Radio-coverage for cellular applications

Electromagnetics
and
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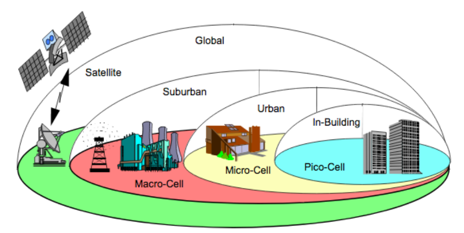
Outline

Why we do care

In a cellular system, cells operate in a hierarchical way



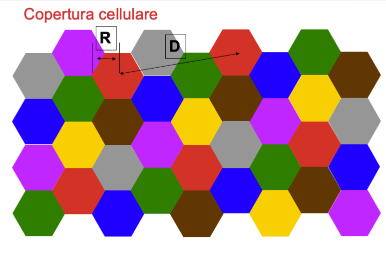
They are commonly encountered in:

- Cellular telephony.
- Broadcasting.
- Private mobile radio.
- WiMax.

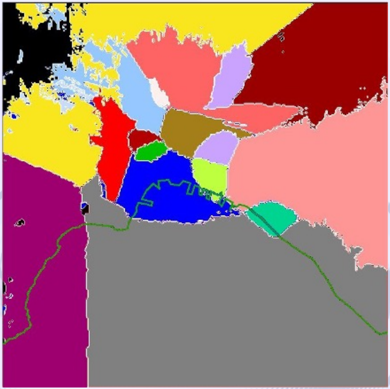
Outline

Radio-coverage

In a cellular system, the service area is divided into cells. A TX is designed to serve an individual cell. The system seeks to make efficient use of available channels by using low-power transmitters to allow frequency reuse at much smaller distances.



Cellular system in the real world



Cellular system: efficiency

To use in an affective way the limited available resources

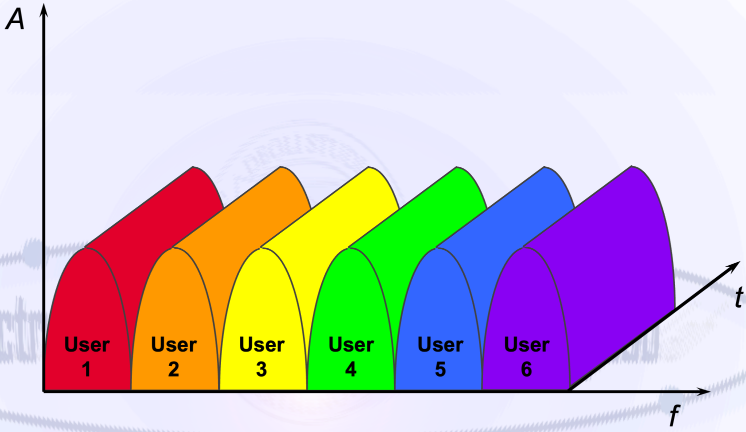
- Optimizing TX signal.
- Optimizing area coverage.

Optimizing area coverage

Maximizing the number of times each channel can be reused in a given geographic area is the key to an efficient cellular system design.

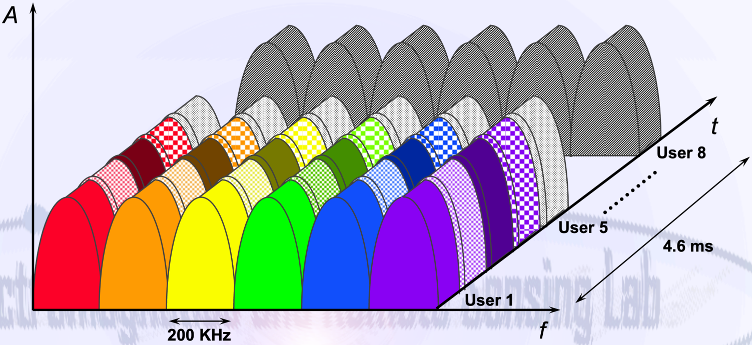
Outline

Frequency division multiple access FDMA



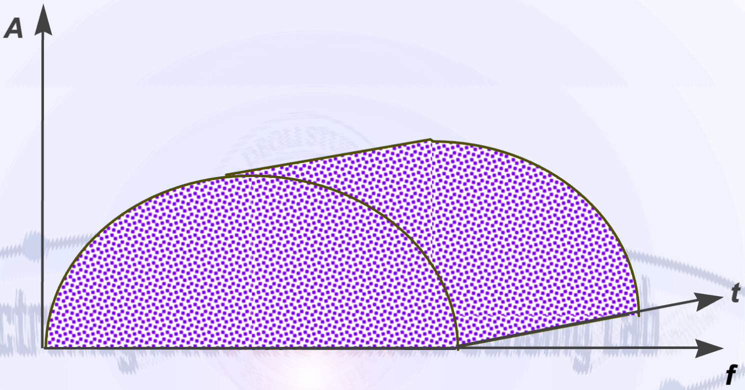
Single channel per carrier (SCPC) - TACS!

FDMA + Time Division Multiple Access (TDMA)



Multiple channels per carrier (MCPC) - GSM!

Code Division Multiple Access (CDMA)



Multiple channels per carrier (MCPC) - UMTS!

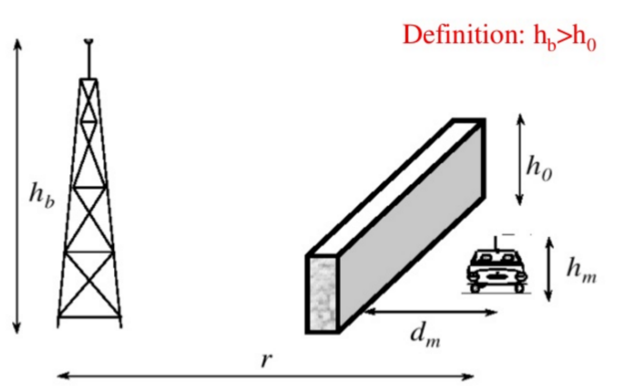
Macrocells

A multi-operator site on a strong tower with separate antennas for each service

The antennas for macrocells are mounted on ground-based masts, rooftops and other existing structures, at a height that provides a clear view over the surrounding buildings and terrain. Macrocell base stations have power outputs of typically tens of watts

What they are

Macrocell geometry



The basic definition of a macrocell is $h_b > h_o$; i.e., the transmitting station height is significant larger than the mean buildings height.

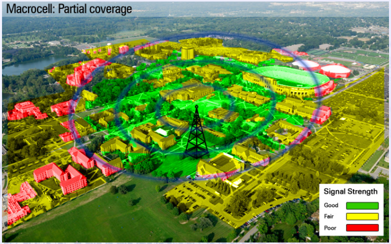
Outline

Path loss models

There are various types of models to predict path loss in a wireless channel that can be sorted as follows:

- Empirical: They are based on extensive in-field measurements campaigns. They parameters are linked to the environment and to the measurements.
- Deterministic: They rely on a specific fixed geometry (buildings, streets, etc.) and are generally used to analyze specific situations.
- Semi-empirical: They rely on the joint use of deterministic models and statistics of various parameters (building heights, street width, etc.).

Empirical models



- Free-space and plane Earth models cannot be used as they stand since a detailed knowledge of the scene is needed.
- The key outcome is the overall extent of the coverage area.
- Empirical models are useful to estimate the extent of the coverage area.

An extensive set of path loss measurements is needed

Empirical models

At the very root empirical models rely on the fitting of the path loss measurements with an appropriate function whose parameters are derived for the particular environment to minimize the error between measurements and the function.

- The simplest fitting function for a path loss model is given by:

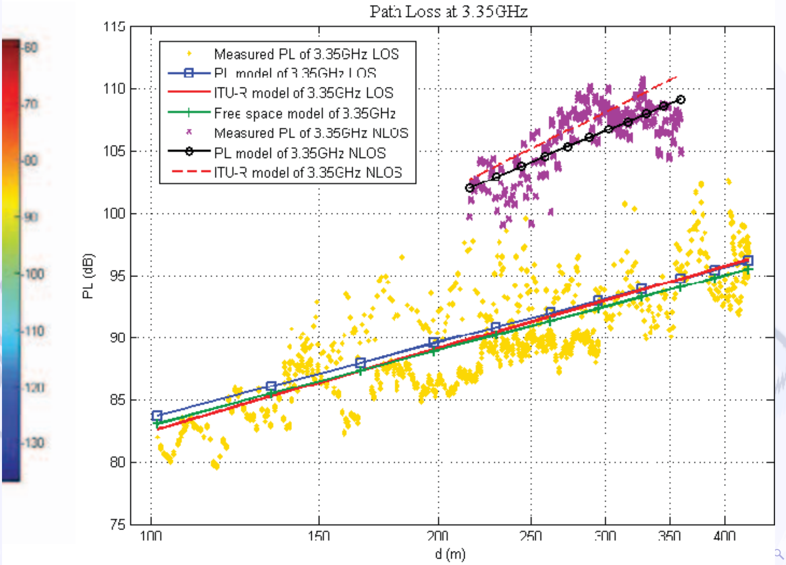
$$L = \frac{P_T}{P_R} = \frac{r^n}{k} \tag{1}$$

Power law model

$$L = 10n \log r + K \tag{2}$$

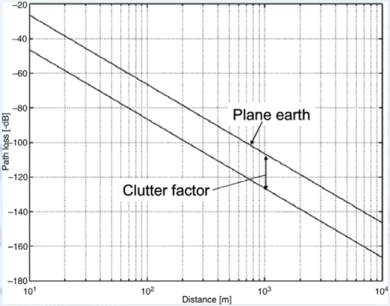
It is a power law model where $K = -10 \log k$ and n are the clutter factor and the path loss exponent, respectively.

Empirical models



Empirical models

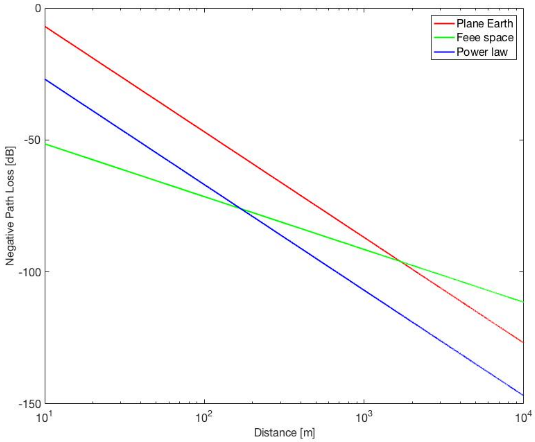
The values assigned to n and K determine the specific empirical model.



- Measurements undertaken in both urban and suburban areas show that n is typically close to the plane Earth one, i.e.; $n \approx 4$.

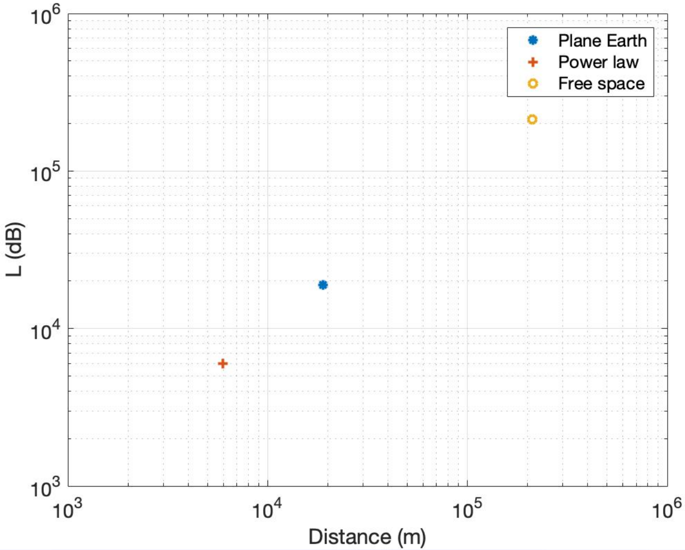
Hence, typically, empirical models are based on plane earth loss plus (in dB) a clutter factor K.

Power law models: do it yourself

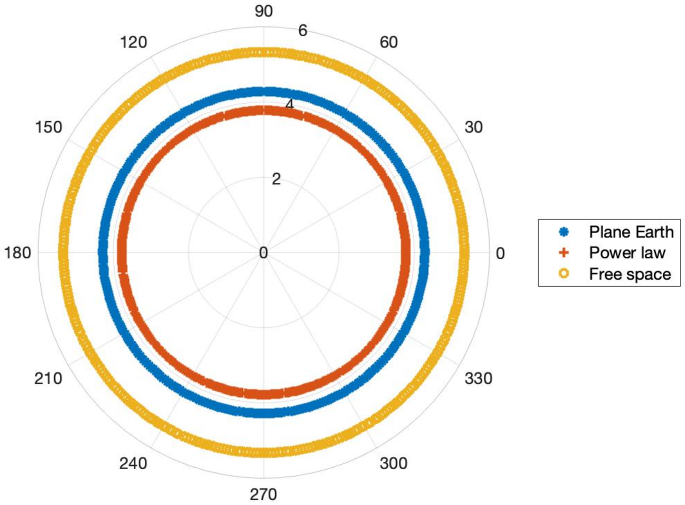


f=900MHz, hm=1.5m, hb=30m

Range predicted by the models: $L = 138$dB



Polar view


90
120
60
6
150
30
4
2
180
0
0
210
330
240
300
270
Plane Earth
Power law
Free space

The Okumura-Hata model

- Okumura collected path loss measurements (in Tokyo city) and plotted a set of curves for path loss in urban areas:
  - Frequency range: 100MHz to 1920MHz.
- Hata came up with an empirical model for Okumura's curves:

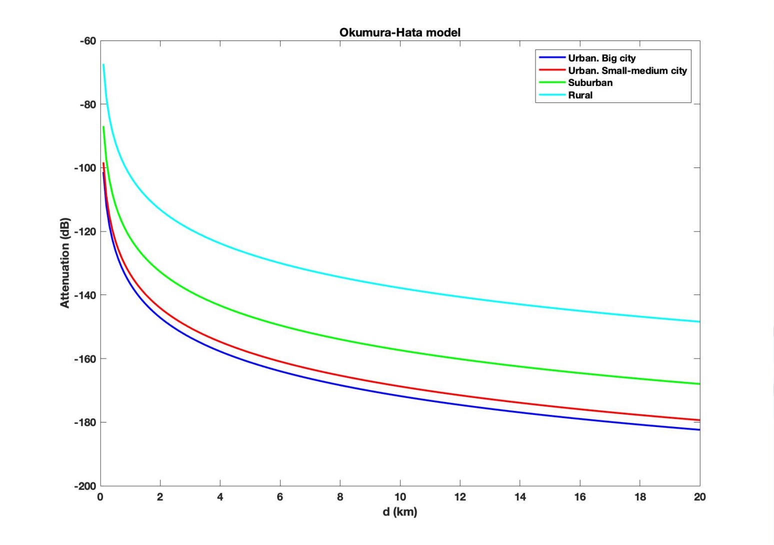
$$L = A + B \log r - C \qquad (3)$$

- where A depends on the carrier frequency and TX height, B depends on the RX height and C depends on the kind of clutter and terrain category, namely: open area; suburban area and urban area.

Comparisons of empirical models in urban area

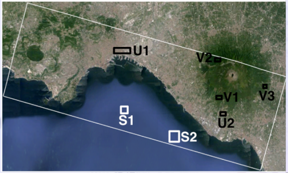
- Open area: there are no tall trees or buildings in the path.
- Suburban area: There are small villages or highways with some obstacles. The scenario is not congested.
- Urban area: High-density urbanized areas with tall buildings.

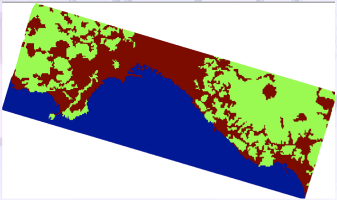
Okumura-Hata model



Comparisons of empirical models in urban area

Remotely sensed data can be of some help allowing a less subjective clutter classification.





Comparisons of empirical models in urban area

Empirical models are widely used since they do not require a detailed knowledge of the scenario and they are computer-time effective. However, they exhibit some drawbacks:

- They rely on the specific parameters used in the measurement campaign.
- Quite subjective partitioning of the environment.
- No physical understanding of the mechanisms involved in the propagation.

Physical models

They are physically based on propagation theory

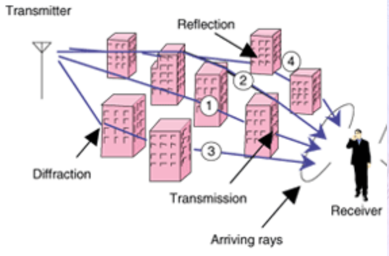
Rationale

They estimate propagation of radio waves analytically. Two approaches are adopted:

- Solving the electromagnetic problem: it is a complex procedure that very often relies on simplifying assumptions.
- Ray tracing: much easier and commonly adopted. However, it requires a large computational effort.

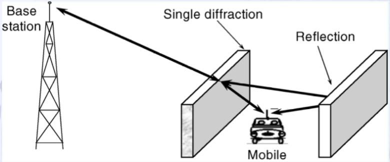
Ray tracing

It is a technique based on Geometric Optic



- It can be used to predict reflected and transmitted rays.
- Diffraction models are added to extend GO.

Ikegami deterministic model



- Detailed maps of building heights, shapes and positions are needed to trace ray paths between TX and RX.
- Only single reflections from walls are included and a fixed reflection loss is assumed.
- Diffraction calculated using single edge approximation.
- Reflected and diffracted rays are power summed.

Ikegami deterministic model

Pros

- It is a first attempt to provide a physical explanation of phenomena involved in NLOS propagation in macrocells.
- It succeeds in predicting fairly well intensity variations of the field within the street.

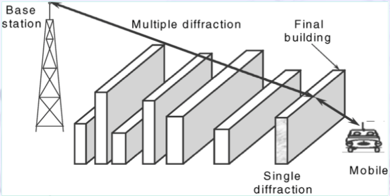
Cons

- It is physically and experimentally untenable that propagation is not affected by h_b.
- It basically predicts a $n \approx 2$ exponent, which results in underestimations at larger distances.
- The variation with frequency is underestimated.

Outline

Multiple diffraction over building rooftops

In built-up areas the key propagation mechanism is multiple diffraction from the rooftops of the buildings.



- Typically the diffraction angle is within 1°. This means that diffraction does not depend on the shape of the building that can be represented as a knife-edge.
- The only exception is the final building that diffracts down to the street-level.

The last building can be either considered as a knife edge or as more complex shape for which the diffraction is known.

Multiple diffraction over building rooftops

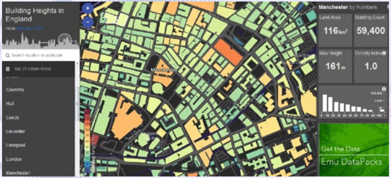
The key problem that arises from diffraction due to multiple edges is that methods based on single-edge diffraction are unreliable.

Single-edge methods do not work

Those methods are not applicable since the low diffraction angle implies that a large number of obstructions (i.e.; rooftops) affect the first Fresnel zone.

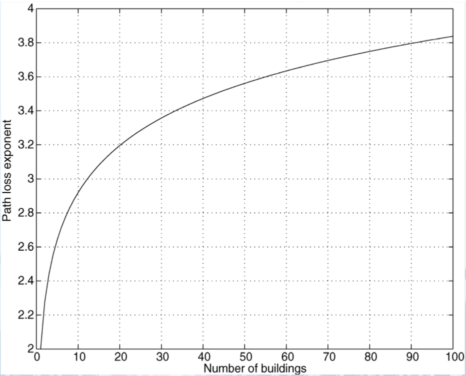
This implies that the full multiple edge diffraction integral must be solved.

Solving the multiple edge diffraction integral problem is a very time consuming procedure that needs detailed information on buildings heights and positions.



- Special methods have been developed to enable reasonably effective calculations.
- They are typically used when accurate results are needed.

The flat edge model - path loss exponent



There is a good matching to what experimentally measured. Hence, multiple building diffraction is the driver to the variation of path loss with range in macrocell measurements.

Semi-empirical models

They combine the analytical formulation of physical phenomena, e.g.; reflection, transmission and diffraction or scattering, with a statistical fitting by variable adjustment using experimental measurements.

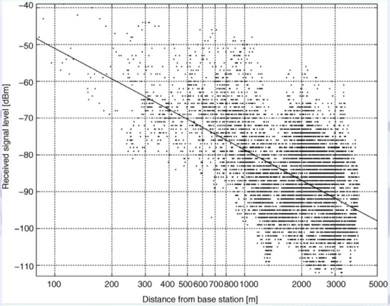
- Those methods are more robust than purely empirical ones.
- The statistical optimization relies on linear regression techniques or more sophisticated approaches based on neural networks.

The most employed semi-empirical method

The COST 231/Walfisch-Igekami model combines: the flat edge model, Igekami model to predict diffraction down to street-level and empirical correction factors to fit actual measurements.

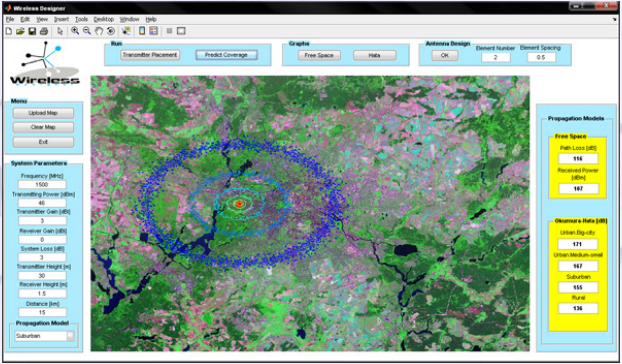
Introduction

Path loss models developed to deal with macrocells include only dependencies on parameters such as antenna heights, environment and distance.



Those parameters alone do not explain the large scatter of measurements

The key problem relies on the fact that, for a given environment, the path-loss is constant for an assigned TX-RX distance.



Shadowing

A mobile receiver that is driven at a constant distance around a transmitting station will measure a signal that fluctuates around its median level.

- The variation occurs over distances comparable to the widths of buildings or hills that are located within the region of the mobile (i.e.; tens or hundreds of meters).

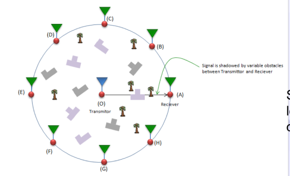
Shadowing - Lognormal

Those fluctuations can be statistically described by a log-normal distribution, i.e.; the signal measured in dB is normally distributed.

The underlying physical phenomenon is termed as shadowing

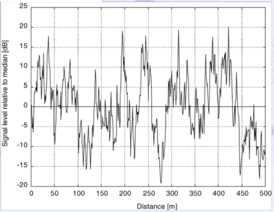
Shadowing

The clutter at a given distance will change from a path to another generating changes with respect to the path loss predicted by the reference model.



Some path suffer increased loss; while others are less obstructed

This results in an received signal that fluctuates wrt its median value



This phenomenon is termed as shadowing or slow fading

Outline

ERSLab

F. Nunziata

Introduction
- Cellular system
- Accessing the channel

Macrocells
- Path loss
- Multiple diffraction integral

Shadowing
- Theoretical facts
- Coverage
- Edge of the cell
- Whole cell coverage

Correlated shadowing
- Autocorrelation
- Cross-correlation

Log-normal distribution

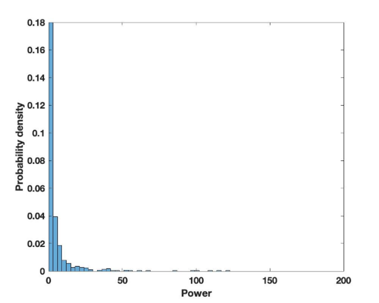
It is assumed that the contributions to signal attenuation act independently from each other.

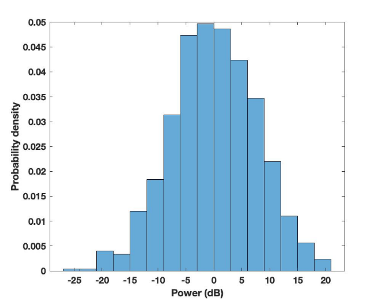
- The total loss (dB) is given by the sum of individual losses:

$$L = L_1 + L_2 + \ldots + L_N \tag{4}$$

- Since each loss is a random variable, according to the central limit theorem, L would be Gaussian distributed.
- This implies that the attenuation in natural values will be Log-normal distributed.

Shadowing statistical distribution





Shadowing statistical distribution

Why we do care

The effect of shadowing is to transform the coverage radius of a cell from a fixed, predictable value into a statistical quantity affecting the coverage and capacity of a system in ways which can be predicted.

The shadowing affects:

- The dynamic of signal variation at the mobile
- The percentage of locations which receive sufficient power.
- The percentage of locations which receive sufficient signal-to-interference ratio.

Outline

Coverage

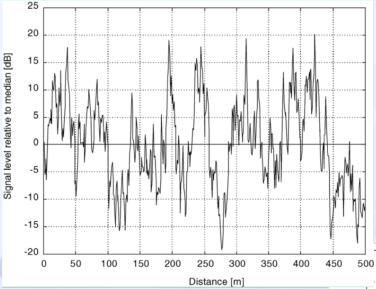
Due to shadowing, the total path loss at a given distance is no longer a deterministic value. This impacts significantly the area coverage.

- The path loss is a random variable given by:

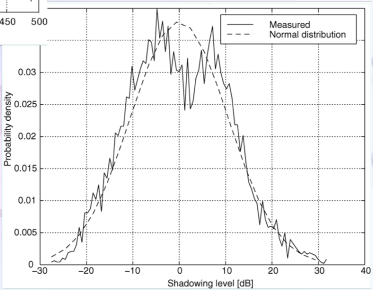
$$L = L_{50} + L_S \tag{5}$$

- L_{50} is the path loss predicted by any path loss model and it represents the path loss not exceeded at 50% of the locations at a given distance, it is often termed as local median path loss.
- L_S is the shadowing component, i.e.; a zero-mean Gaussian random variable with standard deviation σ_L. The latter is termed as location variability.

Shadowing statistical distribution



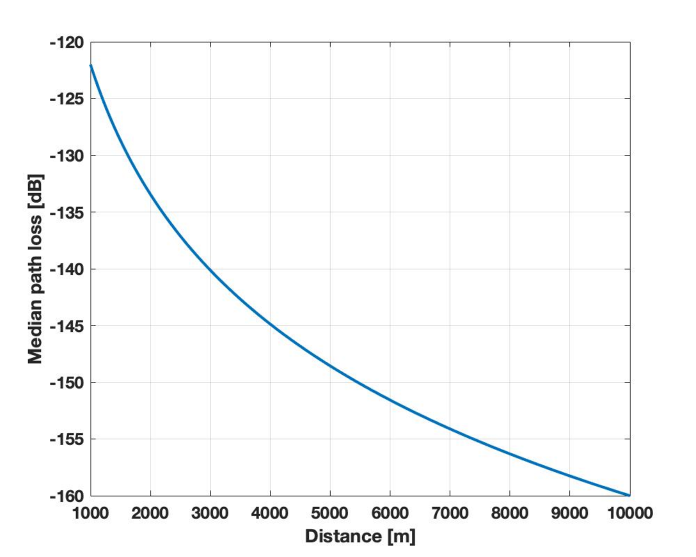
Typical signal variations due to shadowing. Note that the median level [dB] has been subtracted



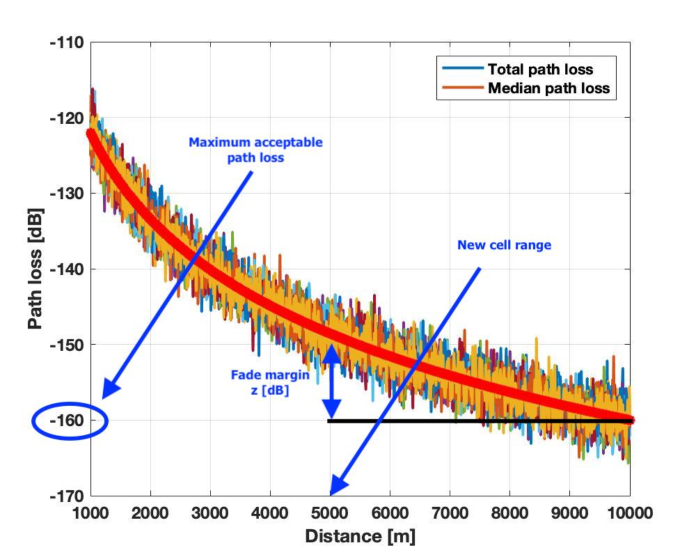
Empirical distribution of the shadowing component, i.e.; total path loss measurement –path loss predicted by a reference model, versus theoretical normal distribution

Outline

Margin of the cell: L_{50}



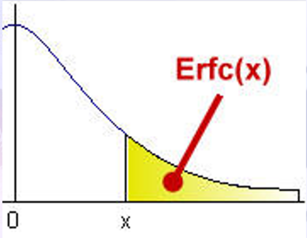
Margin of the cell: $L_S + L_{50}$ and fade margin



Margin of the cell range: shadowing

- Let's assume that the reference path loss model predicts a cell range of around 10km with a maximum acceptable path loss of 160dB.
- Due to shadowing, this median path loss results in 50% of the location at the cell's edge properly covered. L_S must be included!
- Including L_S corresponds to adding a fade margin z that increases the reliability at the expense of the cell's radius.
- The previous picture shows that the inclusion of the fade margin let the cell range reducing from around 10km to around 5km.

How can fade margin be calculated ?



The fade margin shall be related to the reliability required by the QoS

How can fade margin be calculated ?

- The probability that, due to shadowing, the median path loss is increased by the fade margin, i.e.; by z dB is given by:

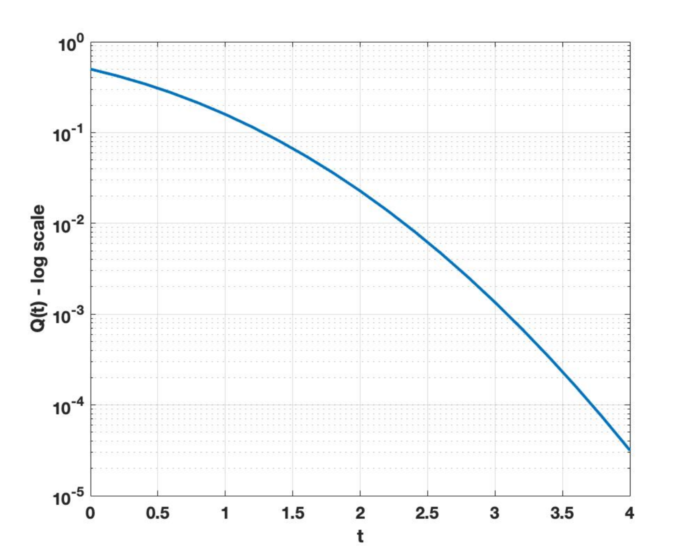
$$Pr[L_S > z] = \int_{L_S=z}^{\infty} p(L_S) dL_S = \int_{L_S=z}^{\infty} \frac{1}{\sqrt{2\pi\sigma_L^2}} e^{-\frac{L_S^2}{2\sigma_L^2}} dL_S \tag{6}$$

- which, normalizing z to the location variability, leads to $(t = z/\sigma_L)$:

$$Pr[L_S > z] = \int_{t}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt = Q(z/\sigma_L) \tag{7}$$

- where $Q(t)$ is the cumulative normal distribution with $t = \frac{z}{\sigma_L}$.

Q(t)



Coverage fraction

Reliability in terms of coverage fraction

According to (7), a system can be designed to meet a given level of reliability.

The latter is usually provided in terms of a user-defined percentage of locations at the edge of the macrocell that result in an acceptable coverage.

Fractional coverage

To evaluate the fractional coverage, i.e., the probability that at a given range r a user-defined probability of coverage is met, one can proceeds evaluating the probability of outage assuming the maximum acceptable path loss is L_{max} dB.

Coverage fraction

- The outage probability can be evaluated as follows:

$$\begin{aligned} p_{out} &= Pr[L_T > L_{max}] = Pr[L_{50} + L_S > L_{max}] \\ &= Pr[L_S > L_{max} - L_{50}] \\ &= Q\left(\frac{L_{max} - L_{50}}{\sigma_L}\right) \end{aligned} \quad (8)$$

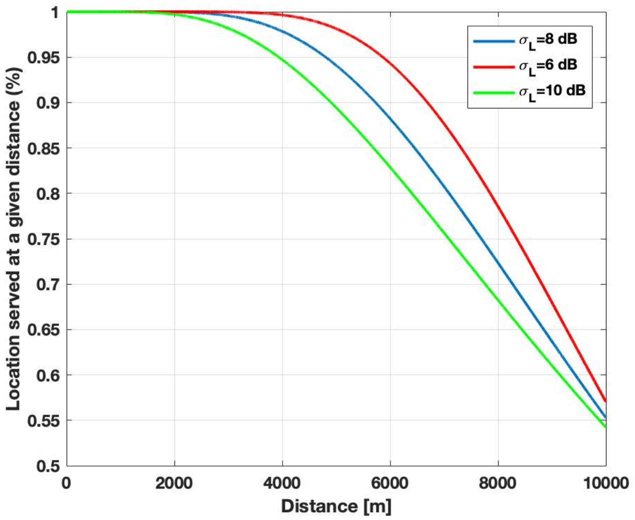
(9)

- Hence, the fraction of locations covered at a given range r is simply given by:

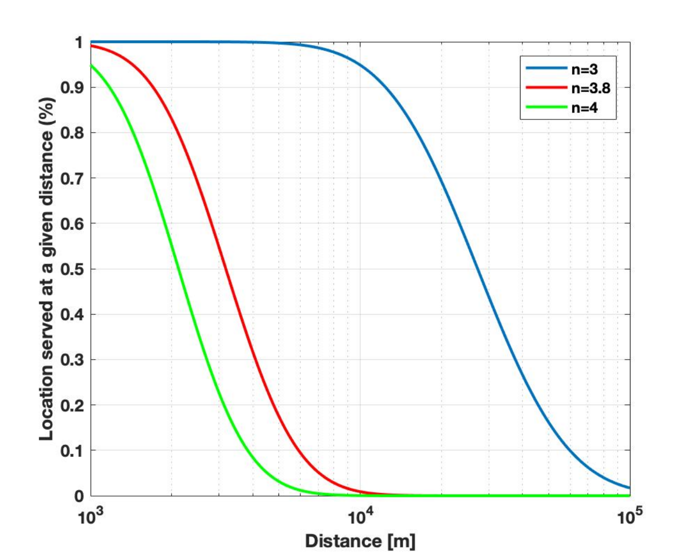
$$p_e(r) = 1 - p_{out} = 1 - Q\left(\frac{L_{max} - L(r)}{\sigma_L}\right) = 1 - Q\left(\frac{z}{\sigma_L}\right) \quad (10)$$

- L_{max} is the maximum acceptable path loss.
- $L(r)$ is the median path loss at a range r.
- z is the fade margin chosen for this system.

Coverage fraction vs σ_L



Coverage fraction vs power law exponent

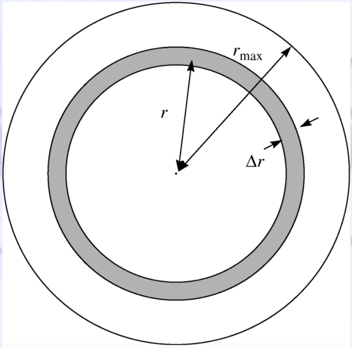


Outline

Whole cell

In general, the closer is the mobile to the base station, the better will be its coverage probability.

- This implies that it is by far better designing the system considering the coverage probability experienced by the whole cell (instead of the edge only).



Probability of coverage

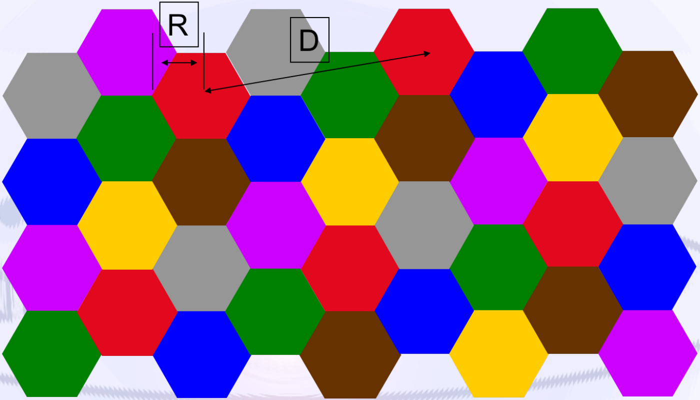
The coverage probability for the whole cell can be evaluated considering rings will small width Δr. Each ring has an area that is $2\pi r \Delta r$ and calls for a probability of coverage $p_e(r)$.

- The probability of coverage of the whole cell p_{cell} can be evaluated integrating all the probability related to the small rings and dividing by the area of the whole cell, i.e.; πr_{max}^2:

$$p_{cell} = \frac{2}{r_{max}^2} \int_{r=0}^{r_{max}} r p_e(r) dr = \frac{1}{2} + \frac{1}{r_{max}^2} \int_0^{r_{max}} r erf\left(\frac{L_{max} - L(r)}{\sigma_L \sqrt{2}} \right) dr. \quad (11)$$

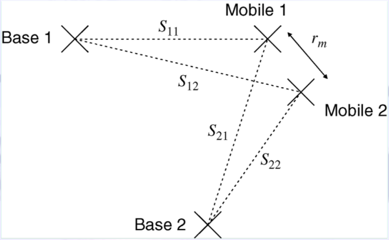
- This integral can be solved numerically. Closed-from solutions exist when a power law model is assumed to describe $L(r)$.

The cellular concept



Correlated shadowing: Why we do care

Real-world shadowing losses on different links in a network are not independent. The correlations have both detrimental and beneficial impacts on networks.



The relationship between shadowing experienced by nearby paths needs to be accounted for.

Correlations

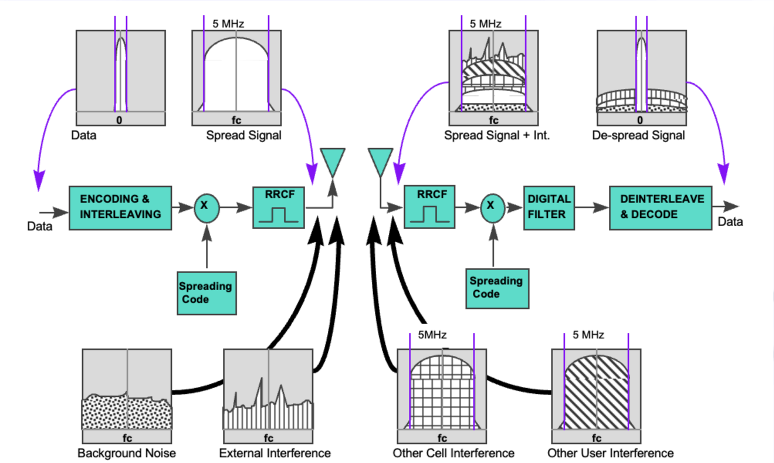
Two TX stations are considered and two mobile locations (or - equivalently - two positions of a single mobile)

- Each path is marked with the value of the associated shadowing S, which is log-normally distributed (i.e.; its dB value is normally distributed).
- Since the four paths may include common obstacles, shadowing values are not independent of each other.

Two kind of correlations:

Autocorrelation - or serial correlation - accounts for the correlation between two mobile positions connected to the same TX station, e.g.; S_{11}, S_{12} or $S_{22} S_{21}$.
Cross-correlation - or site-to-site correlation - accounts for the correlation between two TX stations received by the same mobile position , e.g.; S_{11}, S_{21} or $S_{22} S_{12}$.

CDMA - scrambling codes



Correlated shadowing

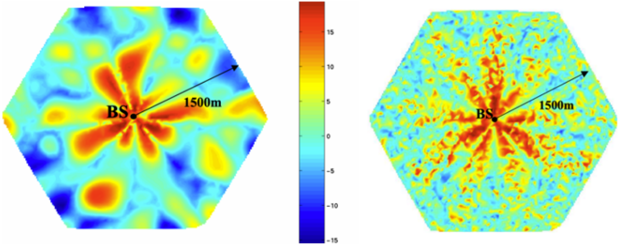
Correlated shadowing

SERIAL

- It affects power control in code division mltiple acces (CDMA) systems

SITE TO SITE

- It affects the Carrier to Signal Interference (C/I) ratio



Outline

Autocorrelation

- It can be defined as follows:

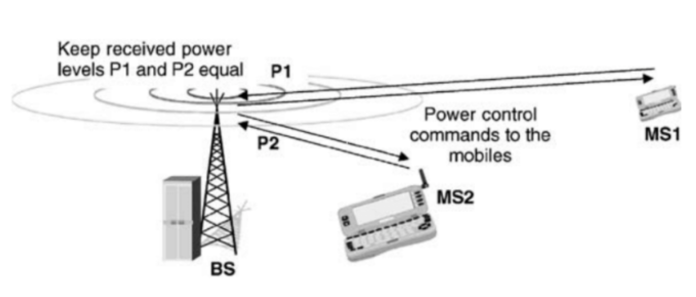
$$\rho_m(r_m) = \frac{E(S_{11}S_{12})}{\sigma_{L1}\sigma_{L2}} \approx \frac{E(S_{11}S_{12})}{\sigma_L^2} \tag{12}$$

- It affects the time variability of the path loss experienced by the mobile when it moves around.

Effects on actual systems

It has a great importance in managing power-control processes, e.g.; network messages between TX station and mobile where the TX station instructs the mobile on how to adjust its transmit power.
Power estimations undertaken by the TX station depend on how rapidly the autocorrelation function reduces in time.

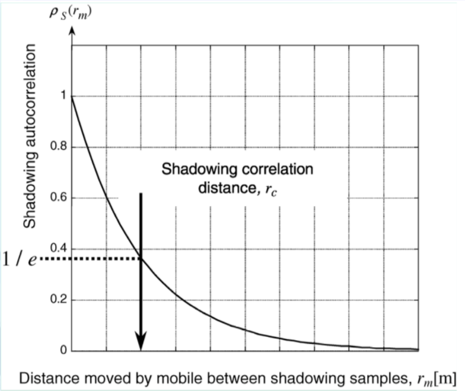
Autocorrelation



Power management - CDMA near/far problem

Mobile stations MS1 and MS2 operate within the same frequency, separable at the base station only by their respective spreading codes. Tight and fast power control is perhaps the most important aspect in CDMA, in particular on the uplink.

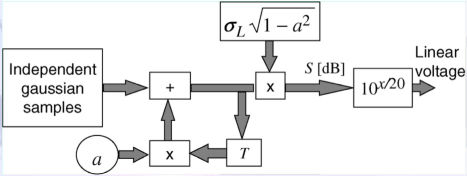
Exponential type autocorrelation function



The shadowing autocorrelation distance r_c is the distance where the normalized autocorrelation function reduces by 37%.It is larger at larger distances.

Generating a correlated shadowing process

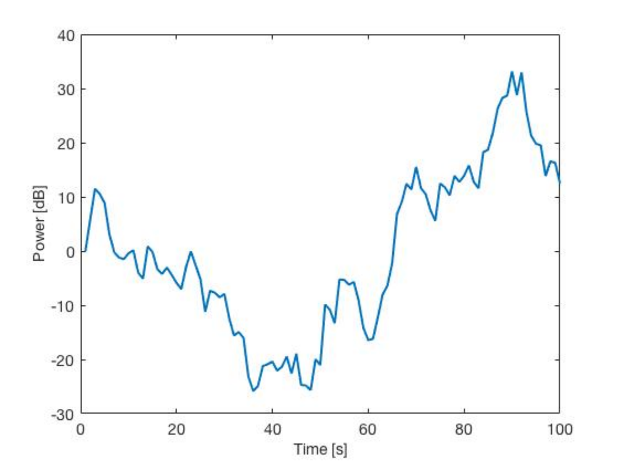
Independent normally-distributed samples are generated at a sampling interval T. Individual samples are then delayed by T, multiplied by the coefficient a and then summed with the new samples. Finally, the filtered samples are multiplied by $\sigma_L\sqrt{1-a^2}$.



$$a = e^{-\frac{vT}{r_c}} \tag{13}$$

where v is the velocity of the mobile and T is the symbol's rate.

Do it yourself



$\sigma_L = 8\text{dB},\ v = 14\text{m/s},\ r_c = 100\text{m},\ T = 1\text{s},\ N = 100$ samples

Outline

Cross-correlation

- It can be defined as follows:

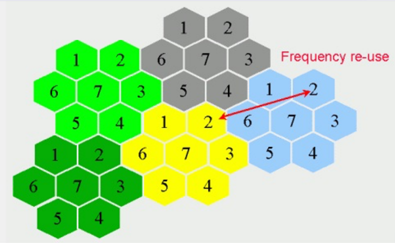
$$\rho_c = \frac{E(S_{11}S_{21})}{\sigma_{L1}\sigma_{L2}} \tag{14}$$

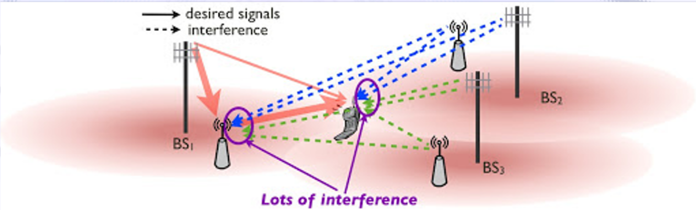
- The paths involved may be widely separated; hence they call for different σ_L values.

Effects on actual systems

The two TX stations may be iso-channel; hence the station that is not connected to the mobile will contribute to worsen the carrier-to-interference ratio (C/I).
When ρ_c is large, the shadowing processes are correlated; hence C/I can be maintained to acceptable values. This is by far more complicated when ρ_c is low.

Carrier to Interference ratio





Carrier to Interference ratio

ERSLab

F. Nunziata

Let's focus on a C/I in the downlink path dominated by only 2 stations whose distances from the mobile are r_1 and r_2, respectively.

- A power law model with exponent n is assumed for the path loss;
- The C/I ratio (R) is itself Normal distributed with mean μ_R and standard deviation σ_R.

It can be shown that:

- The mean value:

$$\mu_R = 10 n log \left(\frac{r_2}{r_1} \right) \tag{15}$$

- The standard deviation (assuming $\sigma_1 \approx \sigma_2 = \sigma_L$):

$$\sigma_R = \sigma_L \sqrt{2(1-\rho_c)} \tag{16}$$

Probability of outage

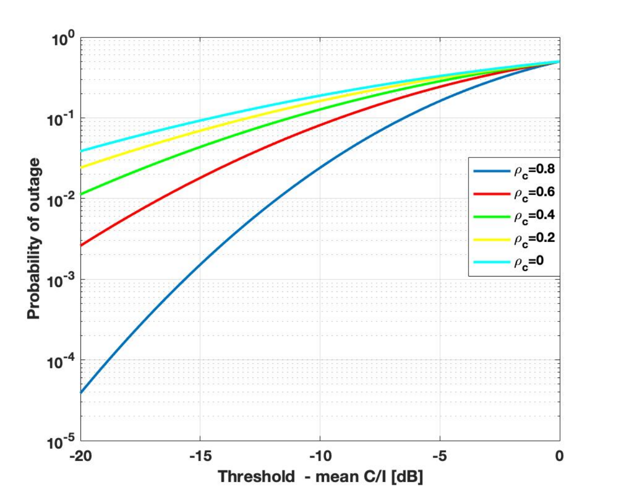
It is the probability that the C/I ratio R is smaller than a system dependent threshold R_T.

$$Pr[R < R_T] = 1 - Q\left(\frac{R_T - \mu_R}{\sigma_R}\right) \tag{17}$$

- This formula gives the probability of outage for a cellular system dominated by only one interferer.
- For a probability of outage equal to 10%, the difference from $\rho_c = 0.8$ and $\rho_c = 0$ is around 7dB.

According to (15) with $\mu_R = 7$ and $n = 4$, the reuse distance r_2 should be increased by around 50%.

The effect of correlated shadowing on system's performance



Cross-correlation affects system design parameters

- Optimum choice of antenna beamwidths for sectorisation.
- Performance of soft handover and site diversity.
- Design and performance of handover algorithms.
- Optimum frequency planning for minimized interference and hence maximized capacity.
- Adaptive antenna performance calculation.
- ...