Propagation Channel Models

Application	Application
Presentation	
Session	
Transport	Transport
Network	Internet
Data Link	Network Interface
Physical Layer	Physical

Radiosystems characterization

- Radiosystems characterized by two quality parameters
  - ➪ BER (as well as cabled systems)
  - ➪ Availability (peculiar)
- BER guaranteed for a certain percentage of the time (usually averaged over a year)
- Availability depends on channel conditions (usually referred to the propagation effects in the troposphere)
  - – Propagation in the troposphere is a random non stationary process and as such characterized statistically that means in terms of probability of attenuation to exceed a certain threshold

Propagation issues

- Tropospheric propagation
  - – Fade countermeasures
- Mobile channel propagation
  - – Shadowing countermeasures (diversity)

Tropospheric propagation impairments

- Tropospheric propagation impairments due to the interactions of the electromagnetic field with the elements and particles contained in the atmosphere

Effect \ Physical phenomenon	ABSORPTION	SCATTERING	REFRACTION	DIFFRACTION	MULTIPATH	SCINTILLATION	SELECTIVE FADING	REFLECTION	MOVING OBJECTS
ATTENUATION	■	■		■		■		■	
DISTORTION					■		■		
DEPOLARIZATION				■					
BANDWIDTH LIMITATION					■		■	■	
ANGLE OF ARRIVAL			■					■	
ANTENNA TRACKING								■	
ADAPTIVITY	■					■			■
TIME DISPERSION				■	■			■	
FREQUENCY DISPERSION									■
INTERFERENCE		■		■				■	

Correlation Matrix

Tropospheric propagation impairments

- In tropospheric propagation, the most relevant impairments on the transfer characteristic of the channel are:
  - the attenuation;
  - the increase of sky noise temperature;
  - the depolarisation.

Total attenuation

- Above 18 GHz, (especially with low elevation and/or margins), **multiple sources** of atmospheric attenuation
- Total attenuation (dB) represents the combination of:
  - $A_R(p)$: attenuation due to rain for a fixed probability (dB), (Rec. ITU-R P.618-7)
  - $A_C(p)$: attenuation due to clouds for a fixed probability (dB), (Recommendation ITU-R P.840)
  - $A_S(p)$: attenuation due to tropospheric scintillation for a fixed probability (dB)
  - $A_G(p)$: gaseous attenuation due to water vapor and oxygen for a fixed probability (dB), (Recommendation ITU-R P.676)

where p is the probability of the attenuation being exceeded (range 50% to 0.001%).

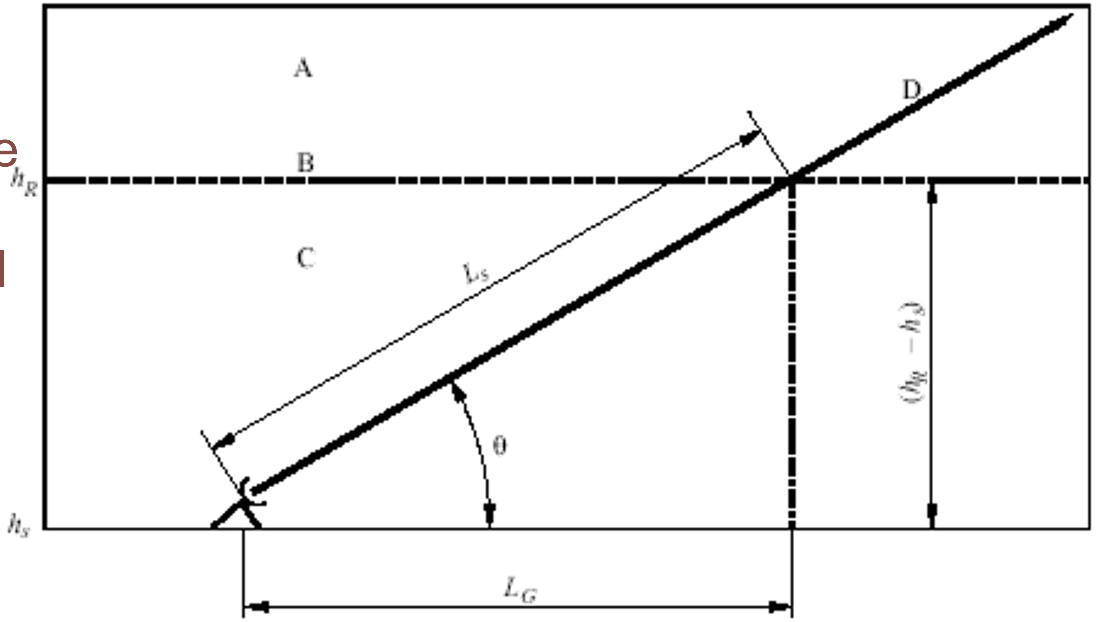
$$A_T(p) = \sqrt{\left(A_R(p) + A_C(p)\right)^2 + A_S^2(p)} + A_G(p)$$

Calculation of long-term rain attenuation statistics from point rainfall rate (Rec. ITU-R P.618-7)

- Long-term statistics of the slant-path rain attenuation at a given location for frequencies up to 55 GHz.
  - $R_{0.01}$: point rainfall rate for the location for 0.01% of an average year (mm/h)
  - h_s: height above mean sea level of the earth station (km)
  - θ: elevation angle (degrees)
  - ϕ: latitude of the earth station (degrees)
  - f: frequency (GHz)
  - R_E: effective radius of the Earth (8500 km)

Geometry

Schematic presentation of an Earth-space path giving the parameters to be input into the attenuation prediction process



A: frozen precipitation
B: rain height
C: liquid precipitation
D: Earth-space path

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STEPS

- **Step 1**: Determine the rain height, h_R, as given in Recommendation ITU-R P.839.
- **Step 2**: For $\theta \geq 5°$ compute the slant-path length, L_S below the rain height from:

$$L_S = \frac{h_R - h_S}{\sin\theta} \quad \text{km}$$

For $\theta < 5°$ the following formula is used:

$$L_S = \frac{2(h_R - h_S)}{\sqrt{\sin^2\theta + \frac{2(h_R - h_S)}{R_E}} + \sin\theta} \quad \text{km}$$

- **Step 3**: Calculate the horizontal projection, L_G of the slant-path length from:

$$L_G = L_S \cos\theta \quad \text{km}$$

STEPS (2)

- **Step 4**: Obtain the rainfall rate, $R_{0.01}$ exceeded for 0.01% of an average year (with an integration time of 1 min). If this long-term statistic cannot be obtained from local data sources, an estimate can be obtained from the maps of rainfall rate given in Recommendation ITU-R P.837.
- **Step 5**: Obtain the specific attenuation, γ_R, using the frequency-dependent coefficients given in Recommendation ITU-R P.838 and the rainfall rate, $R_{0.01}$ determined from Step 4, by using:

$$\gamma_R = k(R_{0.01})^{\alpha} \text{ dB/km}$$

$$k=[k_H+k_V+(k_H-k_V)\cos^2\theta\cos 2\tau]/2;$$

k_H, k_V, α_H, α_V given in tables

$$\alpha=[k_H\alpha_H+k_V\alpha_V+(k_H\alpha_H-k_V\alpha_V)\cos^2\theta\cos 2\tau]/2k$$

θ elevation angle; τ polarization tilt angle relative to the horizontal (τ = 45° circular polarization)

- **Step 6**: Calculate the horizontal reduction factor, $r_{0.01}$ for 0.01% of the time:

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G \gamma_R}{f}} - 0.38(1 - e^{-2L_G})}$$

- **Step 7**: Calculate the vertical adjustment factor, $\nu_{0.01}$, for 0.01% of the time:

$$\zeta = \tan^{-1}\left(\frac{h_R - h_S}{L_G r_{0.01}}\right) \text{ degrees}$$

STEPS (3)

For $\zeta > \theta$ $\quad L_R = \dfrac{L_G r_{0.01}}{\cos\theta}$ km else $\quad L_R = \dfrac{(h_R - h_S)}{\sin\theta}$ km

If $|\phi| < 36°$ then $\chi = [36 - |\phi|]°$

$$\nu_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-(\theta/(1+\chi))}\right)\dfrac{\sqrt{L_R \gamma_R}}{f^2} - 0.45\right)}$$

else $\chi = 0°$

- **Step 8**: The effective path length is: $L_E = L_R \nu_{0.01}$ km
- **Step 9**: The predicted attenuation exceeded for 0.01% of an average year is obtained from: $A_{0.01} = \gamma_R L_E$ dB
- **Step 10**: The estimated attenuation to be exceeded for other percentages of an average year, in the range 0.001% to 5%, is determined:

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}) - \beta(1-p)\sin\theta)}$$

If $p \geq 1\%$ or $|\phi| \geq 36°$ $\quad \beta = 0$

If $p < 1\%$ and $|\phi| < 36°$ and $\theta \geq 35°$ $\quad \beta = -0.005\,(|\phi| - 36)$

Otherwise: $\beta = -0.005(|\phi| - 36) + 1.8 - 4.25\sin\theta$

Clouds Attenuation

- Less significant than rain attenuation, but its frequent presence implies that the time statistics of attenuation due to cloud would be quite high.
- Below 30 GHz, not so critical. Increasing frequency, critical in case of high liquid water content clouds. For low unavailability systems operating above 30 GHz, the effect of cloud attenuation may become critical.
- It depends on frequency, liquid water content and temperature.
  - Specific attenuation for rain clouds and fog γ_C=KM (dB/km)
  - K = $1.2 \cdot 10^{-3} f^{1.9}$ (dB/km)/(g/m^3), f in GHz, M water concentration (g/m^3)
- The clouds contribution is strongly correlated with the one of rain but the degree of this correlation is of difficult assessment.
- The input data for clouds attenuation prediction are:
  - the liquid water content (an average value of *0.5 g/m^3* is assumed);
  - the cloud thickness (an average value of *1 km* is assumed).
- Contribution of ice clouds meaningless

Scintillation

- It consists of **small, rapid fluctuations** in amplitude caused by atmospheric turbulence
- Particularly evident in presence of slant path signals with low elevation angles
- Fluctuations non-absorptive and produce both signal enhancement and fading
- Wet scintillation: in occurrence of rain
- The most rapid component of the fluctuation spectra has been attributed to turbulence, whilst more slowly varying components are attributed to rain.
- The scintillation effect increases with increasing frequency but decreases with decreasing antenna beamwidth.

Gaseous Attenuation

$$A = \gamma_o h_o + \gamma_w h_w \quad \text{(dB)}$$

γ_o specific attenuations (dB/km) due to dry air

h_o path length

γ_w specific attenuations (dB/km) due to water vapour

h_w path length

For an elevation angle φ between 5° and 90°, the path attenuation is obtained using the cosecant law

- For path attenuation based on surface meteorological data

$$A = \frac{\gamma_o h_o + \gamma_w h_w}{\sin\varphi} \qquad \text{dB}$$

- For path attenuation based on integrated water vapor content

$$A = \frac{\gamma_o h_o + A_w(p)}{\sin\varphi} \qquad \text{dB}$$

Depolarization

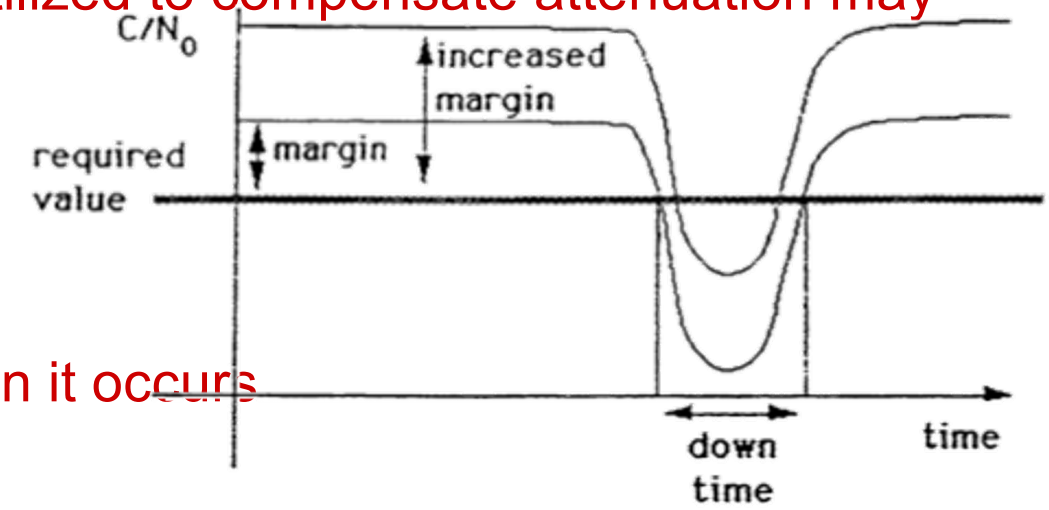
- The Earth's atmosphere can produce changes in the polarisation of radio waves.
- In the case of dual polarisation transmission, depolarisation causes interference between the two channels because the isolation can be severely impaired.
- Depolarisation can be induced on an earth-satellite link by two basic conditions on the path: hydrometeors, primarily rain and ice crystals (clouds).

Attenuation by sand and dust storms

- Specific attenuation (dB/km) inversely proportional to visibility
- Depends on humidity of the particles
- At 14 GHz 0.03 dB/km for dry particles and 0.65 dB/km for particles of 20% humidity

Dimensioning

- To ensure a fixed availability the link must be dimensioned taking into account an amount of attenuation
- A certain amount of dBs must be ensured in the link budget to be sure to compensate attenuation
- Most of contribution of attenuation is present for a percentage of time (rough estimate on average worldwide 5%)
- The rest of the time resources utilized to compensate attenuation may be wasted



Alternative approach

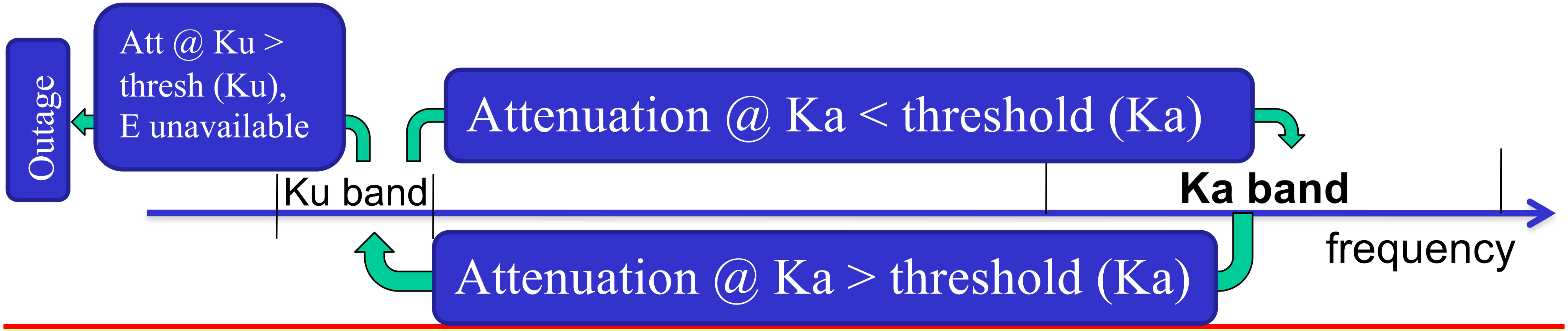
- Counteract attenuation only when it occurs

Rain Fade Countermeasures

- Shared resources
  - Frequency diversity
  - Adaptive data rate
  - Variable gain
  - Power control
  - Adaptive coding rate
  - Punctured coding
  - Burst Length Control
  - Adaptive modulation
  - Fade spreading
  - Repeated transmission (ARQ)
- Re-routing strategies
  - Site diversity
  - Orbit (satellite) diversity

Frequency diversity concept

- In normal conditions a portion of spectrum is utilized as long as a certain threshold is not exceeded
- In case attenuation exceeded the threshold a lower portion of the spectrum is utilized
- Example: Ka band (upper frequency) – Ku band (lower frequency)
- The system can be dimensioned as a function of a lower threshold than the case of single frequency
- Drawbacks: higher spectrum occupancy (although even for just a small percentage); double link; cross strapping on board



Outage probability using frequency diversity

- $P_{out} = P(A_a>M_a) + P(A_0>M_0$, E unavailable)
  - A_a attenuation in assisted conditions
  - M_a power margin in assisted conditions
  - A_0 attenuation in unassisted conditions
  - M_0 power margin in unassisted conditions
  - E common resource.
- Hypotheses:
  - the event would occur for a greater number of stations than the number of stations that is possible to assist simultaneously (N_a)
  - The design of all the stations is supposed to be the same both in terms of capacity and of outage probability in assisted conditions (P_a) and in unassisted conditions (P_0),
  - Statistical independence among the stations

Outage probability using frequency diversity (2)

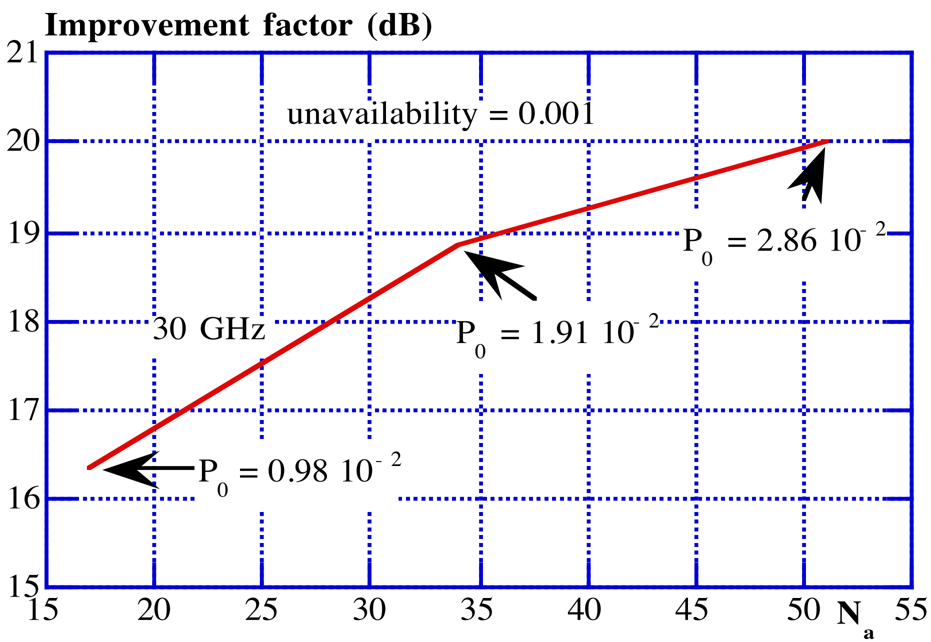
$$P_{ra} = \binom{N_s - 1}{k} (P_0)^k (1 - P_0)^{N_s - 1 - k}$$

$$P_{na} = \frac{k + 1 - N_a}{k + 1}$$

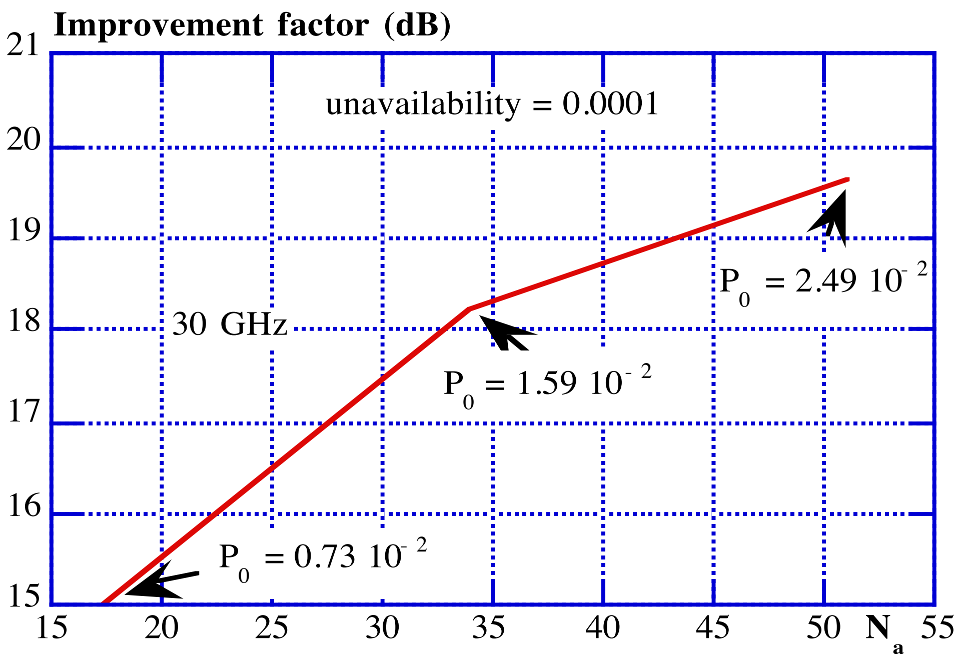
$$P_{out} = P_a + P_0 \sum_{k = N_a}^{N_s - 1} \binom{N_s - 1}{k} \left(\frac{P_0}{\delta_T} \right)^k \left(1 - \frac{P_0}{\delta_T} \right)^{N_s - 1 - k} \frac{k + 1 - N_a}{k + 1}$$

- P_{ra}= probability to require assistance
- N_s total number of stations
- k number of stations simultaneously requiring assistance
- $(1/\delta_T)$ takes into account the statistical dependence among the stations

Improvement factor



Improvement factor for P_a = 0.0002



Improvement factor for P_a = 0.0009

Power control

- It consists in increasing transmitted power, keeping the input power level of the receiver constant
- It needs open-loop or closed-loop algorithm implementation to measure channel variations
- For small terminals the capabilities of transmitted power control may be limited

Variable gain

(as a matter of fact power control)

- It consists in providing the excess HPA power capability and varies according to the desired link availability, transmission bandwidth and number of beams.
- The two main impairments are
  - the possible intermodulation power experienced by any other station using the same transponder
  - the increase of co-channel interference
- The margins have to be able to overcome small atmospheric fades but also maintain the link under the worst intermodulation and interference conditions caused by other stations under assisted conditions.

Adaptive data rate

- Varying the data rate the bandwidth requirement is varied accordingly
- The data rate variation can occur as a function of weather condition
- In bad weather condition the data rate is decreased implying to decrease the needed bandwidth with consequent gain in the link budget

Adaptive coding rate

- Channel coding protects the information flow introducing redundancy
- Varying the coding rate implies to vary the amount of redundancy
- To counteract slowly varying attenuations (rain) it can be implemented in two ways, depending on services and architecture:
  - a pool of reserve transmission capacity is provided, to be assigned on demand to faded users; more time, namely more energy, can be assigned to faded users by adaptive demand assignment of additional time slots kept as reserve capacity in a TDMA frame; the information transmitted in faded slots is then reduced and reserve slots are used to convey the remaining data
  - no reserve slots are provided; when the information transmitted in faded links must be reduced, the corresponding source of data shall transmit at a lower rate, keeping the data in its buffer (i.e., delaying transmission) or encoding data at reduced rate (hence quality)
- Variable throughput tolerable for computer file transfer (no real time services).
- For services requiring constant data rate, data rate reduction is compensated by more time slots assigned to the transmitting station; the common resource is assigned, in an adaptive way, to links experiencing additional path loss.

Punctured coding

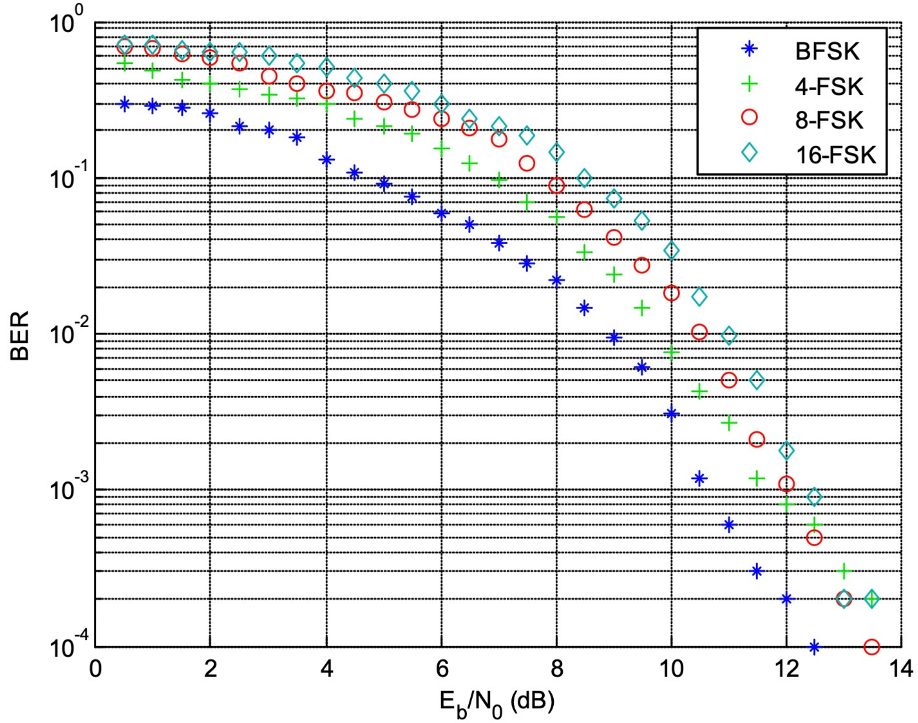
- This technique takes advantage of the capability of convolutional codes to eliminate some bits in order to reduce redundancy
  - Bandwidth requirements are relaxed
  - Performance in terms of error correction worsen

Burst Length Control

- Pool of reserve transmission capacity, to be assigned on demand to faded users; for example, more time, namely more energy, can be assigned to faded users by adaptive demand assignment of additional time slots kept as reserve capacity in a TDMA frame

Adaptive modulation

- The adopted modulation scheme is related to the bandwidth occupation and to the required E_b/N_0 or C/N_0
- To guarantee the same BER the required E_b/N_0 or C/N_0 increases for higher order modulations



- In normal conditions, high spectral efficiency modulation, as 16-PSK, 64-PSK or 256-QAM, are used.
- At the onset of the fade, a more robust modulation method, such as QPSK or BPSK, is introduced.

Fade spreading

- Fade spreading operates reducing data rate to keep constant E_b/N_0 ratio.
- Both energy per bit and unit power are increased without reducing the bandwidth, avoiding problems of interference.
- The efficiency is not very high considering the effects of modem performance at low E_b/N_0
- It looks less attractive than coding schemes.

10 10

1 1 1 1 4 4

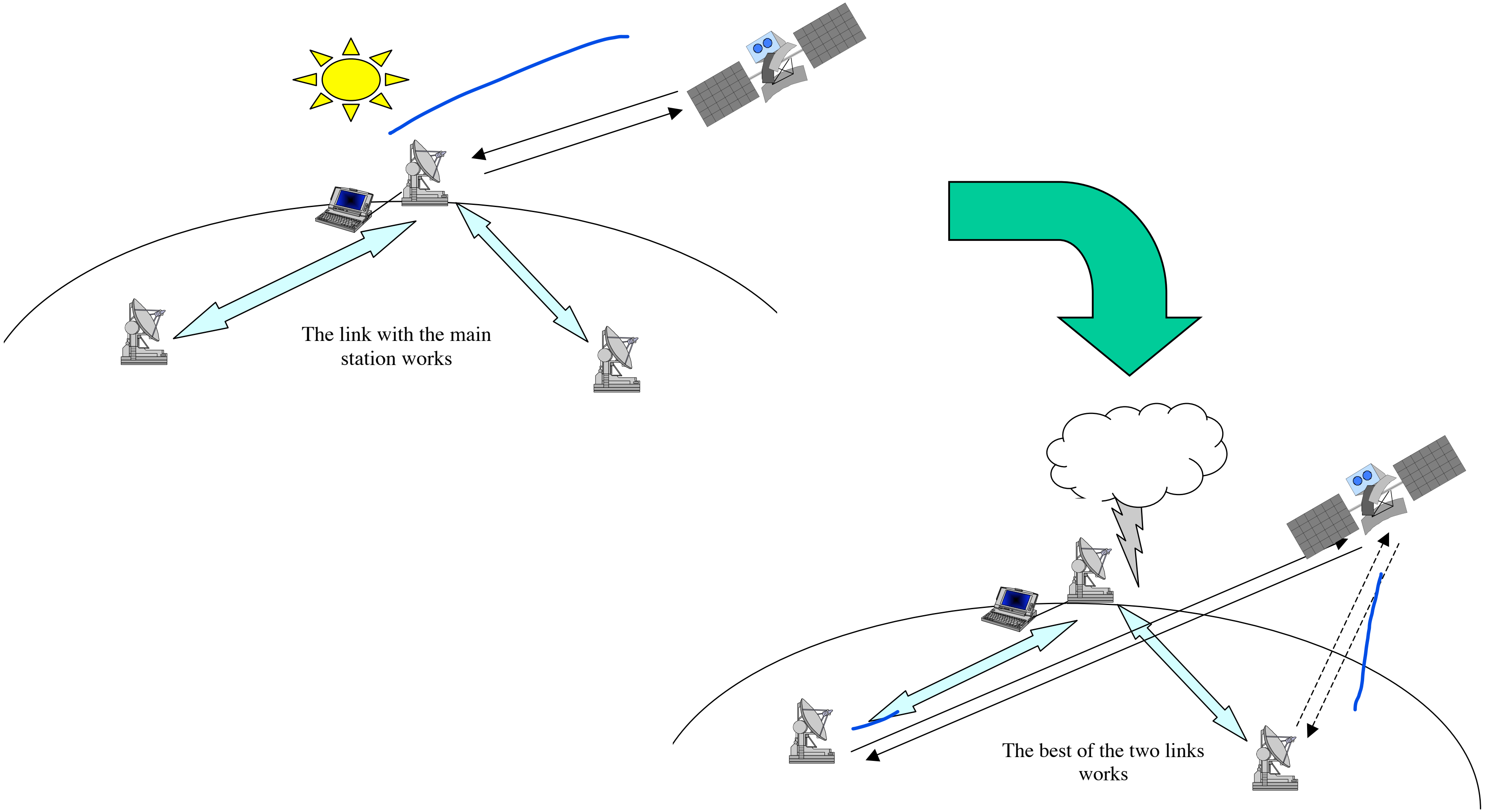
1 0

2 2 .B4

ARQ (Automatic Repeat Request/Query)

- Assuming that not all packages are subject to deep fading, the method is based on repeated transmission of bursts, increasing signal to noise ratio
- Packet retransmission (ARQ): ARQ can be implemented, depending on the type of communication service, when delayed transmission is acceptable (data services with unconstrained delay)
- Not meaningful performance
- Implemented at layer 2

Site diversity: classical concept



Site diversity characterization

Performance characterized by two parameters:

- **Diversity factor**: ratio of the single-site time percentage and the diversity time percentage, at the same attenuation level.

- **Diversity gain**: difference between rain margin with and without diversity at the same time percentage.

The procedure has been tested for frequencies between 10 and 30 GHz and recommended for unavailability lower than 0.1%.

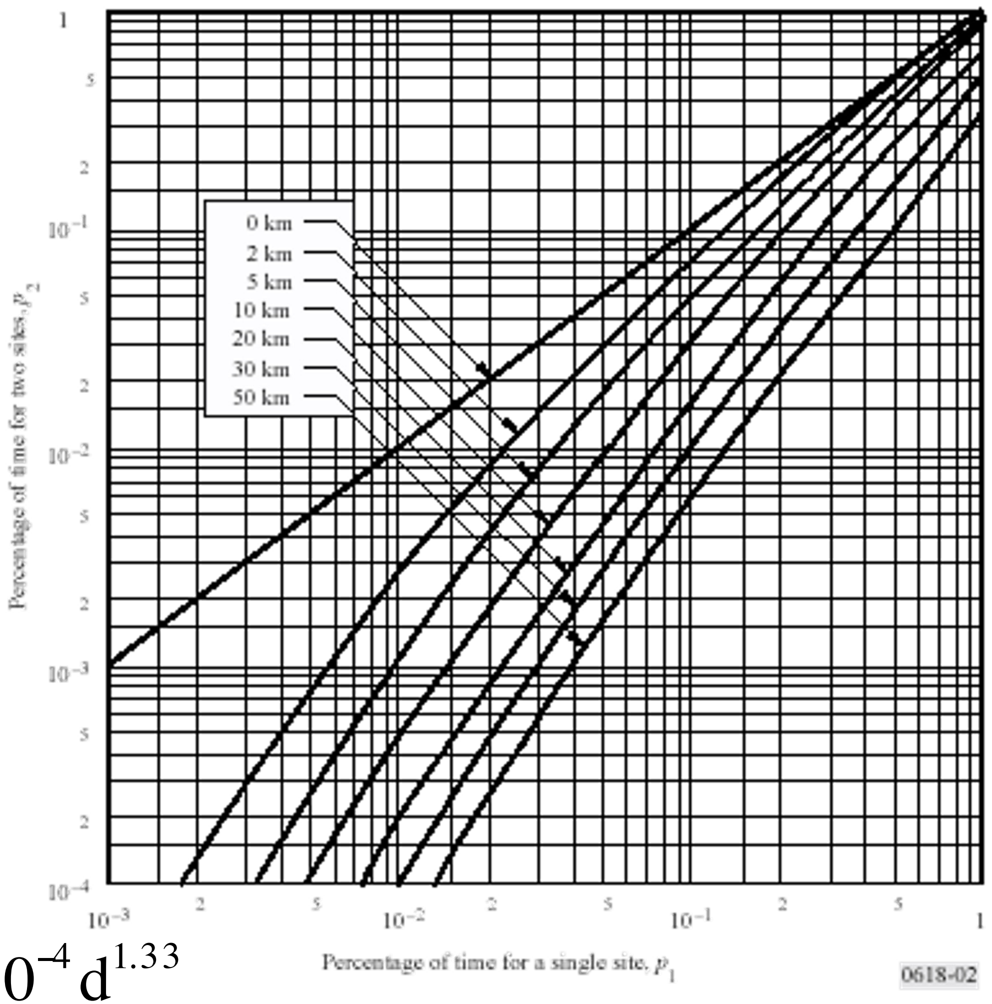
Diversity improvement factor

The diversity factor is given by:

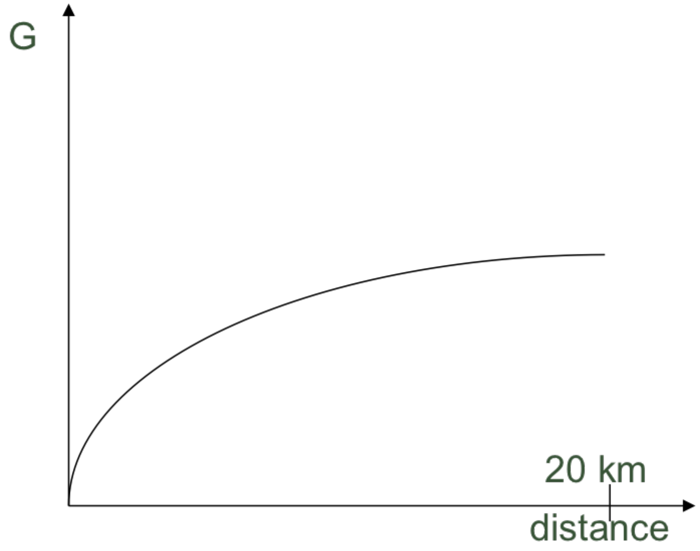
$$I = \frac{p_1}{p_2} = \frac{1}{(1+\beta^2)}\left(1 + \frac{100\beta^2}{p_1}\right) \approx 1 + \frac{100\beta^2}{p_1}$$

where p_1 and p_2 are the outage percentage of time of single site and double site, β is a parameter depending on link characteristics. The approximation is acceptable since β^2 is generally small. β^2 depends basically on the distance, d, between the stations, and only slightly on the angle of elevation and the frequency. Empirically: $\beta^2 = 10^{-4} d^{1.33}$

Relationship between percentages of time with and without diversity for the same attenuation (Earth-satellite paths)



Diversity gain

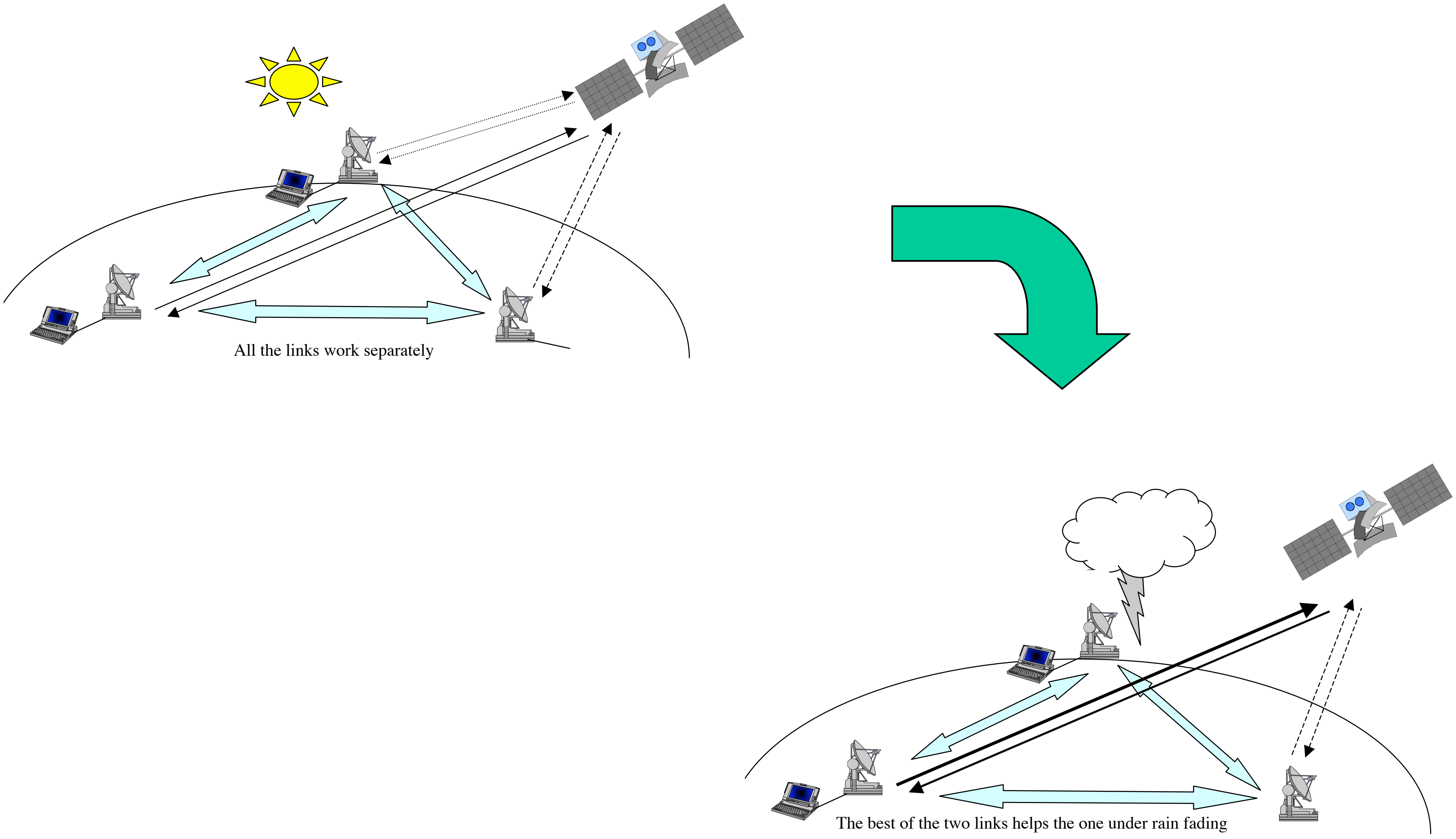


Depends on the following parameters:

- d distance (km) between the two sites
- A rain attenuation (dB) for single site
- f frequency (GHz)
- θ elevation angle (°)
- ψ angle (degrees) made by the azimuth of the propagation path with respect to the baseline between sites, chosen such that $\psi \leq 90°$.

1. Spatial separation: $G_d = a\left(1 - e^{-bd}\right)$
2. Frequency-dependent gain: $G_f = e^{-0.025f}$
3. Elevation angle contribution: $G_\theta = 1 + 0.006\theta$
4. Baseline-dependent term: $G_\Psi = 1 + 0.002\Psi$
5. **Diversity gain:** $G = G_d G_f G_\theta G_\Psi$

Multiple site diversity concept



Multiple site diversity rationale

- This system architecture could be very usefully applied for example in the following cases:
  - the satellite connection is more convenient than the terrestrial links;
  - the set of stations belongs to a proprietary closed network for security reasons, aiming at utilizing the terrestrial networks only in case of necessity;
  - the provided services are more suitable to satellite transmission;
  - the stations are of transportable type and can occasionally utilize the diversity advantage in case they are close to an access point to the terrestrial network;
  - the satellite is preferred in normal working conditions because it provides more efficient interconnection with other systems.

Multiple site model

- Multidimensional model is needed
- Basic hypothesis: the single site and the joint probability of rain attenuation for N-locations have log-normal behaviours.
- The state of the N locations is described by means of an N-dimensional binary variable ("rainy" or "non rainy") with the associated multivariate probability function.
  - It is assigned by means of the probability density of a N-dimensional continuous variable and by a N-dimensional threshold chosen in such a way that the probabilities to be exceeded or not assume the wanted values.
- The continuous "rainy state variable" r_i, for the i-th location, can be selected with high degree of freedom.
  - For example gaussian multivariate variable normalised to zero mean and unit r.m.s., with the covariance matrix forced to represent the measured joint statistics.

Multiple site model (2)

- The normalised attenuation A_i assumed to be independent on r_i and given by logarithmic expression normalised and centred on zero:

$$a_i = \frac{\left(\ln A_i - \langle \ln A_i \rangle\right)}{\sigma_{\ln Ai}}$$

- $\langle \ln A_i \rangle$ the median and $\sigma_{\ln A_i}$ the standard deviation of $\ln A_i$
- a_i is a gaussian variable defined at any time,
  - it is of interest only when the "rainy state variable" exceeds the fixed threshold r_i*.
- The joint statistical process is fully described for any location by a pair of zero-mean, unit power gaussian variables, a_i and r_i, that are independent of each other but correlated with the correspondent ones in the other sites.

Multiple site model (3)

- The joint probability that a set of thresholds A_i (i = 1 to N) are simultaneously exceeded given by the product of two joint probabilities:
  - the **conditioning** one, which gives the "common rainy time" obtained integrating the joint normal density of the r_i's from the set of thresholds r_i^* to infinity
  - the **conditioned** one, similarly obtained by integrating the joint log-normal density of the a_i's from the set of the reduced attenuation thresholds $a_i^* = \left(\ln A_i^* - \langle \ln A_i \rangle\right) / \sigma_{\ln A_i}$ to infinity

Multiple site model (4)

- The quantities needed for the conditioning probability are then:
  - a. the vector of the thresholds r_i^*;
  - b. the matrix r of the normalised co-variances $r_{ij} = \langle r_i r_j \rangle$.
- The quantities needed for the conditioned probability are:
  - a. the vector of the median values $\langle \ln A_i \rangle$;
  - b. the vector of the standard deviations $\sigma_{\ln A_i}$;
  - c. the vector of the thresholds a_i^* ;
  - d. the matrix a of the normalised co-variances $a_{ij} = \langle a_i a_j \rangle$.
- r_i^* obtained by "single station rainy time fractions" vector P_{0i} (to be exceeded with the correspondent probability).
  - P_{0i}'s could be derived from the ITU-R global map of precipitation distribution.
- The rain attenuation distribution for each site can be calculated using a rain attenuation prediction model from the rain intensity distribution obtained with the ITU-R global map of rain intensity (EXCELL).

Multiple site model (5)

- The vectors of the medians $\langle \ln A_i \rangle$ and of the standard deviations $\sigma_{\ln A_i}$ calculated from the given prob. distr. (least square regression). The terms of the matrixes **r** and **a** can be expressed by the following functions of the distances **d**$_{ij}$ between locations:

$$r_{ij} = 0.7\exp\left(-d_{ij}/60\right) + 0.3\exp\left[-\left(d_{ij}/700\right)^2\right] \quad i \neq j \qquad a_{ij} = 0.94\exp\left(-d_{ij}/30\right) + 0.06\exp\left[-\left(d_{ij}/500\right)^2\right] \quad i \neq j$$

$$r_{ij} = 1 \quad i = j \qquad a_{ij} = 1 \quad i = j$$

- The vector of the thresholds a_i^* is a design-oriented input depending on the margins (possibly different) allowed for the individual earth terminal.
- The multivariate probability density functions:

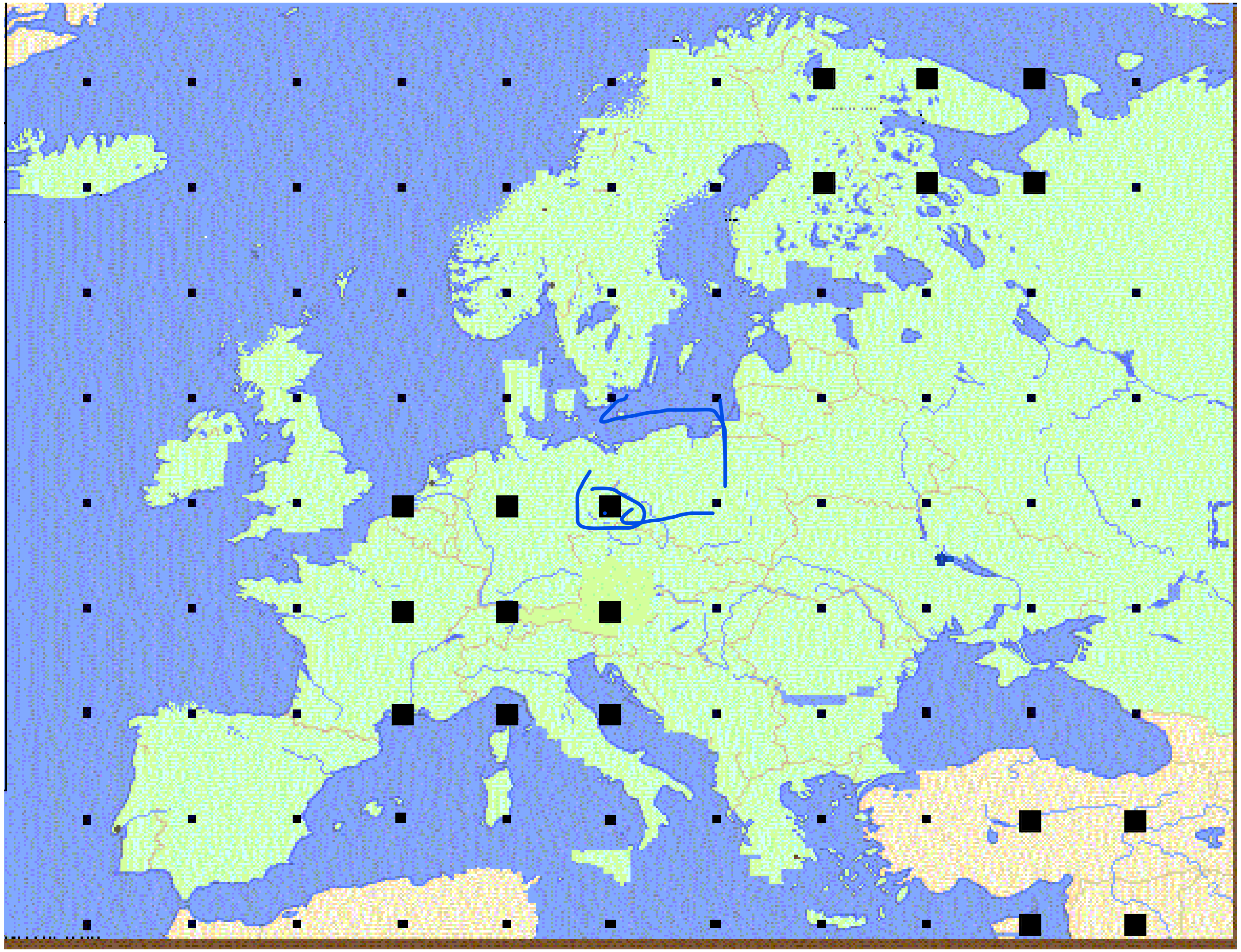
$$p(r_1, r_2, \ldots, r_N) = k_r \exp\left(-\frac{1}{2}\sum_1^N \sum_1^N c_{r,ij} r_i r_j\right) \ , \ p(a_1, a_2, \ldots, a_N) = k_a \exp\left(-\frac{1}{2}\sum_1^N \sum_1^N c_{a,ij} a_i a_j\right)$$

- where $c_{r,ij}$ and $c_{a,ij}$ are the generic terms of the matrixes $\boldsymbol{c_r}$ and $\boldsymbol{c_a}$ respectively, that are inverse of **r** and **a**, and:

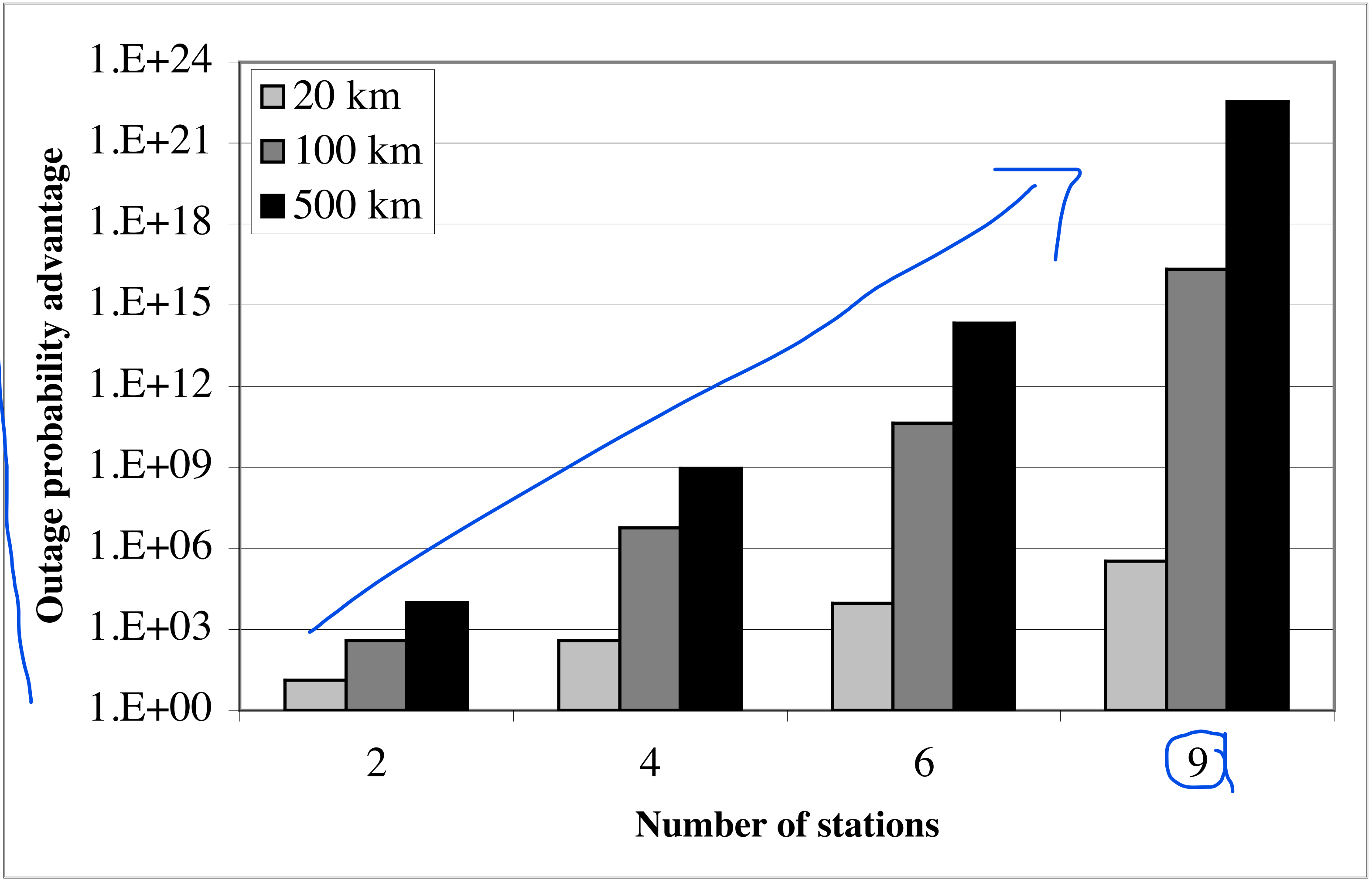
$$k_r = \sqrt{\frac{c_r}{(2\pi)^N}} \ , \ k_a = \sqrt{\frac{c_a}{(2\pi)^N}}$$

- in which c_r and c_a are the determinants of $\boldsymbol{c_r}$ and $\boldsymbol{c_a}$.

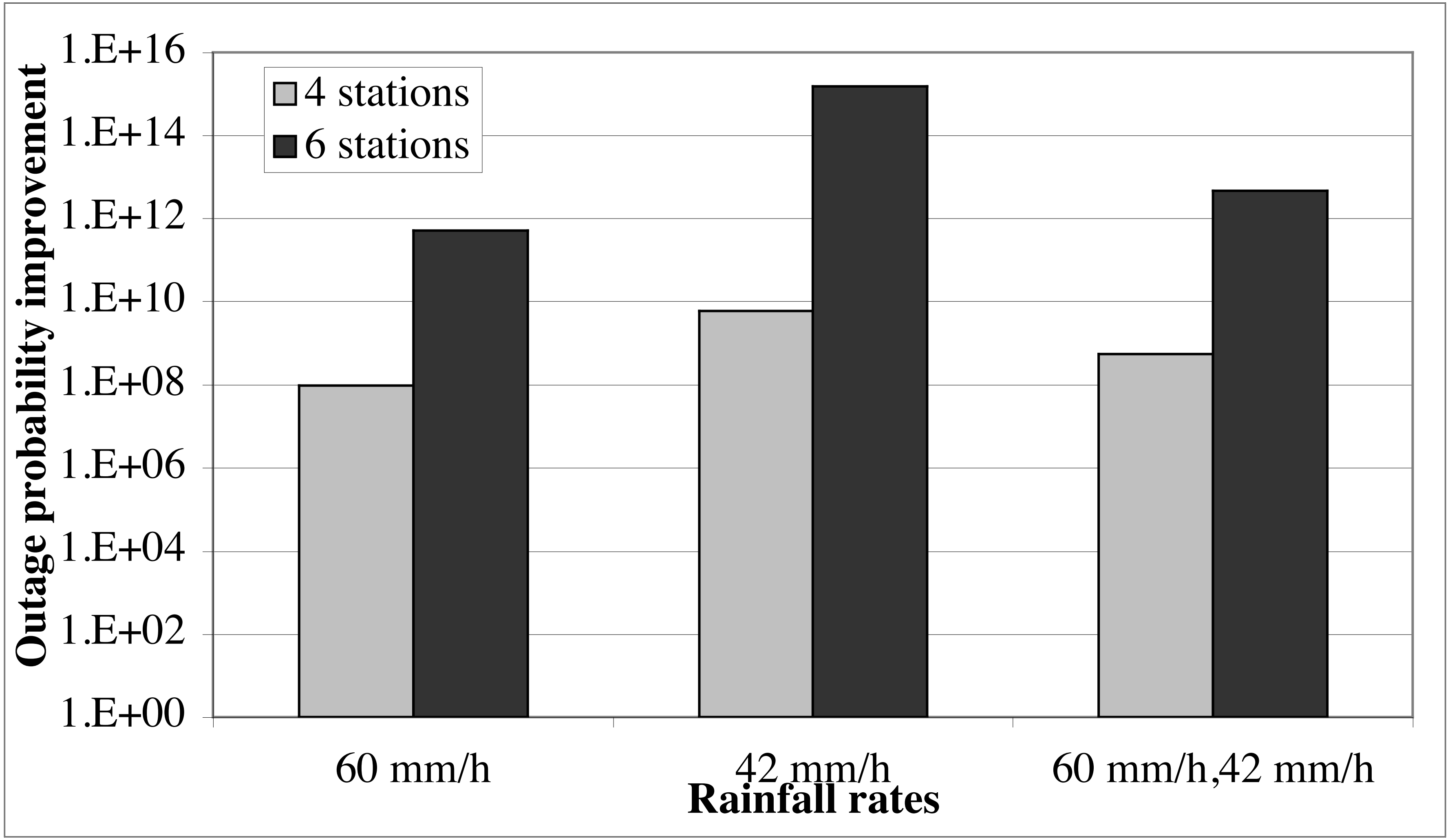
Selected subset of stations



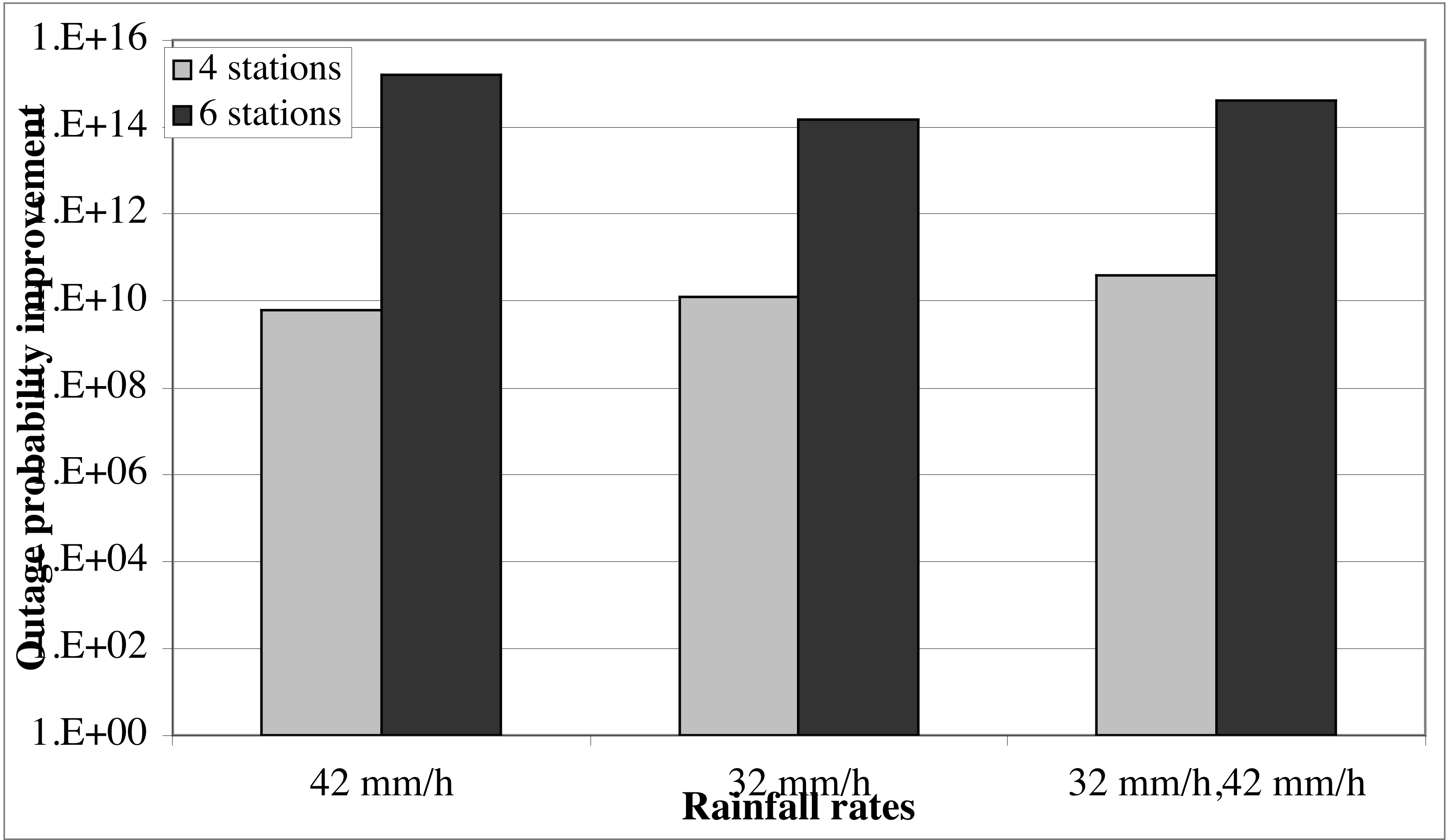
Site diversity Improvement (1)



Site diversity Improvement (2)



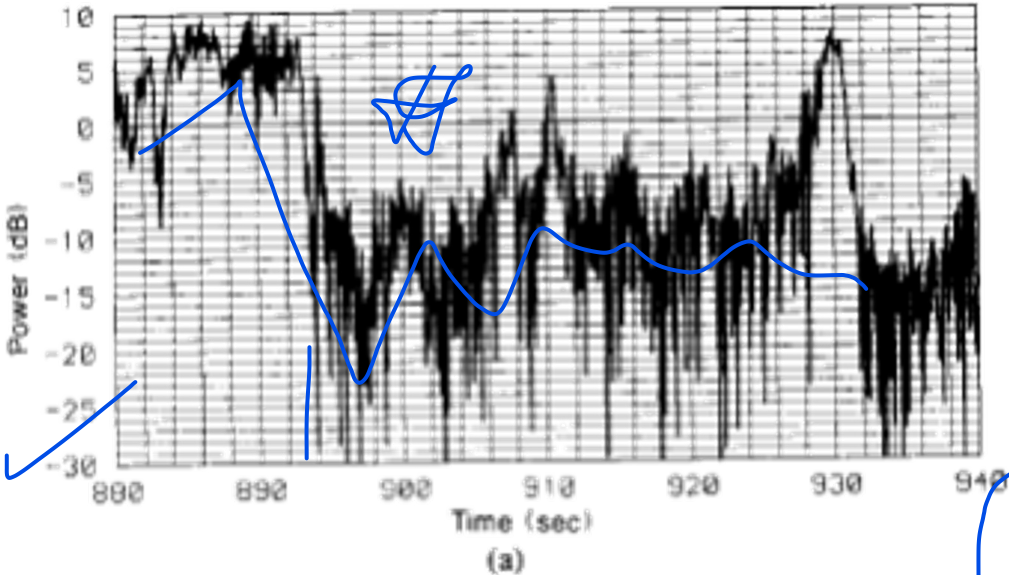
Site diversity Improvement (3)



Orbit (satellite) diversity

- It consists in using a backup spacecraft, located in the geostationary orbit, to protect the link against rain outages.
- The backup satellite is located on the same orbit (GEO), the two links are correlated
- The measured data indicates that rain attenuations on two converging paths are highly correlated and that the improvement factor is trivial (≤1.2) if applied at 12 GHz but it can be meaningful if applied at 20 GHz.

Mobile channel description: experimental data



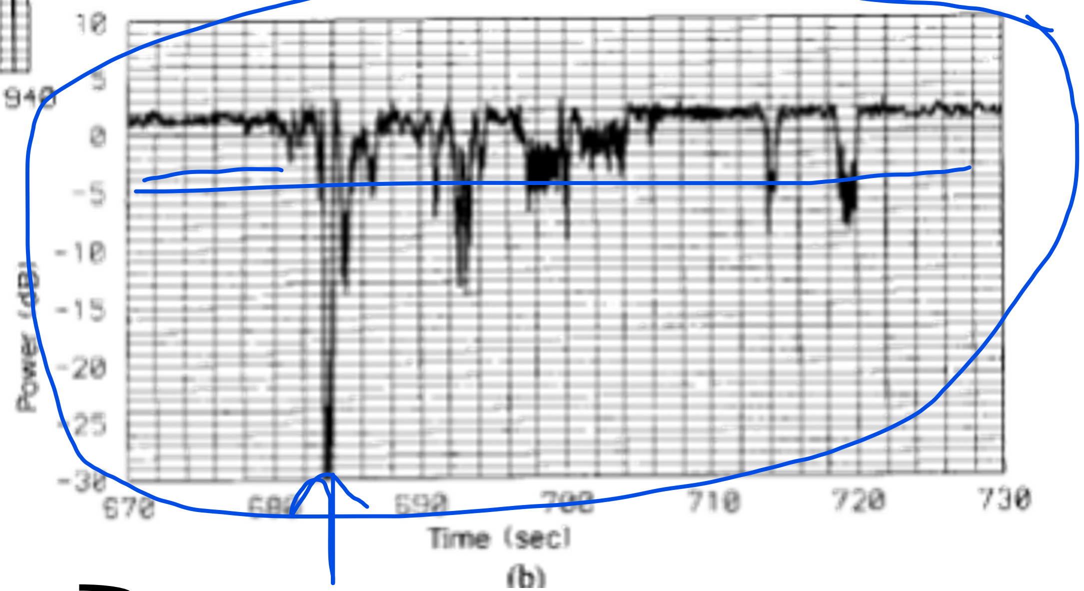
(a)

0 dB: average received power

Speed: 10 km/h
Urban environment

0 dB: average received power

Speed : 60 km/h
Higway environment



(b)

Environments classified as:

- Urban (tall buildings)
- Suburban (medium/low height buildings)
- Rural (country, open)

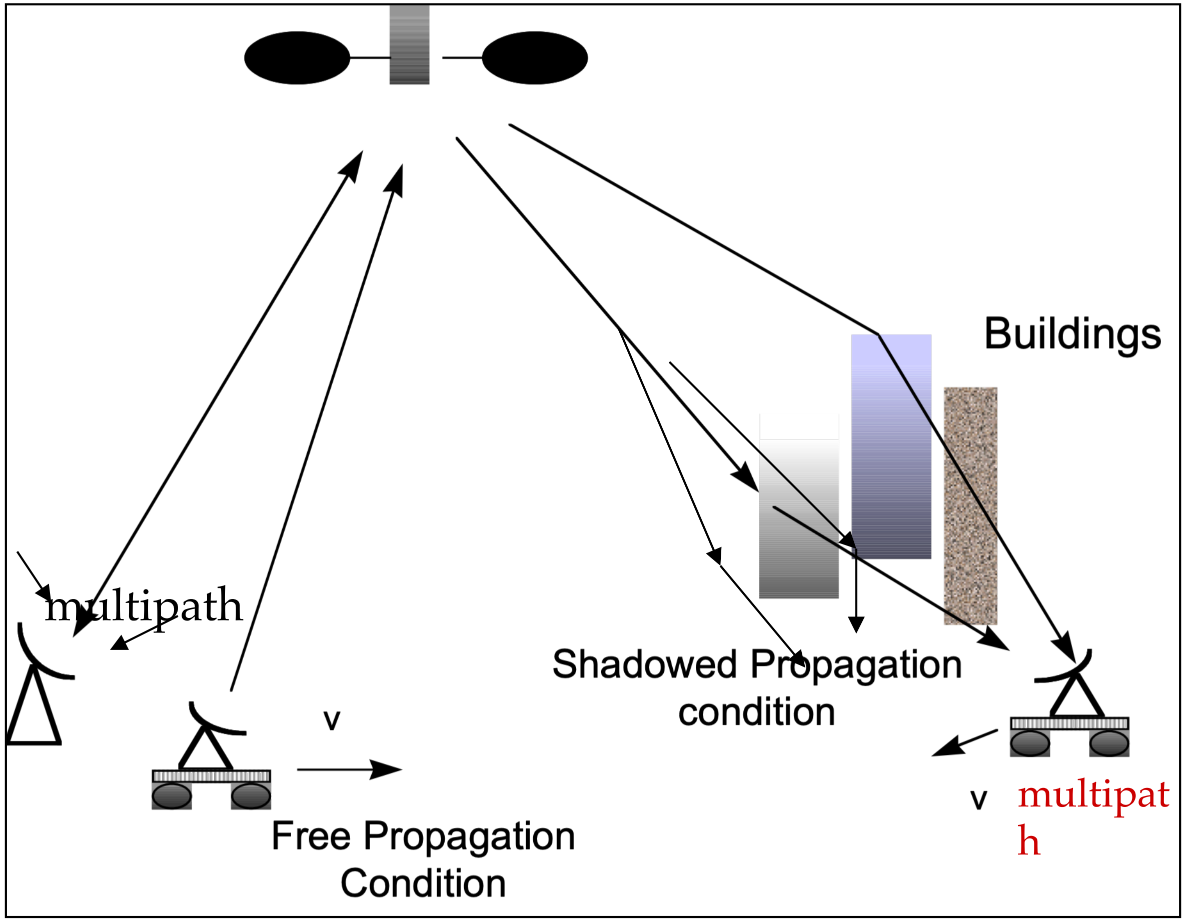
Not standard, location dependent

Problem description: phenomenology

- From measured data, for modelling simplicity, two phenomena are identified:
  - Fast fading (multipath)
  - Slow fading (shadowing)

In terrestrial systems multipath diversity is exploited to improve C/N

In satellite systems multipath contribution is meaningless because signal arrives on ground strongly attenuated



Problem description: phisical characteristics

- **Fast fading**: several replicas of the transmitted signal delayed attenuated and phase shifted are added (with the relative phase) on the receiving antenna, experiencing constructive and/or destructive interference. Thus **fast** variations of the **instantaneous power level** are experienced.

- **Shadowing**: takes into account the **average** received **power level** variation; this phenomenon shows a meaningful time variation much slower than fast fading.

The two events overlap

Channel models: general aspects

Communication Channel characteristics depend on the environment typology (presence of obstacles, density, movement, …) and on the relative position user-satellites. Due to the great complexity of the electromagnetic characterization the channel description is achieved through the **Random Processes Theory**.

- Channel model requirements
  - Frequency selective or not selective channels
  - Fast fading description
  - Shadowing description

Channel models: generalities

- Narrowband models (signal bandwidth < coherence channel bandwidth)

$H(f;\, t) = H(f_0;\, t) = z(t)$ Attenuation factor

f_0: *carrier frequency* - $H(f;\, t)$ *time variant frequency response*

Received signal:

$$R(t) = z(t)s(t) + n(t)$$

$z(t)$: *fading channel term,* $s(t)$: *transmitted signal,* $n(t)$: *thermal noise*

Channel Models: expressions

- A channel model is based on the characterization of the fading process ***z*(*t*)**
- The process ***z*(*t*)** is usually described as overlapping of correlated stocastic processes.
- The process ***z*(*t*)** is complex.

Two types

Single state | **Multiple states**

Main statistical models: single state

- Models proposed in literature: generalized expression

$$Z(t) = S_1(t)(A+x_1(t)+j\cdot y_1(t)) + S_2(t)(x_2(t)+j\cdot y_2(t))$$

A, (complex) LOS component,

x_i , y_i =1,2 zero mean, independent Gaussian (fast fading) r.vs.,

S_i lognormal (shadowing) r.vs.

- Main models

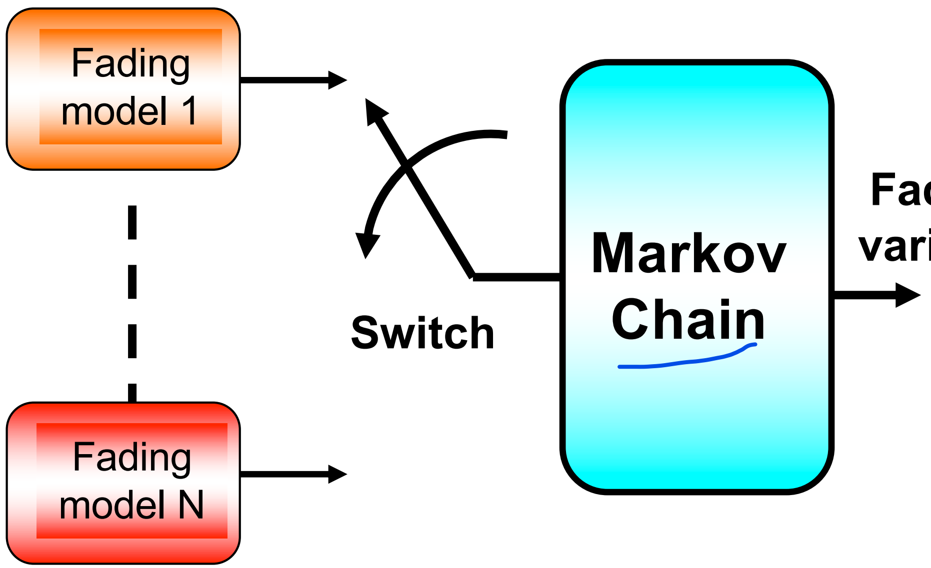
$x_1=y_1=0, S_2=1$ →	Loo's model	$z(t) = S_1 A + (x_2 + j\cdot y_2)$
$S_2=0$ →	**RLN** model – $\lvert z\rvert=r=RS$	$z(t) = S_1(A + x_1 + j\cdot y_1)$
$S_2=1$ →	**GRLN** model	$z(t) = S_1(A + x_1 + j\cdot y_1) + (x_2 + j\cdot y_2)$
$x_1=y_1=0$ →	Hwang, Kim et al.	$z(t) = S_1 A + S_2(x_2 + j\cdot y_2)$

Each model applies to a specific environment (e.g. Loo fits rural environment)

Main statistical models: multiple state

- Multistate - single satellite

Single channel



Lutz et al. Model: **N=2**, - channel state: good or bad

State statistics:

Good state – Rice

Bad state – Rayleigh-Lognormal

Performance evaluation: generalities

Transmission quality in personal communications via nongeostationary (LEO, MEO) satellite links is mainly influenced by:

- Constellation parameters:
  - ✓ satellite altitude,
  - ✓ number of satellites,
  - ✓ orbits selection
- Communication TX/RX techniques
  - ✓ multiple access scheme,
  - ✓ modulation,
  - ✓ coding,
  - ✓ interleaving
- Geometrical scenario:
  - ✓ elevation angle,
  - ✓ azimuth angle,
  - ✓ spatial correlation

Time varying propagation conditions

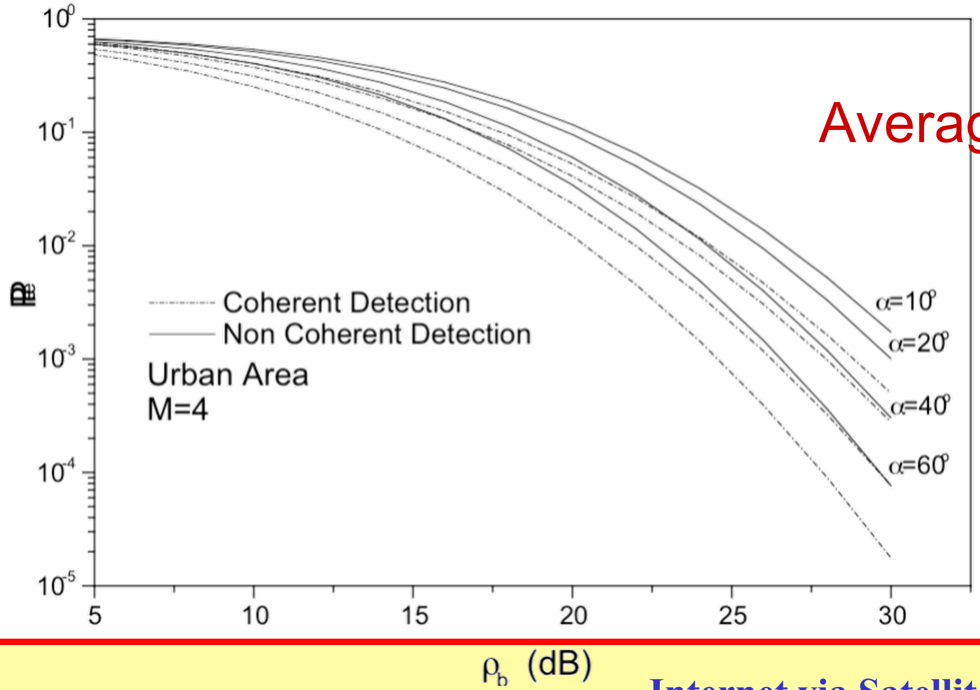
Multipath
(fast fading)

Shadowing
(slow fading)

Performance evaluation

- Average error probability $$P_e = \int_0^\infty P(e|r)\,p_r(r)\,dr$$
- Outage probability $$P_{out} = \mathrm{Prob}\{P_e > P_{e0}\} = \mathrm{Prob}\{\rho_b < \rho_{b0}\}$$

ρ_b: Signal/average noise ratio
ρ_{b0}: Signal/reference noise ratio



Average error probabilty vs elevation angles

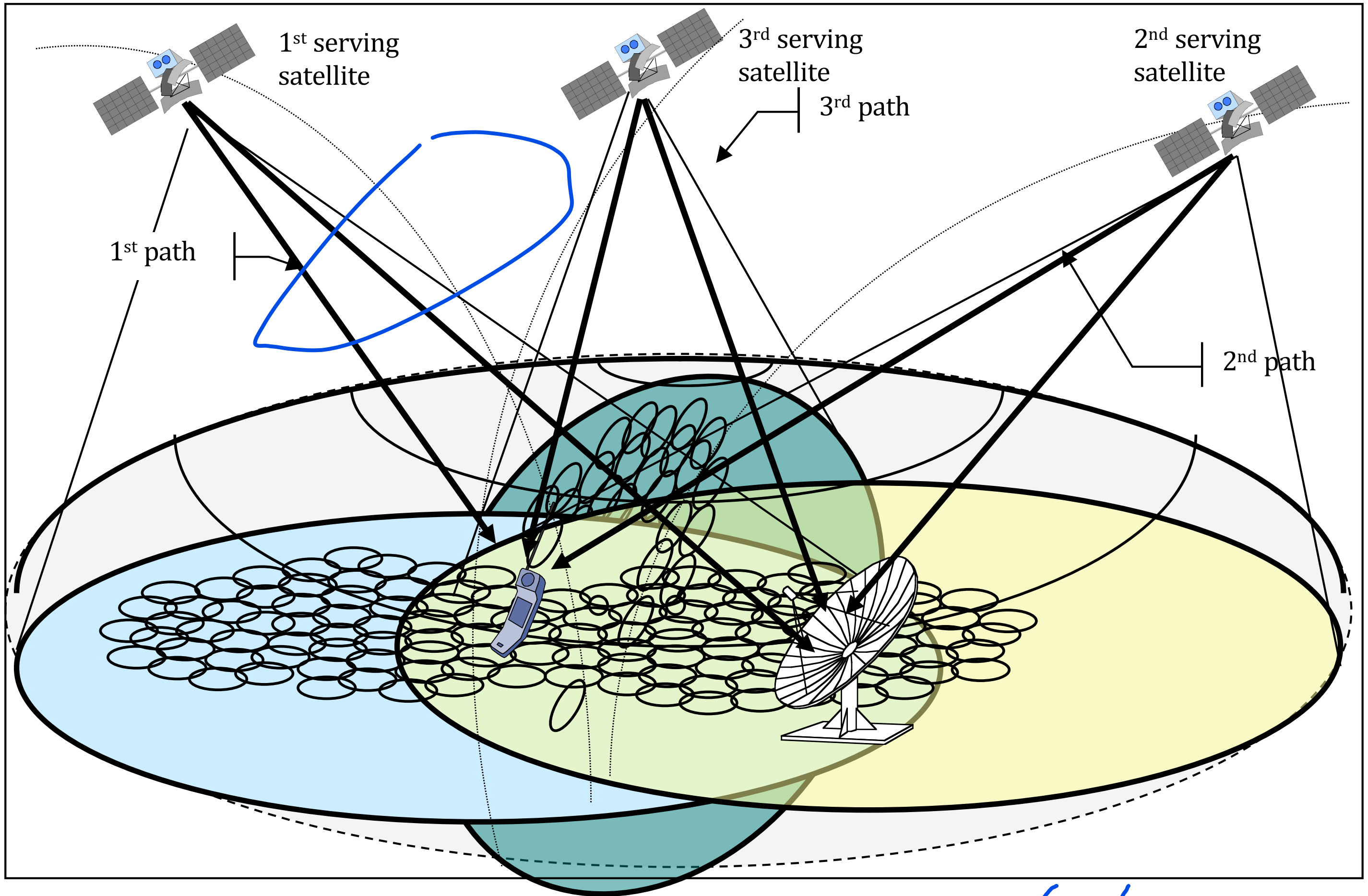
RLN channel model

Satellite (path) diversity: generalities

- **Shadowing** is an additional contribution (other than rain) that **decreases link availability** (not BER).
- **Concept**: alternative or simultaneous use of different satellites (on the same or on different orbits) to differentiate paths taking advantage of multipath ad hoc set up
- Diversity allows to counteract shadowing impairments
- Performance depend on correlation among paths
- For LEO and MEO constellations diversity seems to be a good solution (for GEO investigation needed because correlation may be high)

To evaluate diversity performance a suitable channel model is needed

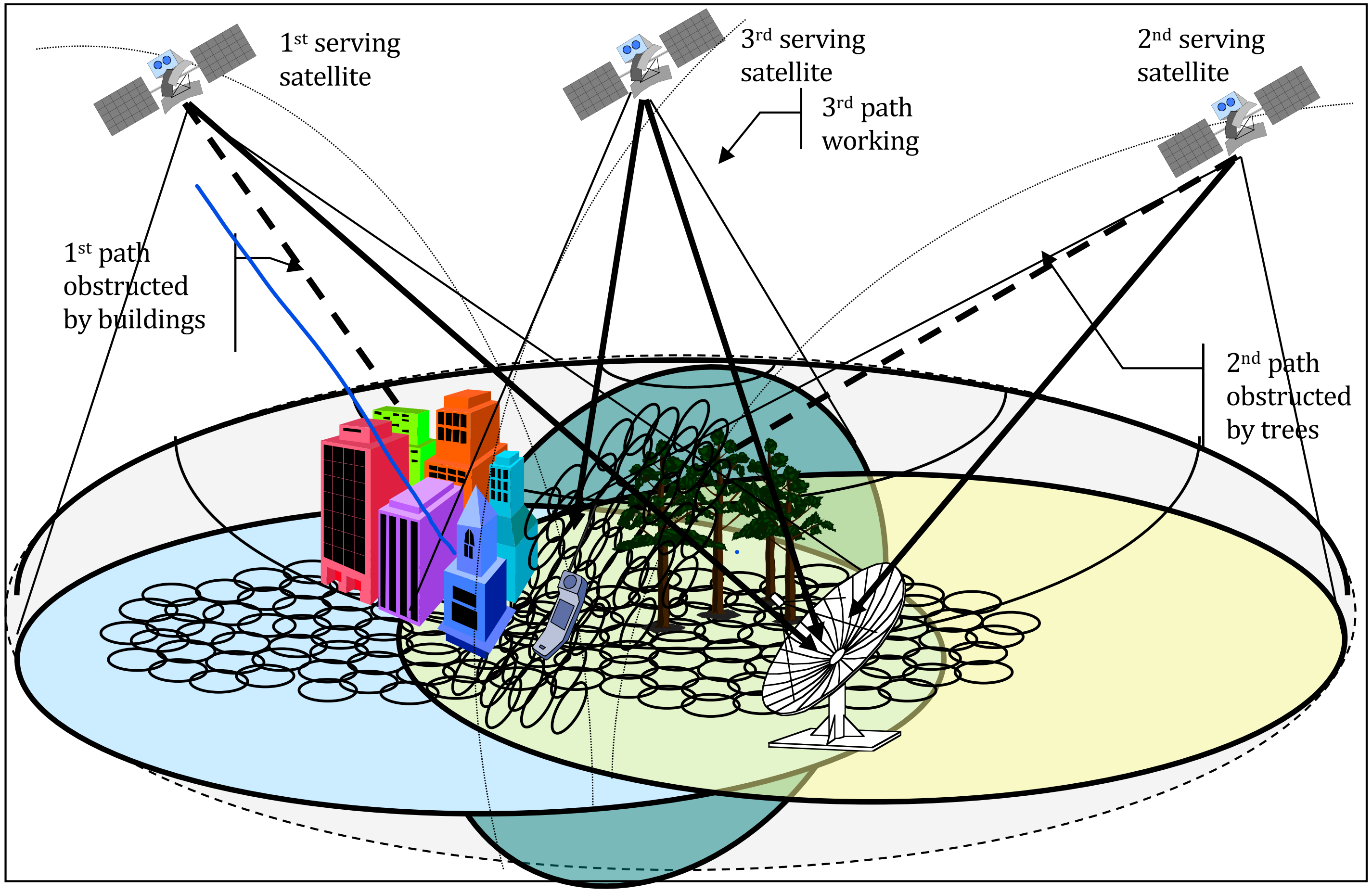
Mobile channel effects countermeasures: Satellite diversity



Improving C/N

S/N

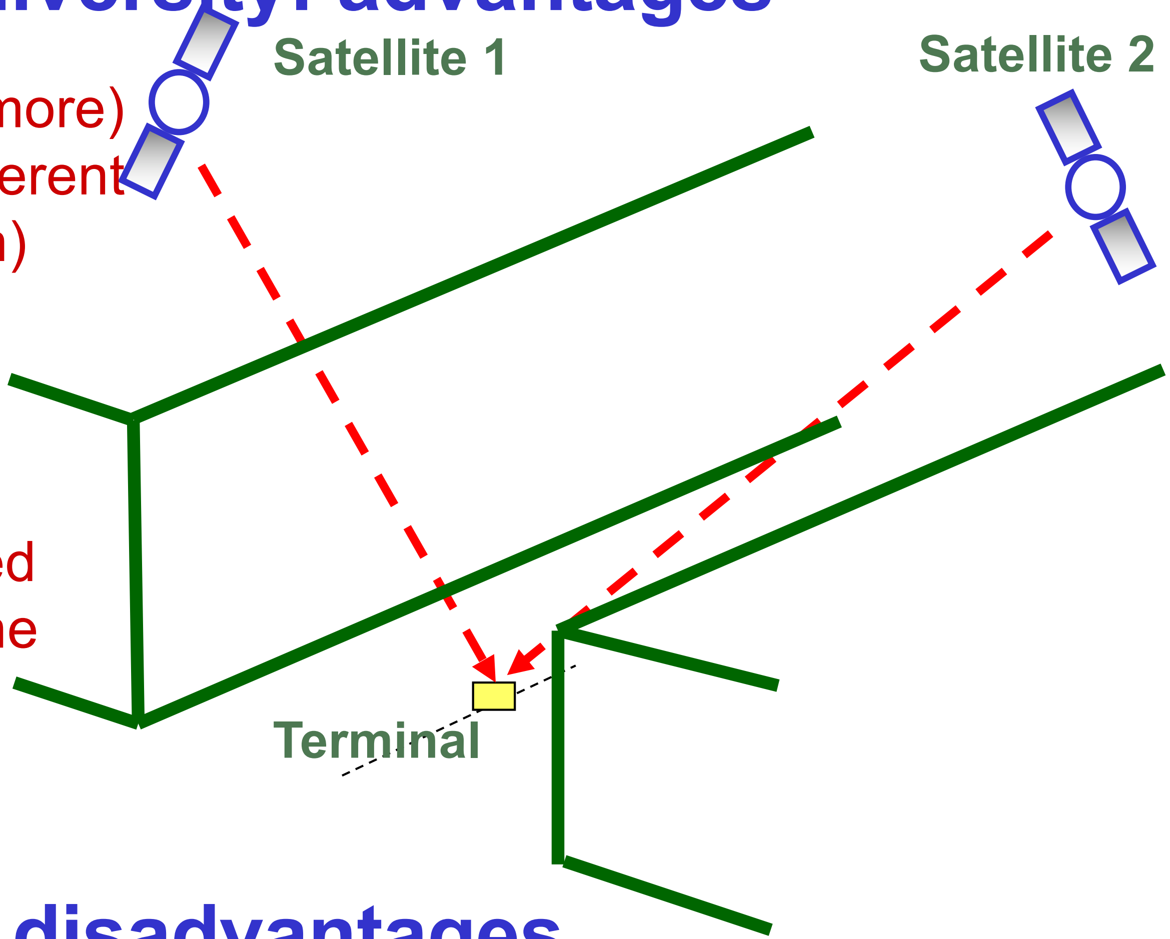
Mobile channel effects countermeasures: Satellite diversity (2)



Improving availability

Satellite diversity: advantages

- One user sees two (or more) satellites under (possibly) different angles (azimuth and elevation)
- Signals from different satellites can be (optimally) combined in the receiver
- If one satellite link is shadowed there is still chance to route the communication through another unobstructed link



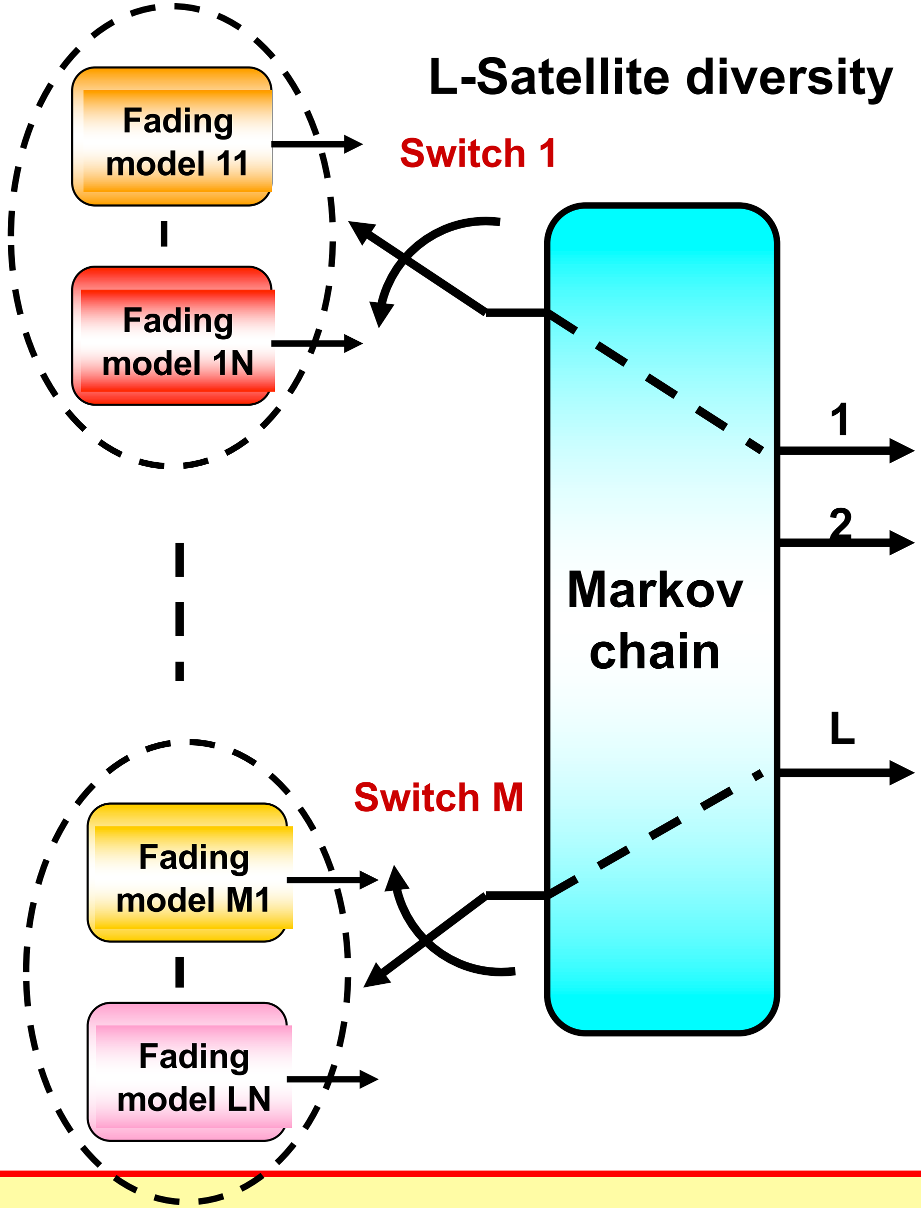
Satellite diversity: disadvantages

- Many satellite channels must be utilized for just one communication link
- Accurate synchronization among the different paths must be implemented

Satellite diversity: models

- Models proposed in literature:
  - Single state, multistate
  - Frequency Selective or not
  - Statistical or deterministic

Satellite diversity: multistate models



Ex. L=2 and for each satellite channel a two state model is adopted (N=2)

Channel sates

(good,good)
(good,bad)
(bad,good)
(bad,bad)

Satellite diversity: single state model

- The fading statistics are assumed to be unique in the area
- The single channel is assumed to be described by RLN

$$r_i(t) = z_i(t)s(t) + n_i(t) \quad , \quad i = 1,\ldots,L$$

received signal from the i-th satellite

$z_i(t)$: *channel term*, $s(t)$: *transmitted signal*, $n_i(t)$: *termal noise*

Characterization of a multiple satellite channel with diversity requires the statistical description of the following
Vector Channel Random Process

$$\mathbf{z}(t) = [z_1(t), z_2(t), \ldots, z_L(t)]^T$$

z_i is RLN

Satellite diversity: single state model assumptions

RLN hypotesis:

$$z_i = S_i(A_i + x_i + jy_i) \quad i = 1,\dots,L$$

Statistical hypoteses:

1) $(A_i + x_i + jy_i) \quad i = 1,\dots,L$ **Statistically independent**
2) $S_i \quad i = 1,\dots,L$ **Lognormal - Statistically correlated**

x_i,y_i: independent Gaussian random variables, $i=1,\dots,L$

S_i: lognormal correlated random variables, $i=1,\dots,L$

To characterize the channel it is necessary to determine the shadowing statistics ($S_1,\dots,S_L$)

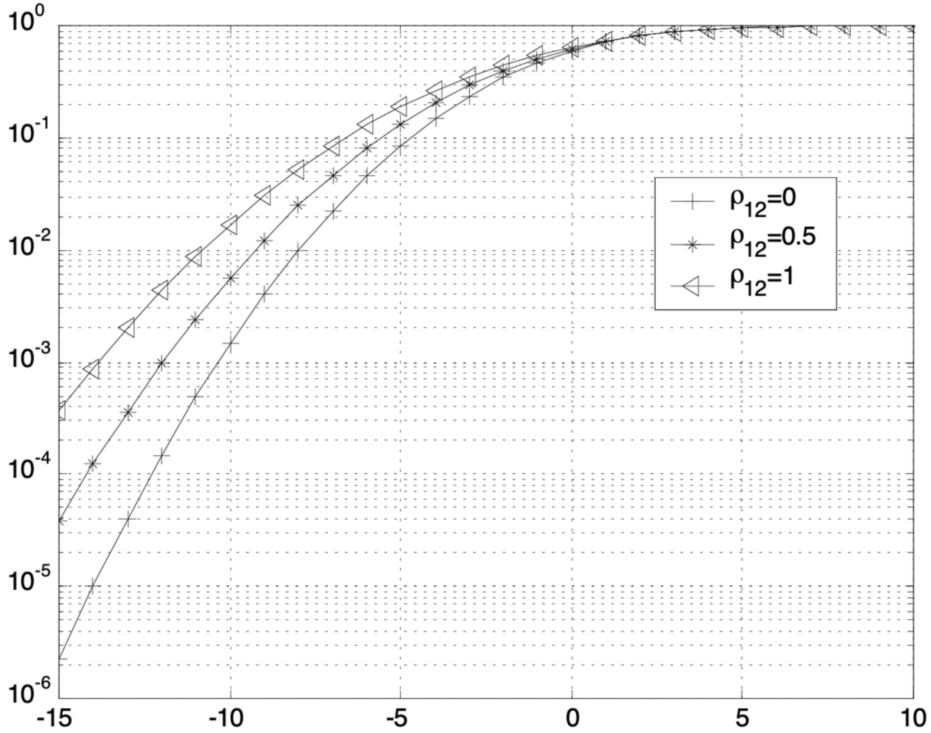
↓

These have been determined with suitable models

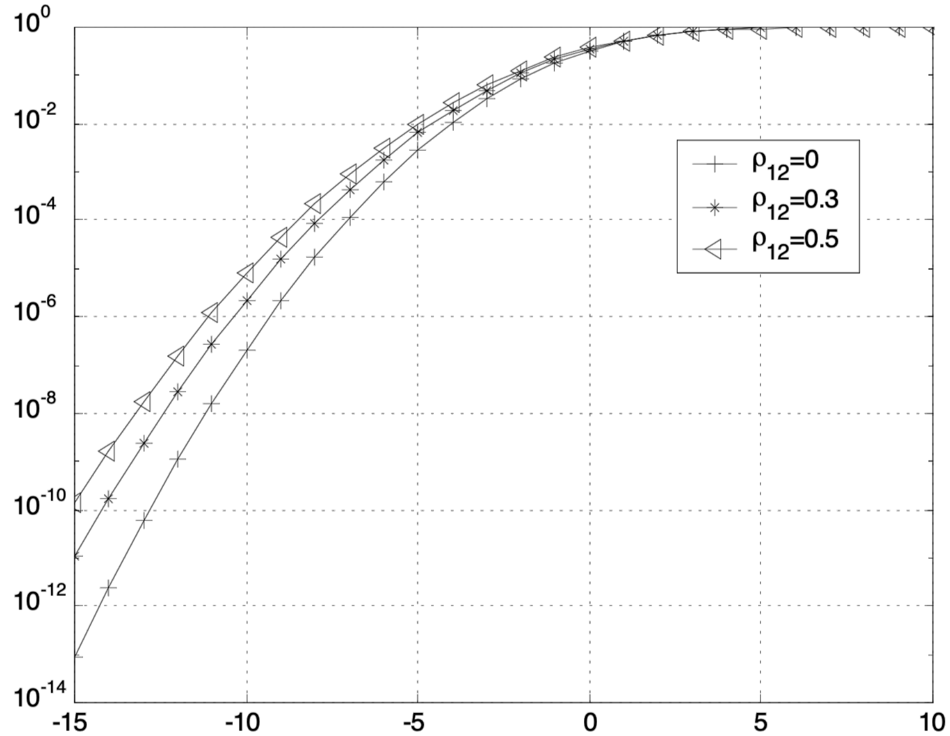
Satellite diversity: performance

- Outage probability – BPSK and MRC (Maximal Ratio Combining) criterion

$$P_{out} = \Pr\left(E\left\{ (R_1^2 S_1^2 + R_2^2 S_2^2)\frac{E_b}{N_0} \right\} < \left(\frac{E_b}{N_0}\right)_{target} \right)$$



$\theta_1=\theta_2=20^o$, $\mu_1=\mu_2$=-4.5 dB, $\sigma_1=\sigma_2$=4 dB



θ_1 =20 ^{o}, θ_2 =40 ^{o}, μ_1=-4.5 dB, μ_2=-1 dB, σ_1=4 dB, σ_2=2 dB

Satellite diversity combining schemes

- Selection Combining

$$U_o = \sum_{k=1}^{S} c_k u_k$$

S = number of satellites
U_o = output signal
u_k = k-th contributor
c_k all equal to zero but that corresponding to the selected path which is equal to one

- Equal Gain Combining

$$U_0 = \frac{1}{S} \sum_{k=1}^{S} u_k$$

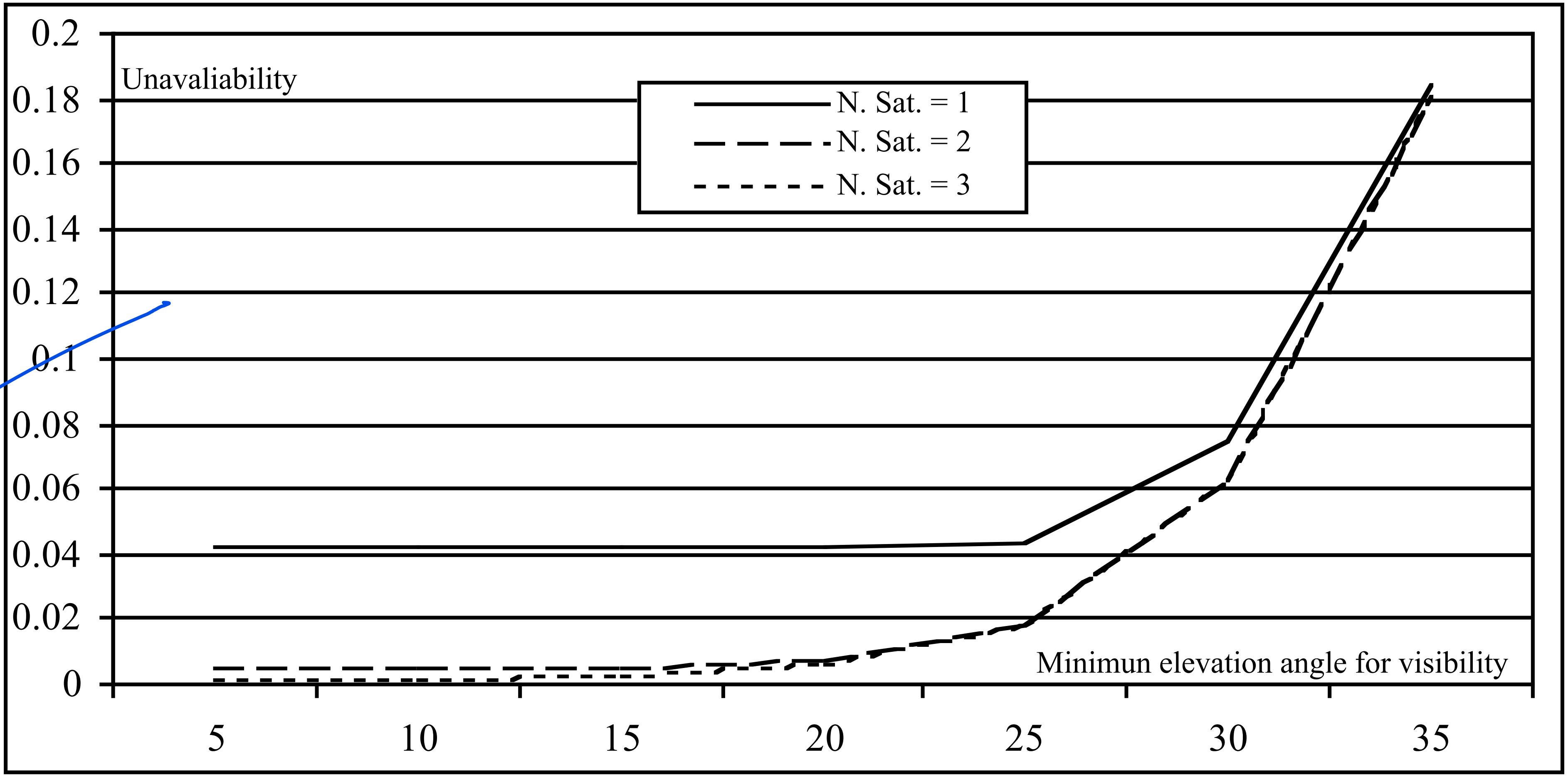
- Maximal Ratio Combining

$$SNR = \frac{\left| \sum_{k=1}^{S} c_k u_k \right|^2}{\sum_{k=1}^{S} |c_k|^2 E\{n_k^2\}}$$

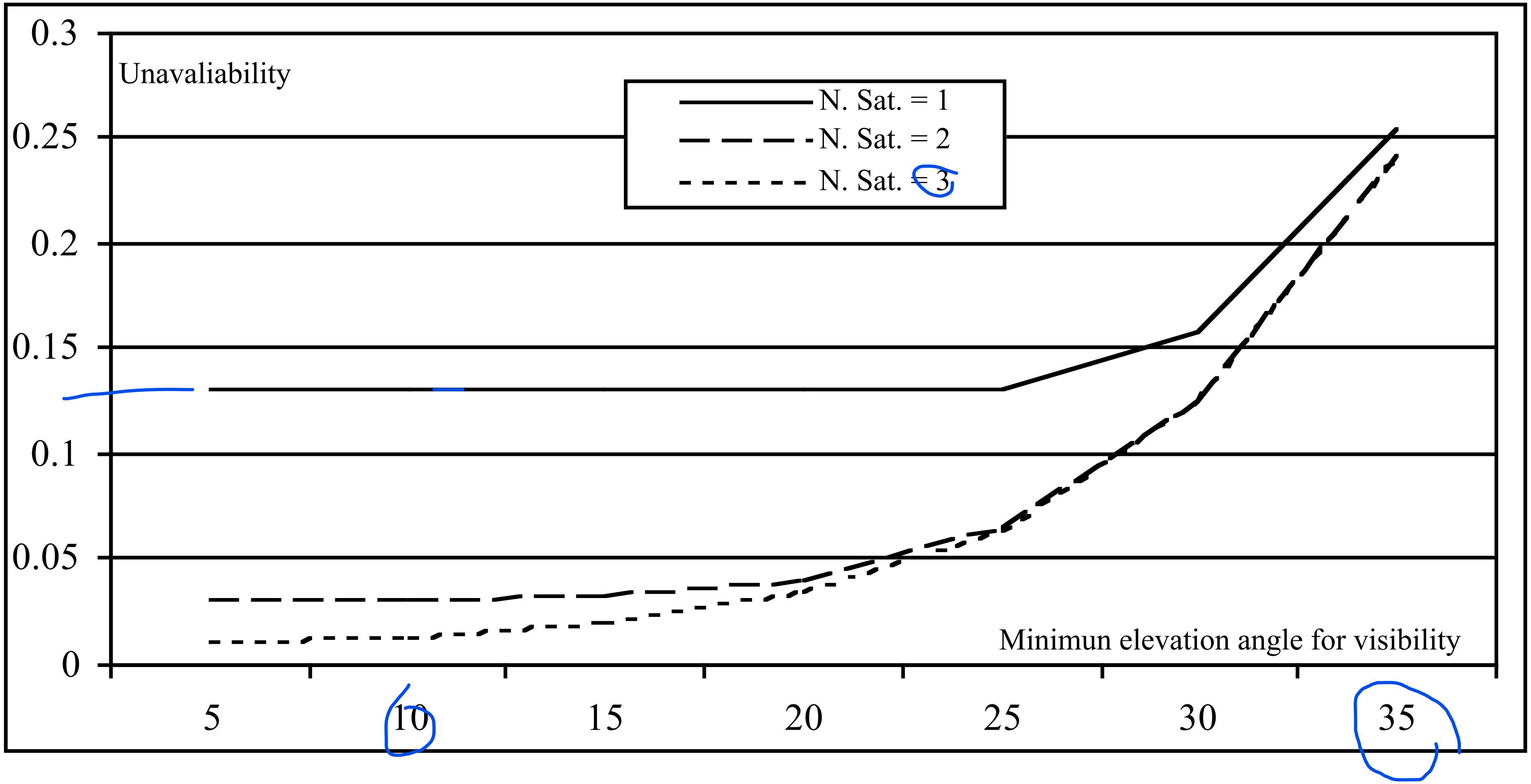
c_k = complex conjugate of the impulse response coefficients of the k^{th} path

n_k is the noise plus interference signal

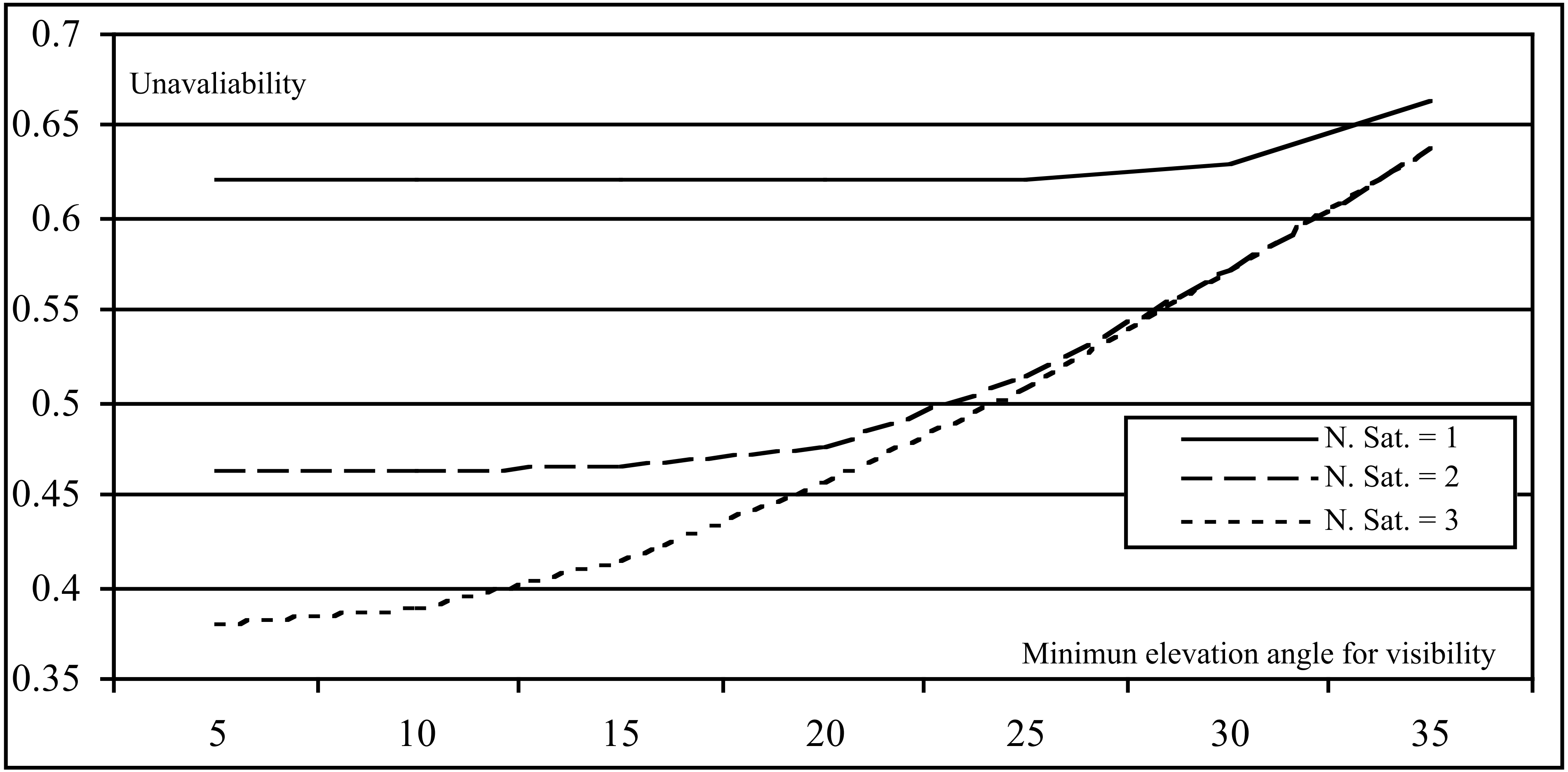
Diversity advantage in rural environment



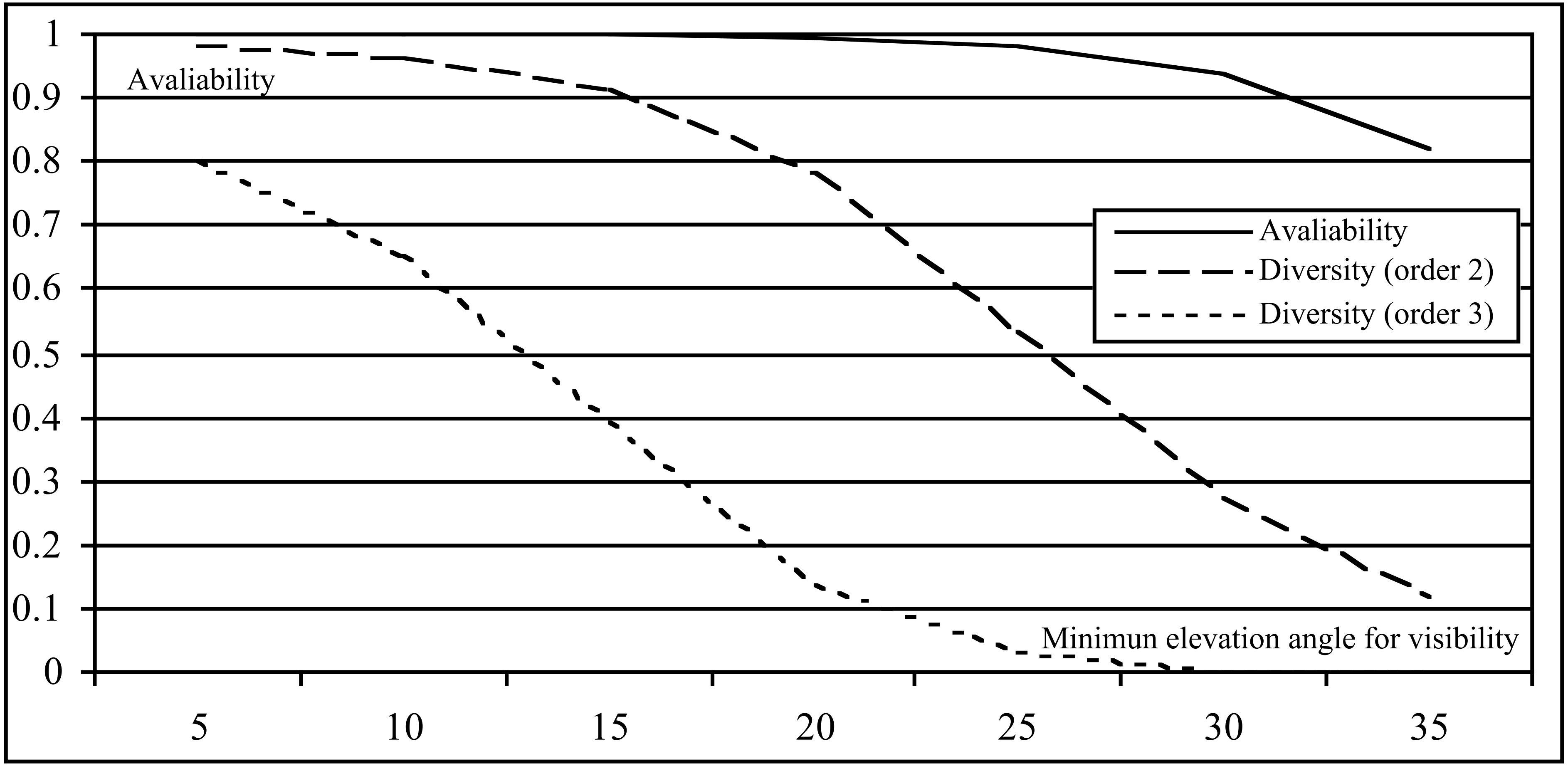
Diversity advantage in suburban environment



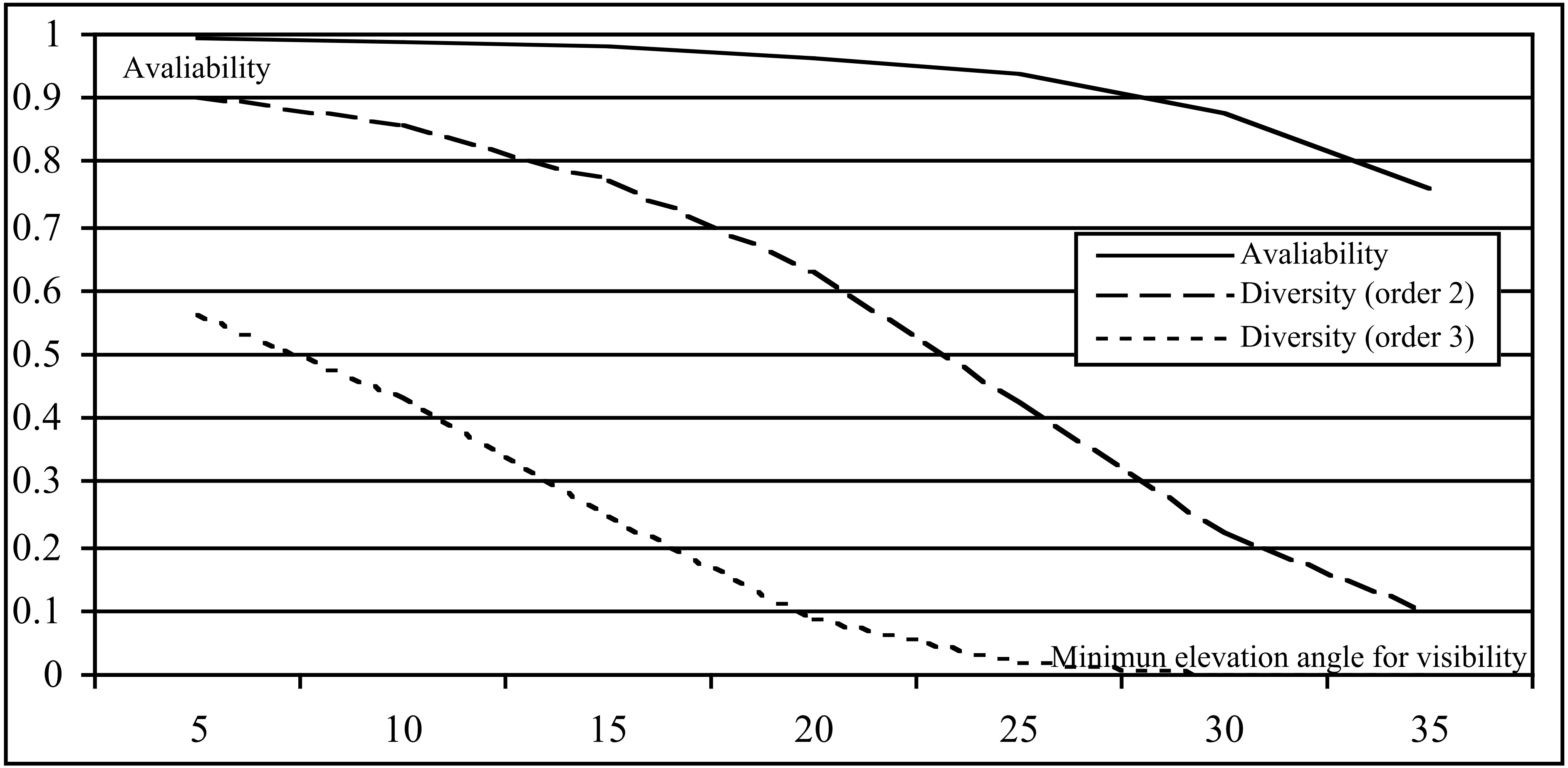
Diversity advantage in urban environment



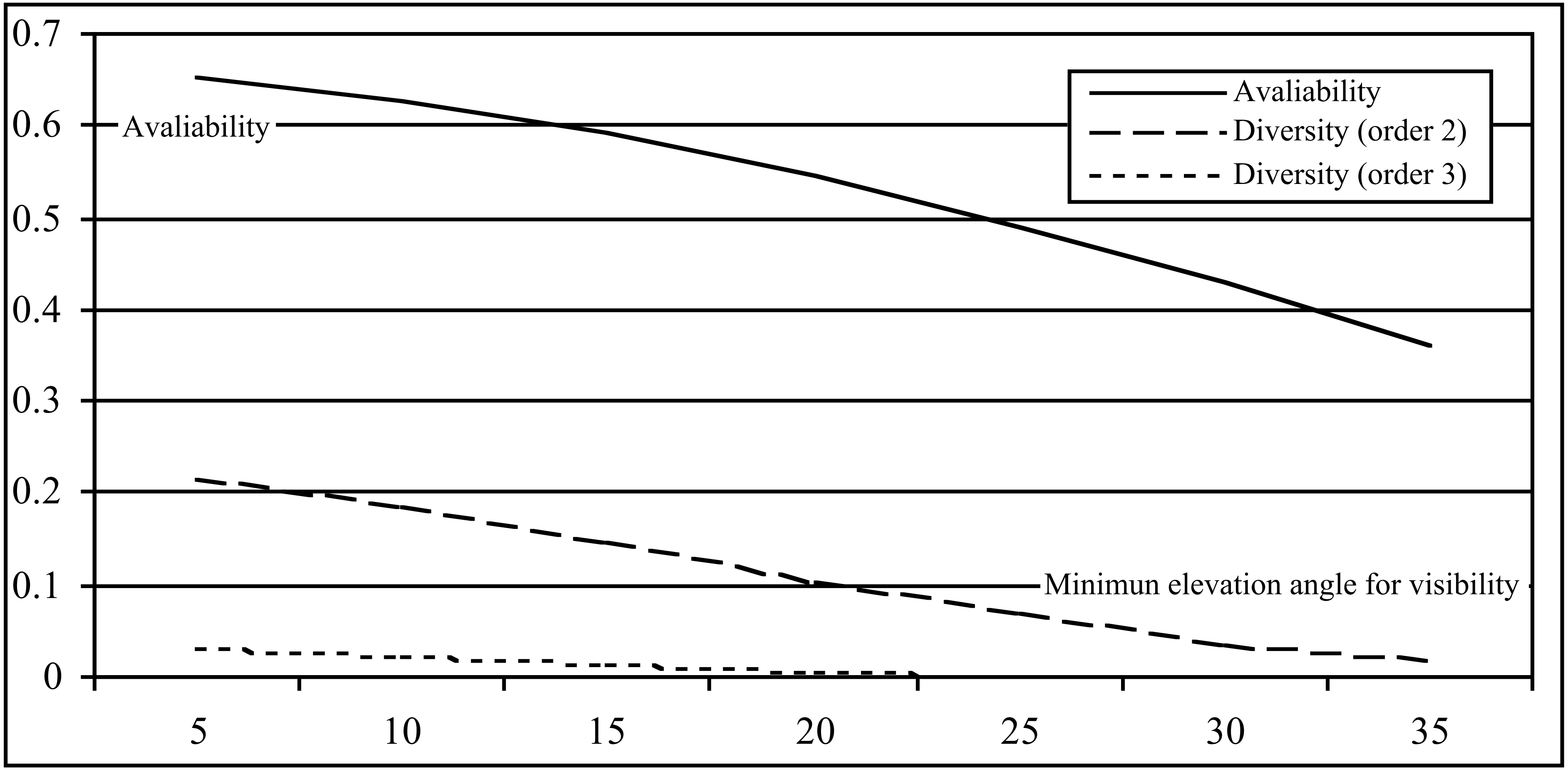
Diversity probability in rural environment



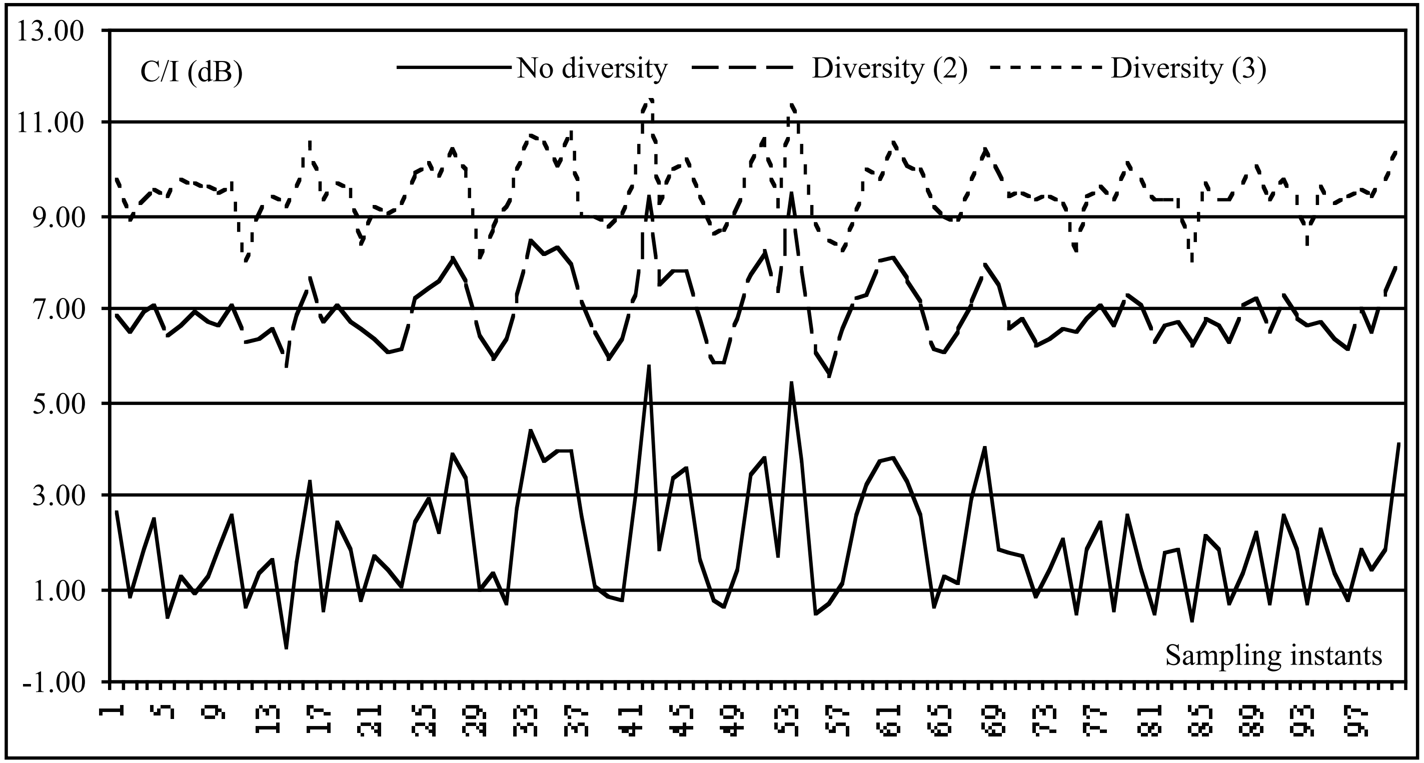
Diversity probability in suburban environment



Diversity probability in urban environment



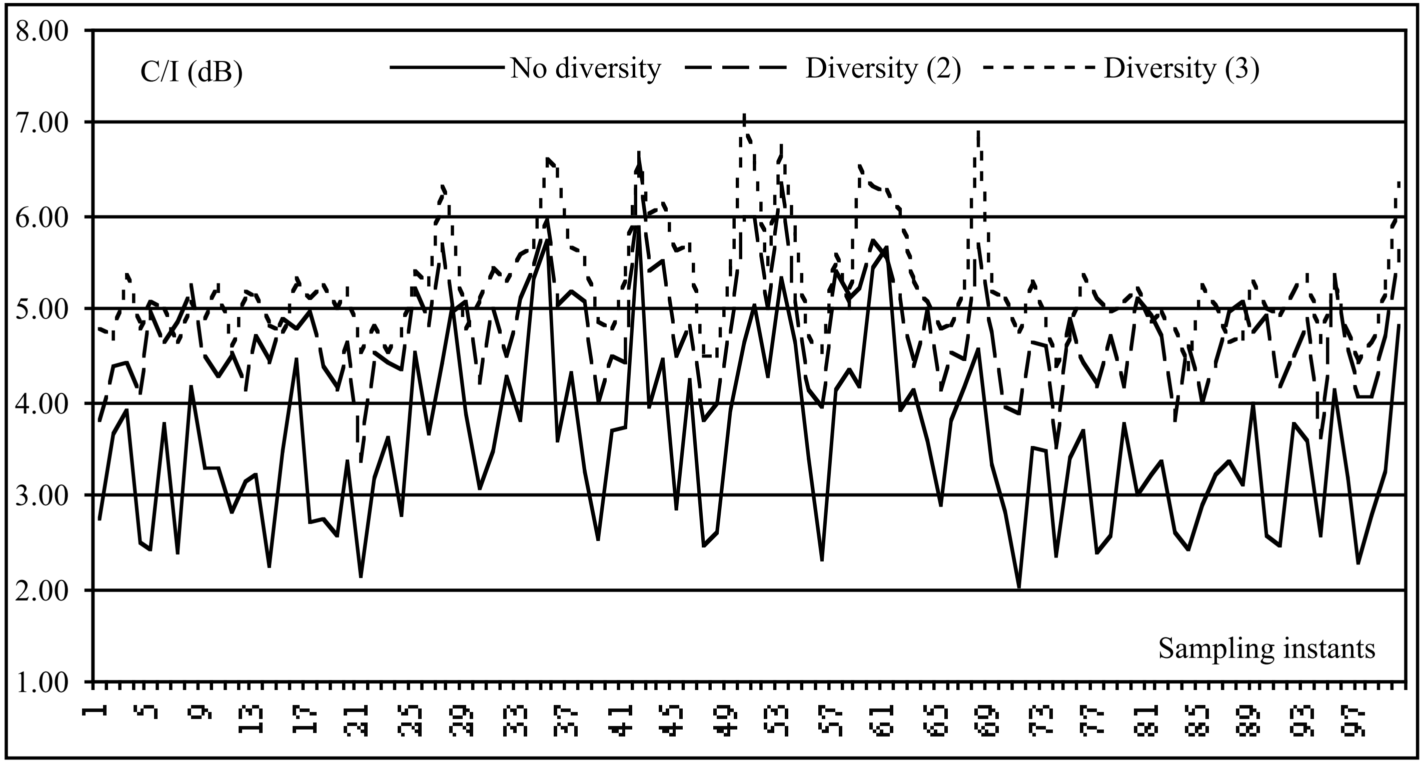
Up link C/I time behavior



	C/I up link (dB)		
	No diversity	Diversity 2	Diversity 3
minimum	-0.3	5.57	8.04
average	1.98	6.97	9.55

Improvement of the average and minimum values of C/I using diversity

Down link C/I time behavior



	C/I down link (dB)		
	No diversity	Diversity 2	Diversity 3
minimum	2.03	3.36	4.35
average	3.54	4.73	5.26

Improvement of the average and minimum values of C/I using diversity

Wideband models

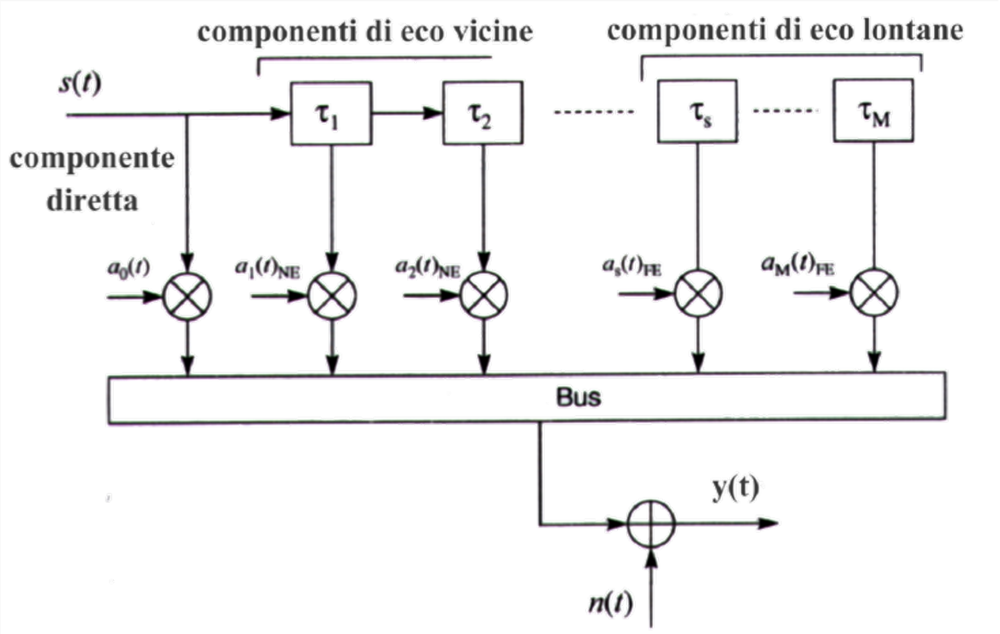
- If signal bandwidth > coherence channel bandwidth $\Rightarrow$ channel effects are frequency selective
- Limited number of models available in literature because the delay spread for satellite systems providing narrow band channels (capacity) is smaller than terrestrial systems
- For systems providing wideband services the identification of suitable models is important.

Jahn-Bischl model

- Hypotheses:
  - satellite channel wide sense stationary
  - signals associated to different delays are independent

$$h(t,\tau) = \sum_{k=0}^{M} a_k(t)\delta(t-\tau_k(t))$$

$$\underbrace{\begin{array}{ll} a_k(t) = r_k(t)e^{j\phi_k(t)} & \text{Total attenuation} \\ \tau_k(t) & \text{Total delay} \end{array}}_{\text{k-th component}}$$



Jahn-Bischl model (2)

- Signal composed of 3 components:
  - Direct path ($\tau_0(t)=0$)
  - Far echo M_{FE}
  - Near echo M_{NE}

$$y(t) = a_0(t)s(t) + \sum_{k=0}^{M_{NE}} a_k(t)_{NE} s(t - \hat{o}_k(t)^{NE}) + \sum_{k=0}^{M_{FE}} a_k(t)_{FE} s(t - \hat{o}_k(t)^{FE}) + n(t)$$

- Each component can be separately characterized as narrow band models
- The number of Far Echoes and Near Echoes are Poisson random variables with average λ_{FE} and λ_{NE}
- Total envelope:
  - Direct component $\Rightarrow$ Lutz model
  - Far Echo $\Rightarrow$ Rayleigh
  - Near Echo $\Rightarrow$ exponential