$P(\text{Duration} > d \mid \text{Attenuation} > A_{threshold}) = \tfrac{1}{2}\left\{1 - erf\left[\frac{\ln d - \ln \alpha}{\sqrt{2}\sigma}\right]\right\}$$

$\ln\alpha$ represents the mean, σ the variance of $\ln d$.

Roadside buildings

Fading is also caused by roadside buildings

The percentage probability of blockage $P = 100 \exp\left[-(h_1 - h_2)^2 / 2h_b^2\right]$ for $h_1 > h_2$



Geometry of roadside building shadowing model

$$h_1 = h_m + (d_m \tan\theta / \sin\varphi)$$

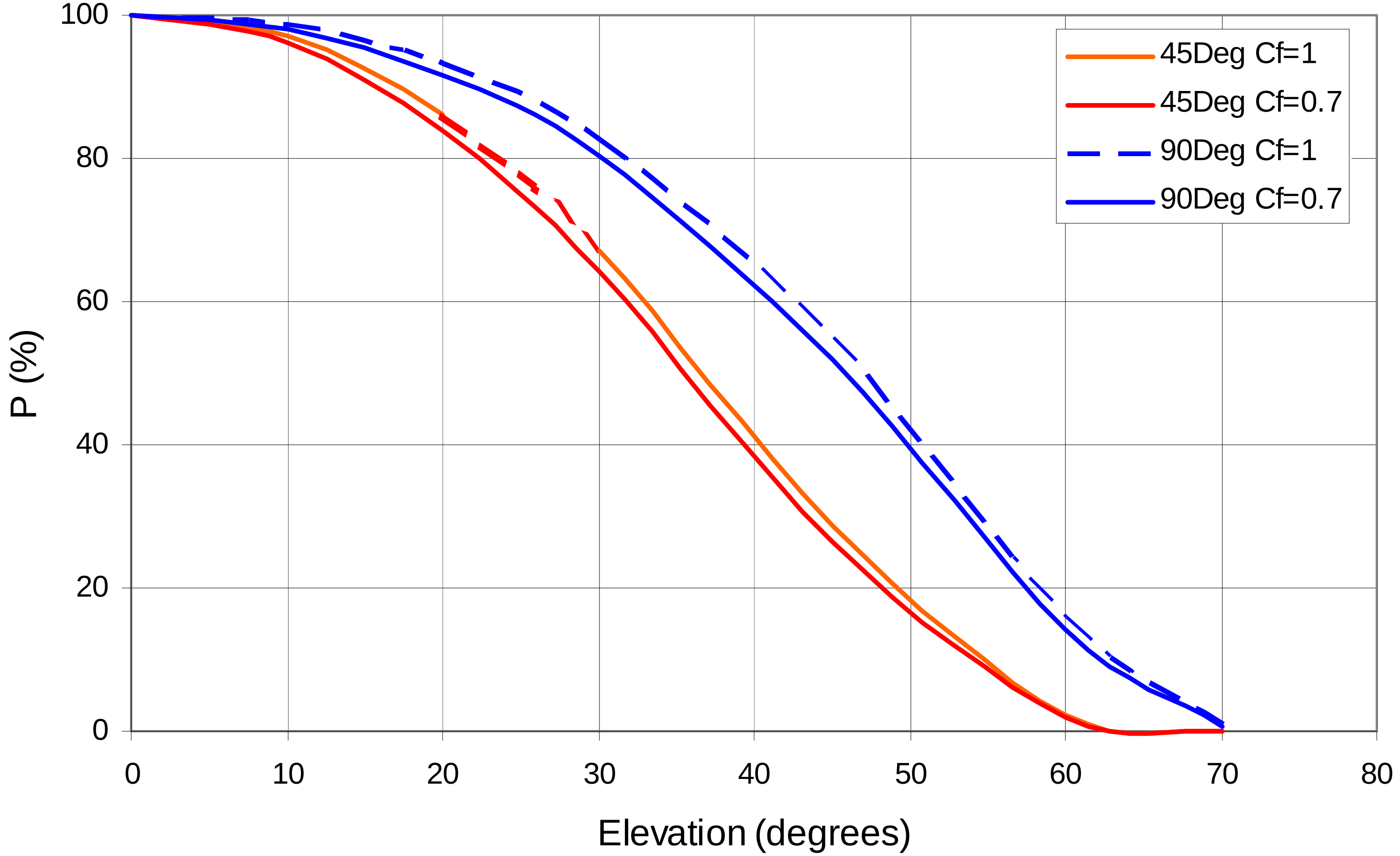
$$h_2 = C_f \, (\lambda \, d_r)^{0.5}$$

$$d_r = d_m / (\sin\varphi \cdot \cos\theta)$$

C_f = required clearance as a fraction of the first Fresnel zone

Roadside buildings

Building shadowing example



h_b = 15 m, h_m = 1.5 m, d_m = 17.5 m, f = 1.5 GHz

Building penetration

Signal levels inside depend strongly on the position inside a building

- Highest near windows and on upper floors

Building Attenuation (6 story office block)

	Penetration Loss (dB)		
Floor Level	*450 MHz*	*900 MHz*	*1.4 GHz*
Ground	16.4	11.6	7.6
1	8.1	8.1	4.9
2	12.8	12.5	8.0
3	13.8	11.2	9.1
4	11.1	9.0	6.0
5	5.4	6.0	3.3
6	4.2	2.5	2.5

High levels of multipath give a diffuse signal

Gain of antenna is degraded

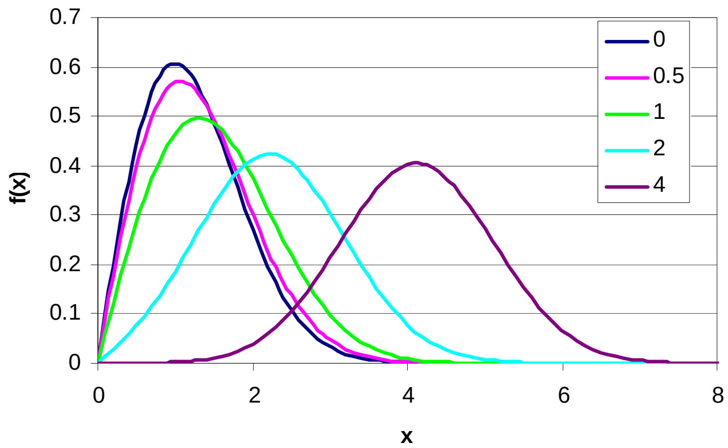
Doppler spread occurs with the satellite motion

Multipath - statistical distribution

We have looked at the shadowing, but there is also multipath to consider

- Typically there will be a line of sight path plus some diffuse multipath
  - The line of sight component is log normally distributed
  - The diffuse path component Rayleigh distributed
- This is equivalent to a Rician distribution

$$f(x,v,\sigma) = \frac{xe^{-(x^2+v^2)/2\sigma^2}}{\sigma^2} I_0\left(\frac{xv}{\sigma^2}\right)$$



I_o is the first order Bessel function

Satellite mobile summary

In general many of the propagation effects are similar between terrestrial and satellite systems

- The main differences are:
  - Elevation angle – the channel is more likely to be line of sight and will have less multipath
  - Coverage – the coverage from a satellite is potentially much larger
  - Path loss – because it is further away the path loss to a satellite is larger. This can be mitigated to some extent by using high gain antennas on the satellite
  - Motion – in satellite systems, the base station is moving leading to increased Doppler, even for “stationary” mobiles