

# Propagation Channel Models

<b><i>Application</i></b>	Application
<b><i>Presentation</i></b>	
<b><i>Session</i></b>	
<b><i>Transport</i></b>	Transport
<b><i>Network</i></b>	Internet
<b><i>Data Link</i></b>	Network Interface
<b><i>Physical Layer</i></b>	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)

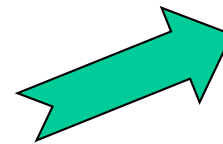
# Propagation impairments

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

ATTENUATION	■	■		■		■		■	
DISTORTION					■		■		
DEPOLARIZATION				■					
BANDWIDTH LIMITATION					■		■	■	
ANGLE OF ARRIVAL			■					■	
ANTENNA TRACKING								■	
ADAPTIVITY	■					■			■
TIME DISPERSION				■	■			■	
FREQUENCY DISPERSION									■
INTERFERENCE		■		■				■	

Effect

Correlation Matrix



Physical phenomenon

ABSORPTION	SCATTERING	REFRACTION	DIFFRACTION	MULTIPATH	SCINTILLATION	SELECTIVE FADING	REFLECTION	MOVING OBJECTS
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# 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%).

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

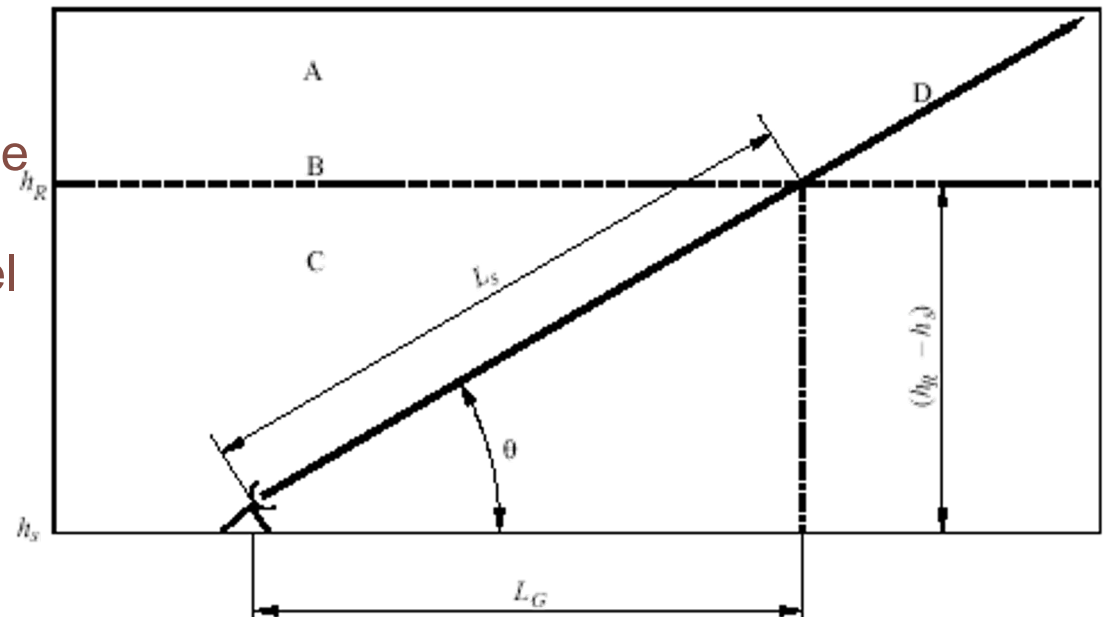
# Calculation of long-term rain attenuation statistics from point rainfall rate (Rec. ITU-R P.618-7)

- 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)
- $\theta$ : elevation angle (degrees)
- $\phi$ : 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  $\theta \geq 5^\circ$  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  $\theta < 5^\circ$  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,  $\gamma_R$ , 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:

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

$$k = [k_H + k_V + (k_H - k_V) \cos^2 \theta \cos 2\tau] / 2; \quad k_H, k_V, \alpha_H, \alpha_V \text{ given in tables}$$

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

$\theta$  elevation angle;  $\tau$  polarization tilt angle relative to the horizontal ( $\tau = 45^\circ$  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,  $v_{0.01}$ , 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  $\zeta > \theta$   $L_R = \frac{L_G r_{0.01}}{\cos \theta}$  km else  $L_R = \frac{(h_R - h_S)}{\sin \theta}$  km

If  $|\phi| < 36^\circ$  then  $\chi = [36 - |\phi|]^\circ$  else  $\chi = 0^\circ$

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

- **Step 8:** The effective path length is:  $L_E = L_R v_{0.01}$  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  $|\phi| \geq 36^\circ$   $\beta = 0$

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

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  $\gamma_C = KM$  (dB/km)
  - $K = 1.2 \cdot 10^{-3} f^{1.9}$  (dB/km)/(g/m<sup>3</sup>),  $f$  in GHz,  $M$  water concentration (g/m<sup>3</sup>)
- 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  $0.5 \text{ g/m}^3$  is assumed);
  - the cloud thickens (an average value of  $1 \text{ km}$  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

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

$\gamma_o$  specific attenuations (dB/km) due to dry air

$h_o$  path length

$\gamma_w$  specific attenuations (dB/km) due to water vapour

$h_w$  path length

For an elevation angle  $\varphi$  between  $5^\circ$  and  $90^\circ$ , the path attenuation is obtained using the cosecant law

- For path attenuation based on surface meteorological data

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

- For path attenuation based on integrated water vapour content

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



## 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

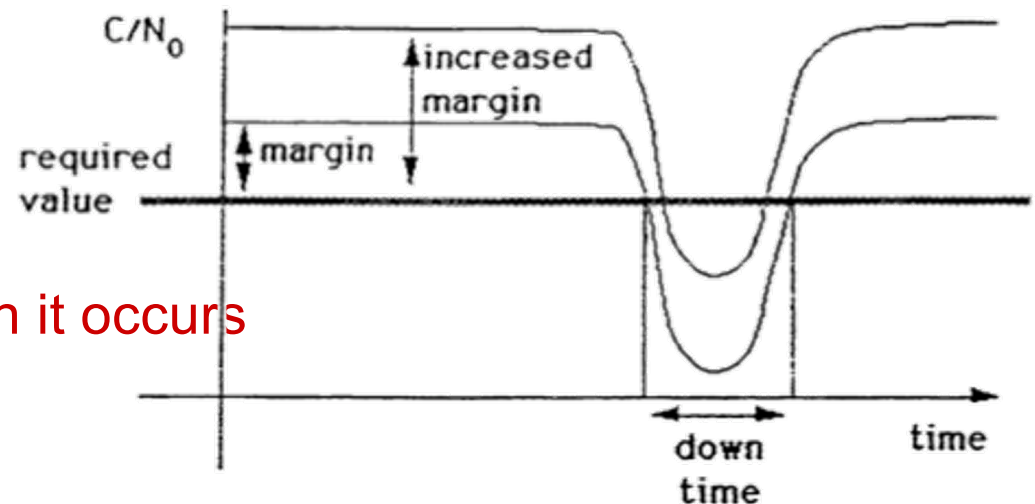
- Specific attenuation (dB/km) inversely proportional to visibility
- Depends on humidity of the particles
- At 14 GHz 0.03 dB/km for dry particles and 0.65 dB/km for particles of 20% humidity

# 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 are present for a percentage of time
- The rest of the time resources utilized to compensate attenuation may be wasted

## Alternative

- Counteract attenuation only when it occurs

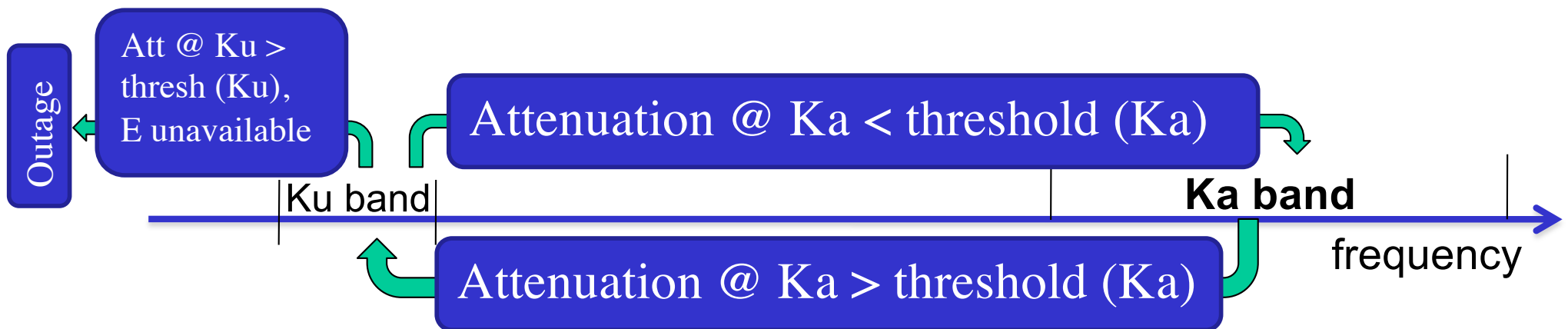


# Rain Fade Countermeasures

- 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

- $P_{\text{out}} = P(A_a > M_a) + P(A_0 > M_0, E \text{ unavailable})$ 
  - $A_a$  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)

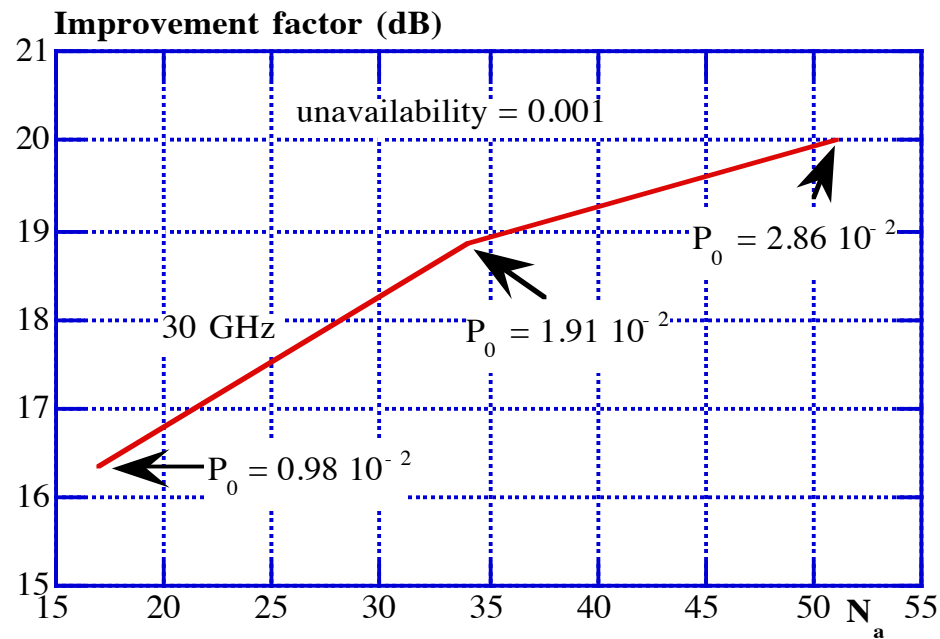
$$P_{ra} = \binom{N_s - 1}{k} (P_0)^k (1 - P_0)^{N_s - 1 - k}$$

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

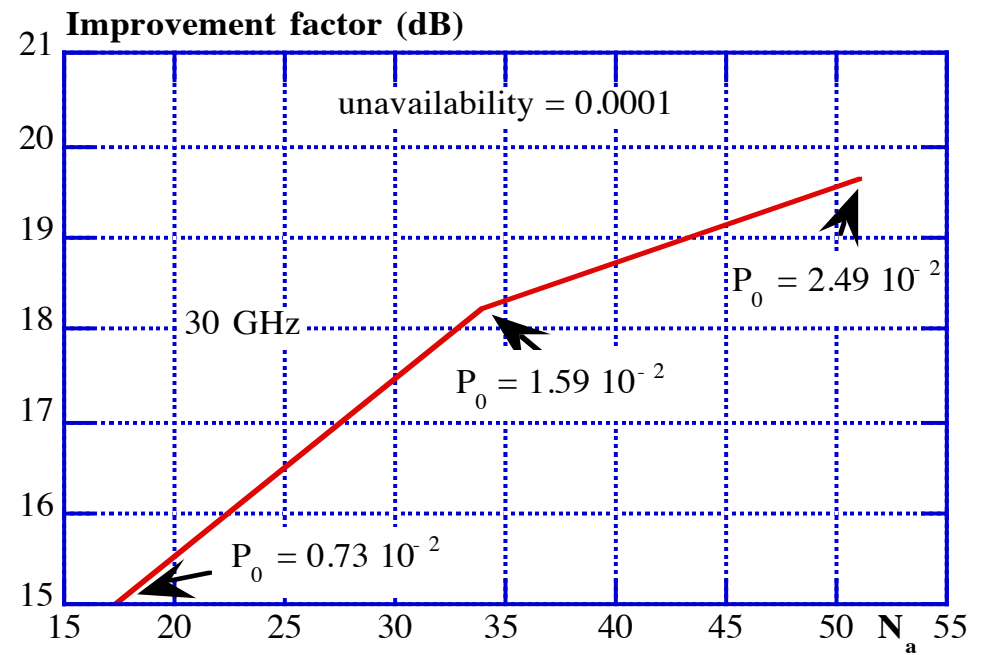
$$P_{out} = P_a + P_0 \sum_{k=N_a}^{N_s-1} \binom{N_s - 1}{k} \left( \frac{P_0}{\delta_T} \right)^k \left( 1 - \frac{P_0}{\delta_T} \right)^{N_s - 1 - k} \frac{k + 1 - N_a}{k + 1}$$

- $P_{ra}$  = 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 variability can occur as a function of weather condition
- In bad weather condition the data rate is decreased implying to relax the needed bandwidth with consequent gain in the link budget

# Adaptive coding rate

- 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.
- 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

- These techniques 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

- 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

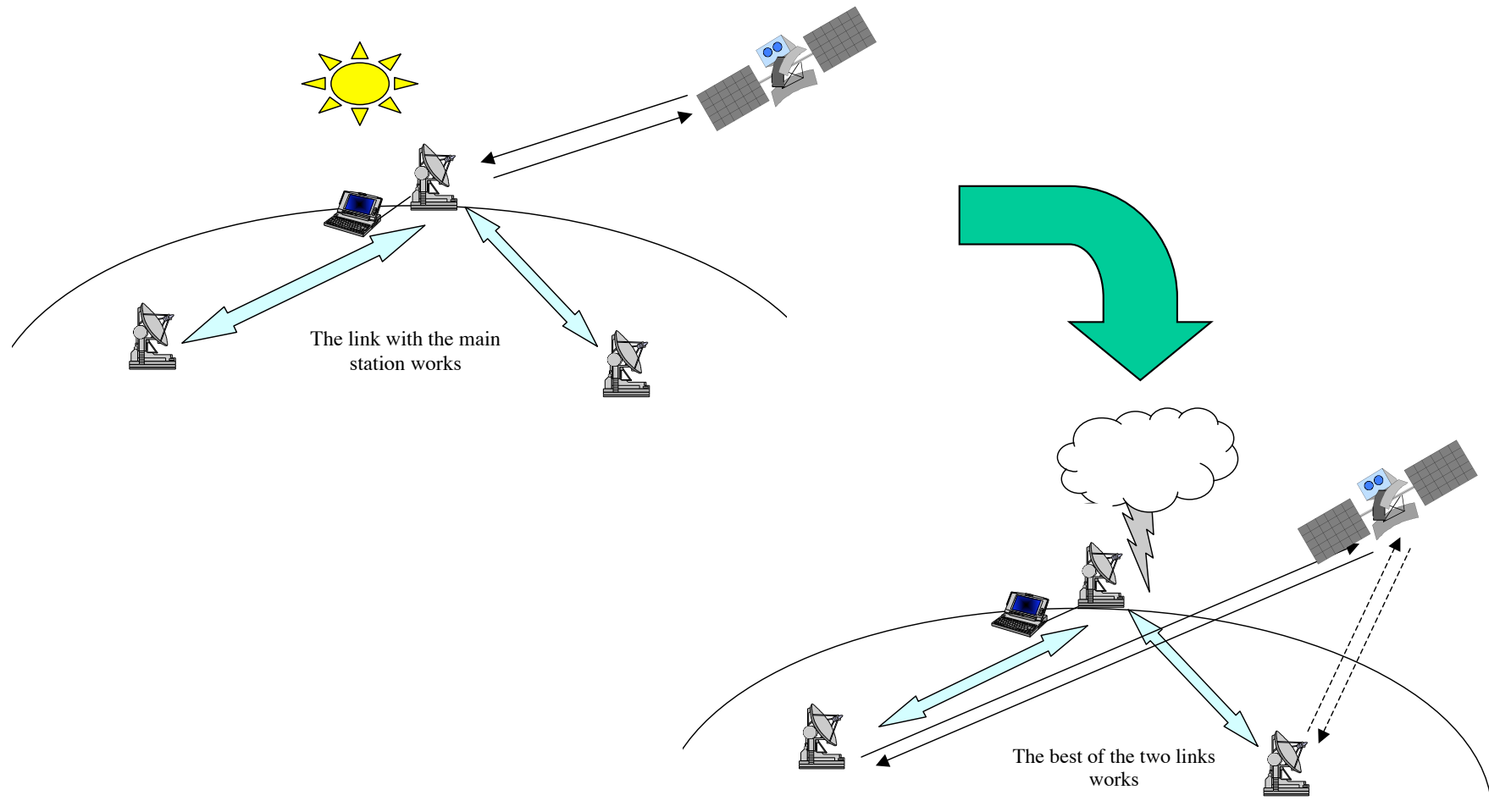
- Fade spreading operates reducing data rate to keep constant  $E_b/N_0$  ratio.
- Both energy per bit and unit power are increased without reducing the bandwidth, avoiding problems of interference.
- The efficiency is not very high considering the effects of modem performance at low  $E_b/N_0$
- It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

## 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%.

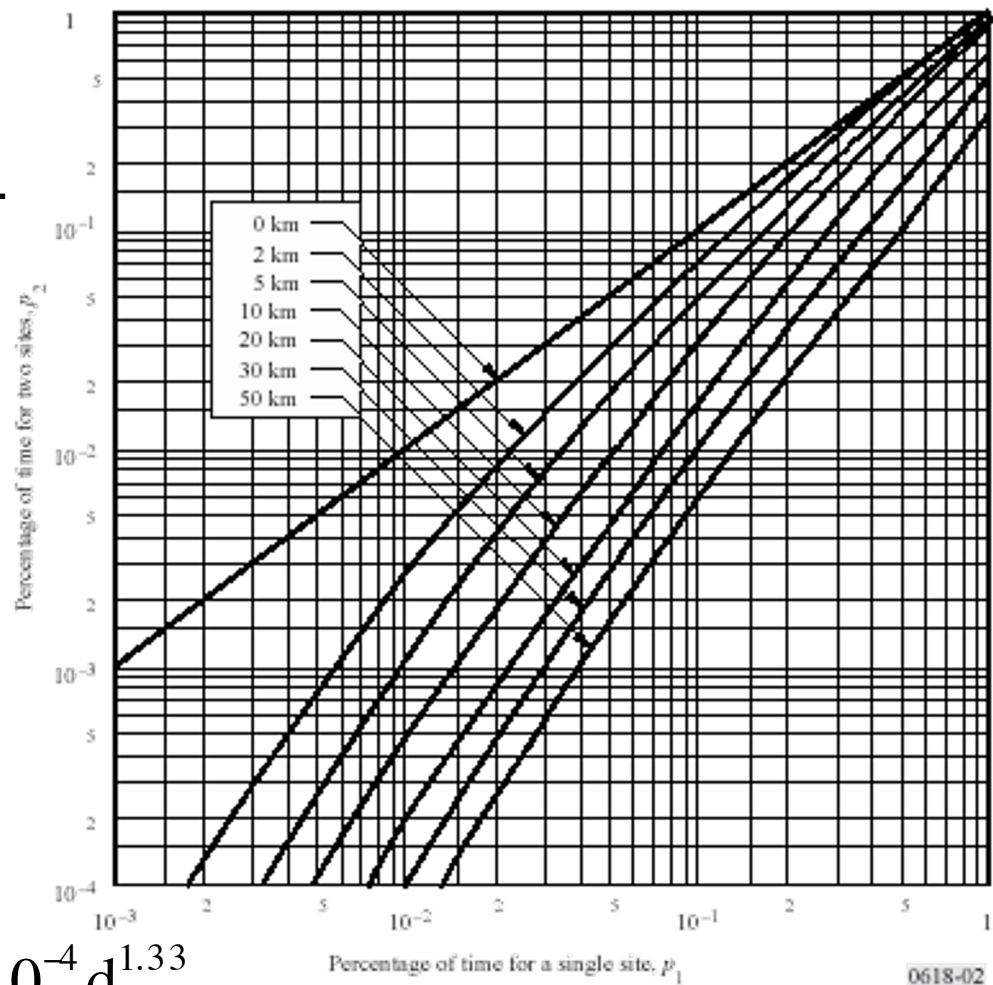
## Diversity improvement factor

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,  $\beta$  is a parameter depending on link characteristics. The approximation is acceptable since  $\beta^2$  is generally small.  $\beta^2$  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:

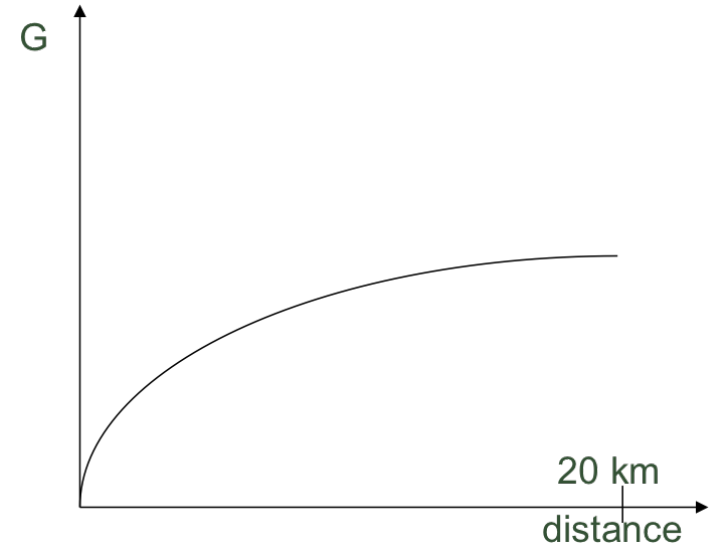
$d$  distance (km) between the two sites

$A$  rain attenuation (dB) for single site

$f$  frequency (GHz)

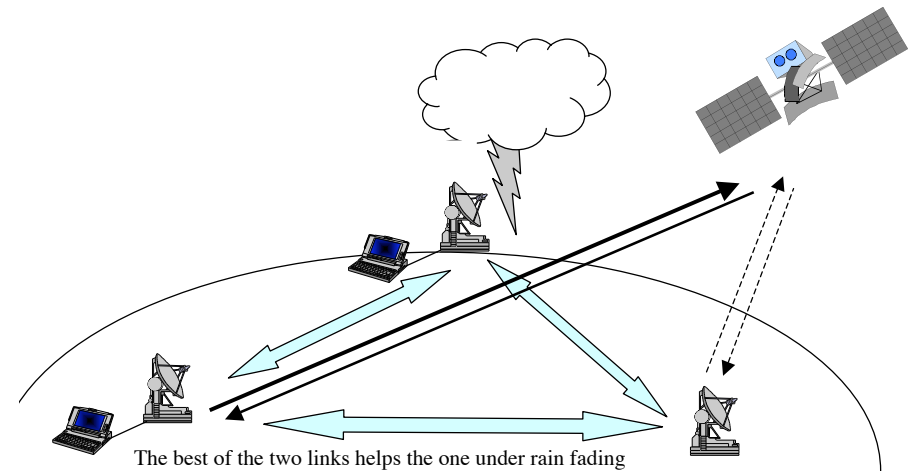
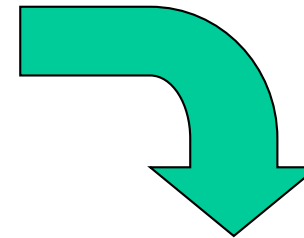
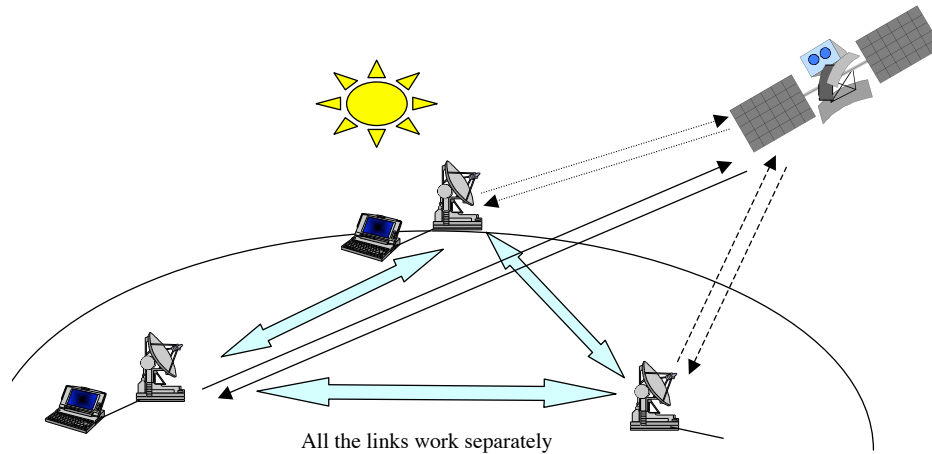
$\theta$  elevation angle ( $^\circ$ )

$\psi$  angle (degrees) made by the azimuth of the propagation path with respect to the baseline between sites, chosen such that  $\psi \leq 90^\circ$ .



1. Spatial separation:  $G_d = a(1 - e^{-bd})$
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:

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

- $\langle \ln A_i \rangle$  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  $\mathbf{r}_i^*$ ;
  - b. the matrix  $r$  of the normalised co-variances  $r_{ij} = \langle \mathbf{r}_i \mathbf{r}_j \rangle$ .
- 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  $\mathbf{a}_i^*$ ;
  - d. the matrix  $a$  of the normalised co-variances  $a_{ij} = \langle \mathbf{a}_i \mathbf{a}_j \rangle$ .
- $\mathbf{r}_i^*$  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  $\mathbf{r}$  and  $\mathbf{a}$  can be expressed by the following functions of the distances  $d_{ij}$  between locations:

$$r_{ij} = \begin{cases} 0.7 \exp(-d_{ij}/60) + 0.3 \exp\left[-(d_{ij}/700)^2\right] & i \neq j \\ 1 & i = j \end{cases} \quad a_{ij} = \begin{cases} 0.94 \exp(-d_{ij}/30) + 0.06 \exp\left[-(d_{ij}/500)^2\right] & i \neq j \\ 1 & i = j \end{cases}$$

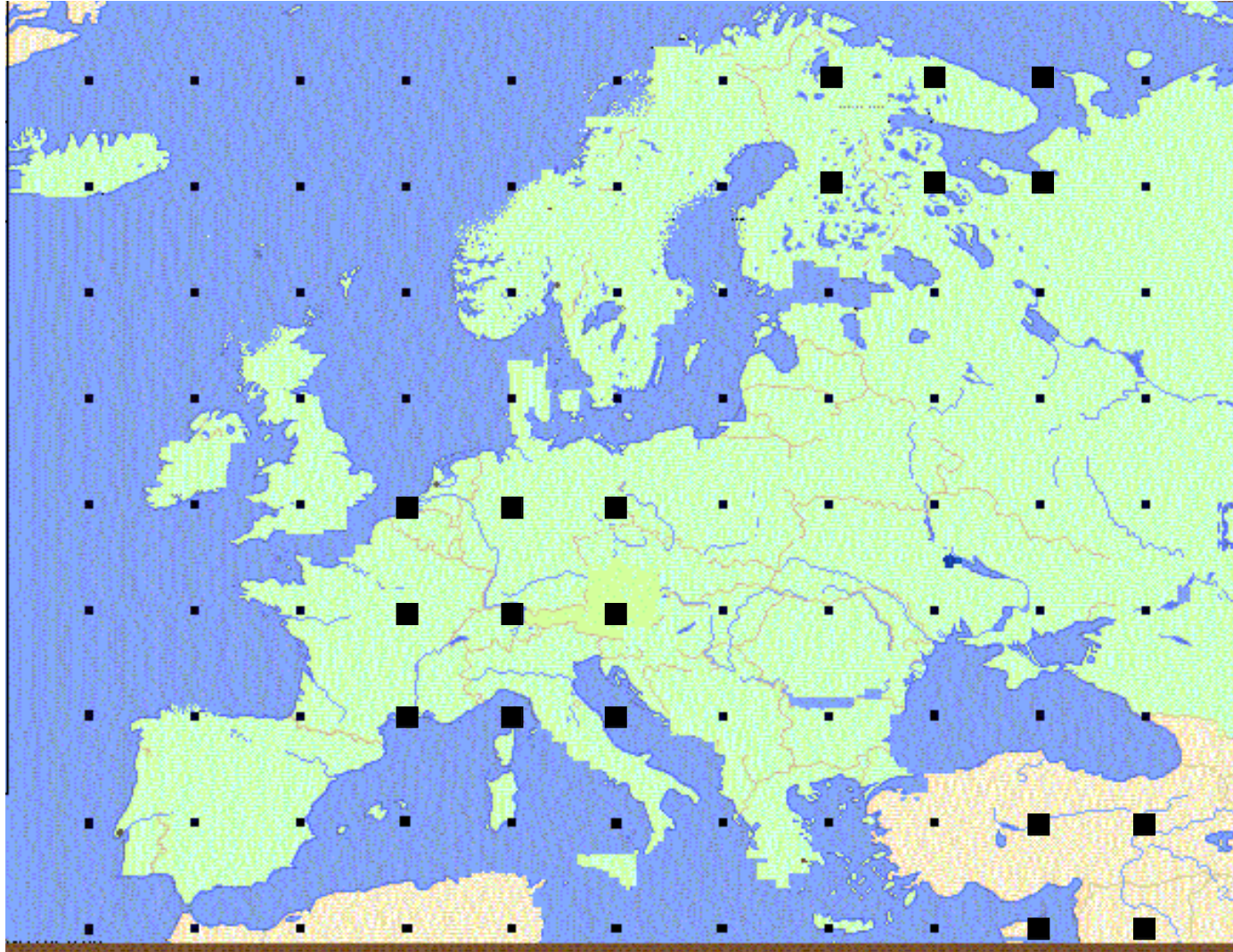
- The vector of the thresholds  $\mathbf{a}_i^*$  is a design-oriented input depending on the margins (possibly different) allowed for the individual earth terminal.
- The multivariate probability density functions:

- $$p(r_1, r_2, \dots, r_N) = k_r \exp\left(-\frac{1}{2} \sum_{i=1}^N \sum_{j=1}^N c_{r,ij} r_i r_j\right), \quad p(a_1, a_2, \dots, a_N) = k_a \exp\left(-\frac{1}{2} \sum_{i=1}^N \sum_{j=1}^N c_{a,ij} a_i a_j\right)$$
- where  $c_{r,ij}$  and  $c_{a,ij}$  are the generic terms of the matrixes  $\mathbf{c}_r$  and  $\mathbf{c}_a$  respectively, that are inverse of  $\mathbf{r}$  and  $\mathbf{a}$ , and:

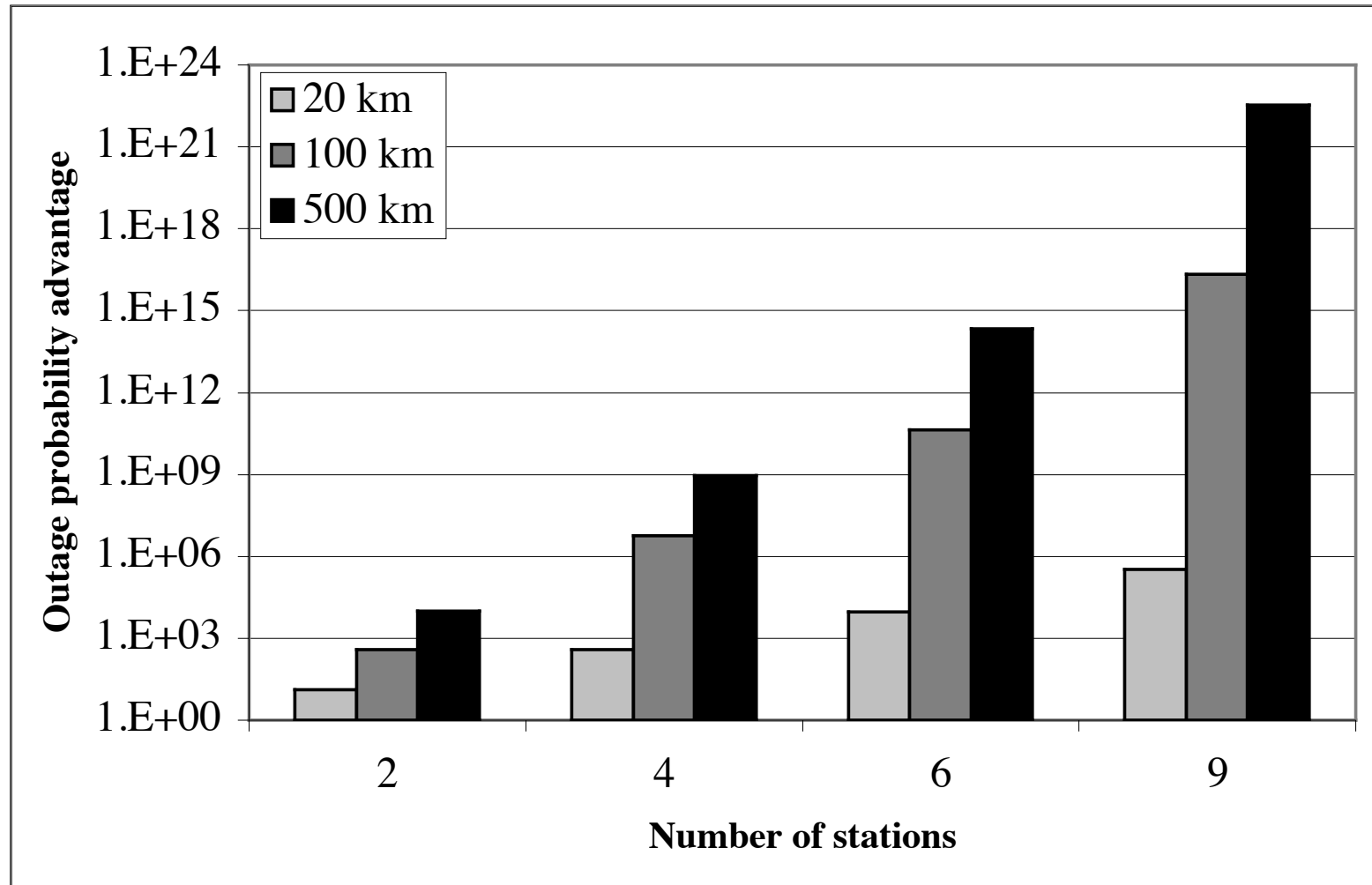
$$k_r = \sqrt{\frac{c_r}{(2\pi)^N}}, \quad k_a = \sqrt{\frac{c_a}{(2\pi)^N}}$$

- in which  $c_a$  and  $c_r$  are the determinants of  $\mathbf{c}_r$  and  $\mathbf{c}_a$ .

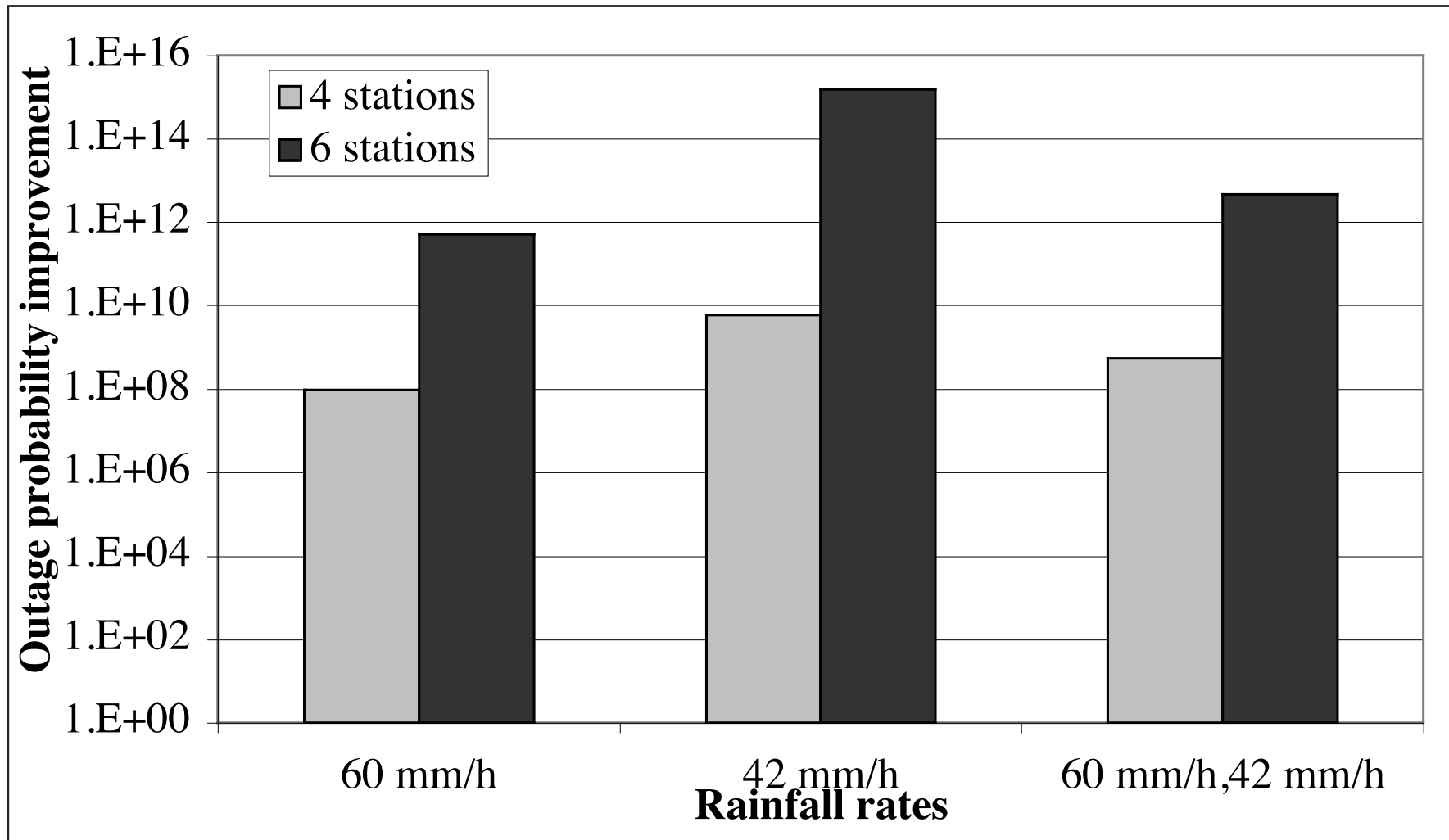
## Selected subset of stations



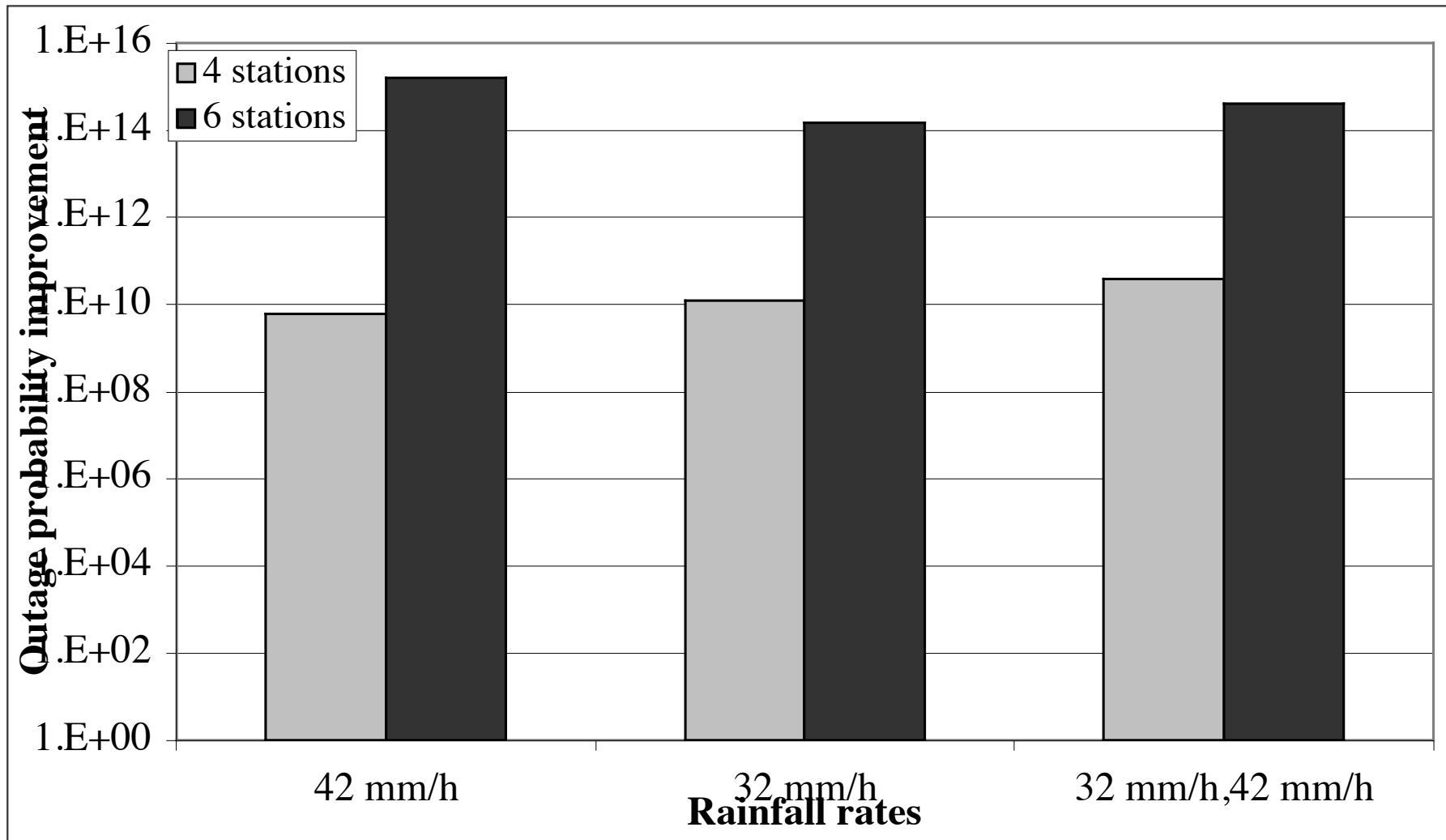
## Site diversity Improvement (1)



## Site diversity Improvement (2)



## Site diversity Improvement (3)



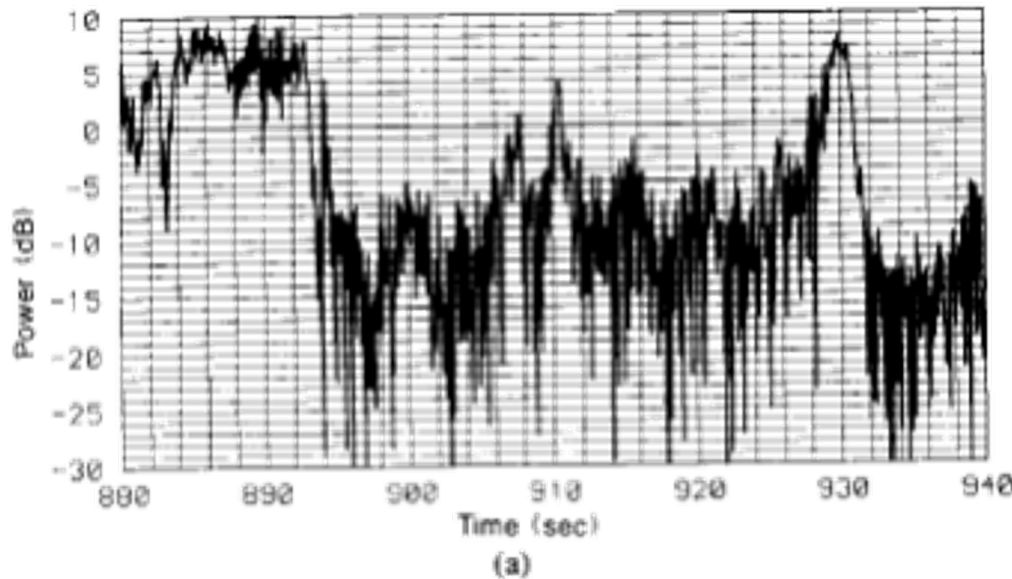


## Orbit (satellite) diversity

- 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 ( $\leq 1.2$ ) if applied at 12 GHz but it can be meaningful if applied at 20 GHz.



# Mobile channel description: experimental data



0 dB: average received power

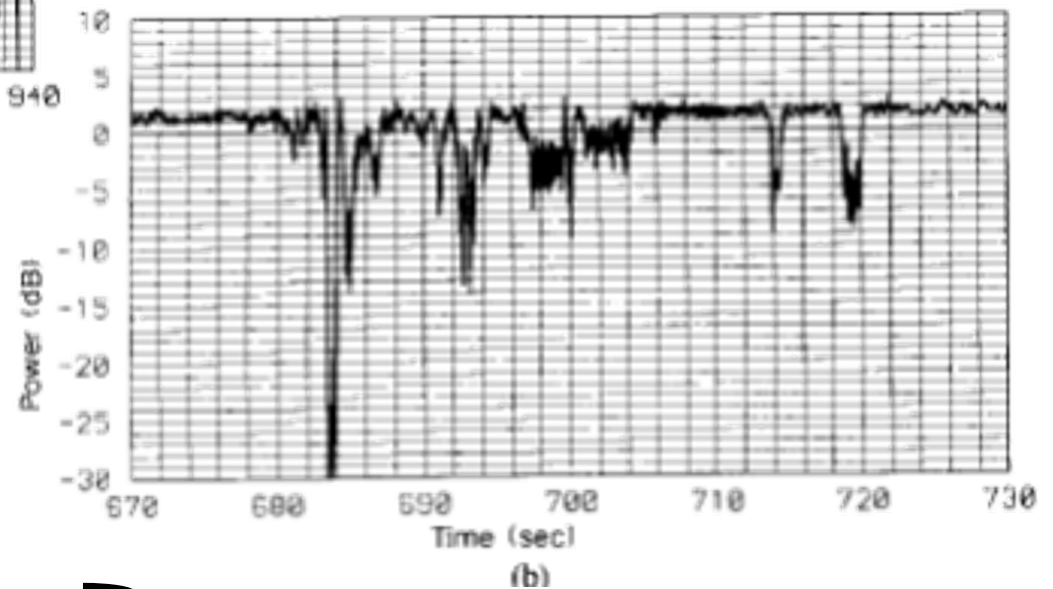
Speed: 10 km/h

Urban environment

0 dB: average received power

Speed : 60 km/h

Highway environment



Environments classified as:

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

Not standard, location dependent

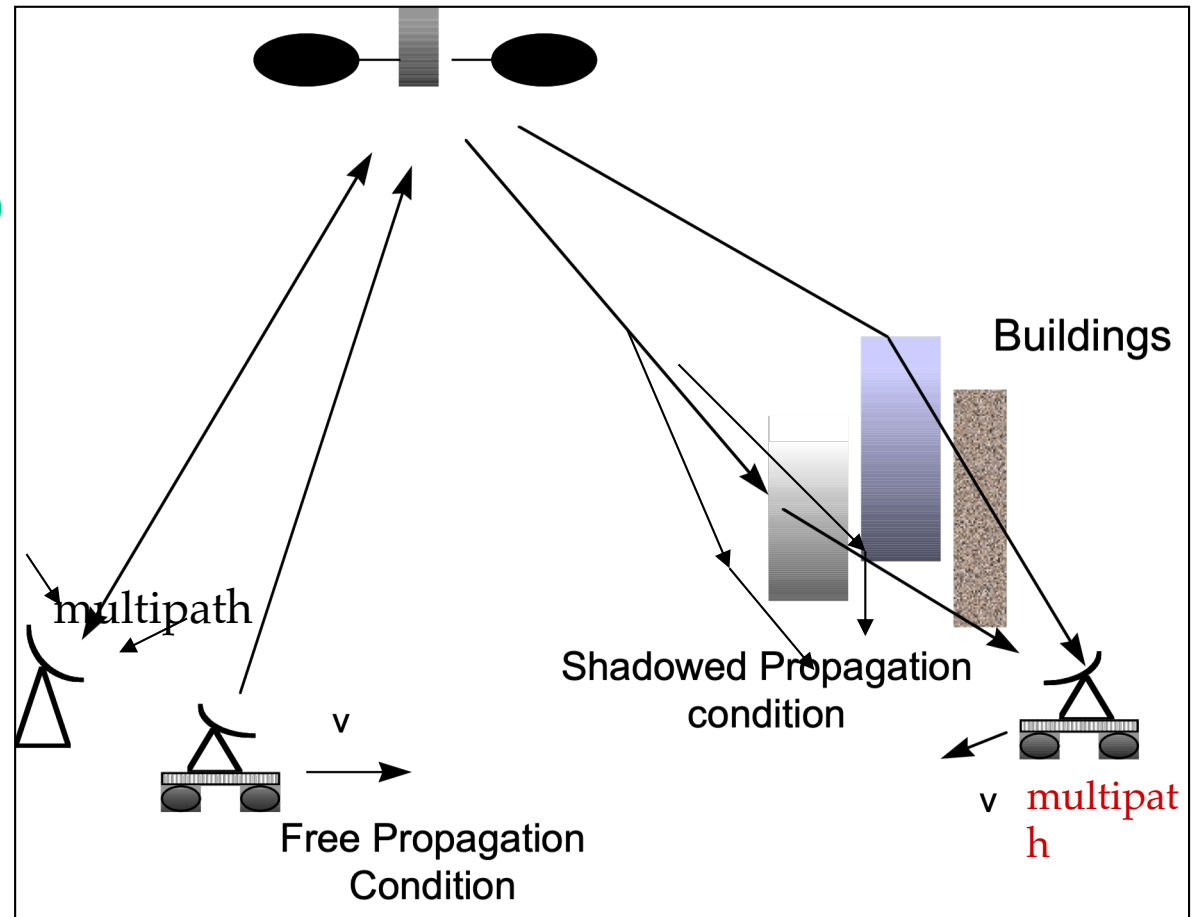
## Problem description: phenomenology

- From measured data, for modeling 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: physical 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

$$H(f; t) = H(f_0; t) = z(t) \quad \text{Attenuation factor}$$

$f_0$ : 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  $\mathbf{z}(t)$
- The process  $\mathbf{z}(t)$  is usually described as overlapping of correlated stochastic processes.
- The process  $\mathbf{z}(t)$  is complex.



## 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 –  $|z|=r=RS$

$$z(t) = S_1 (A + x_1 + j \cdot y_1)$$

$$S_2=1$$

→ **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.

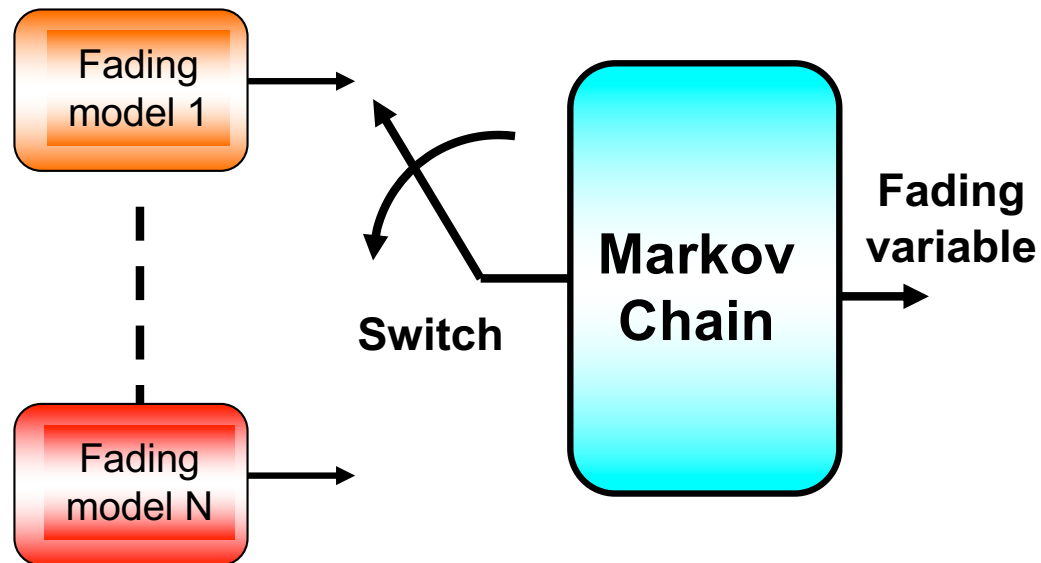
$$z(t) = S_1 A + S_2 (x_2 + j \cdot y_2)$$

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

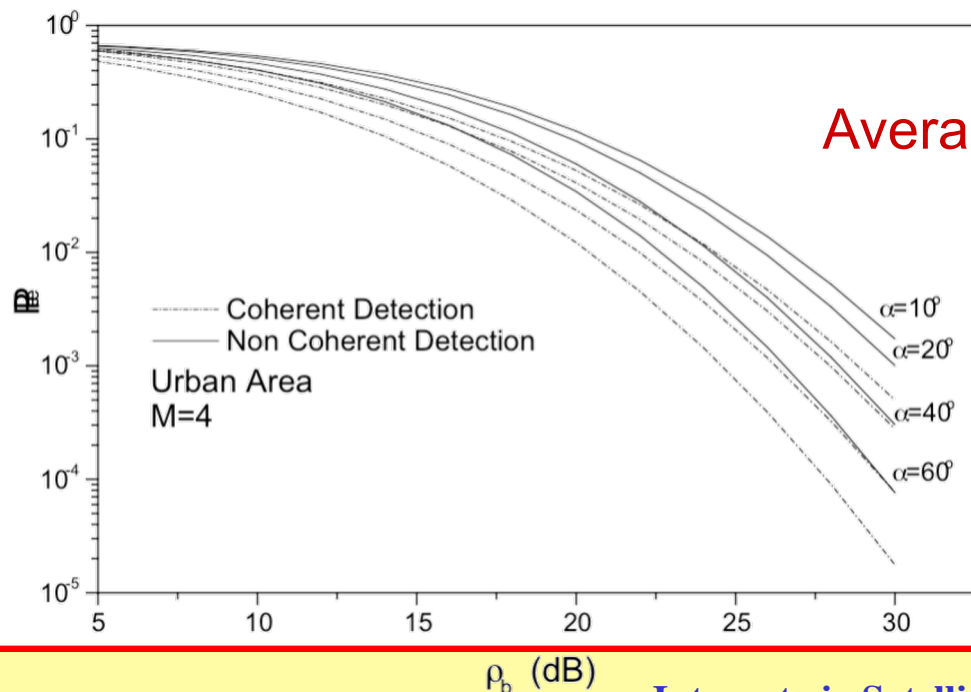
- Average error probability

$$P_e = \int_0^{\infty} P(e|r)p_r(r)dr$$

- Outage probability  $P_{\text{out}} = \text{Prob}\{P_e > P_{e0}\} = \text{Prob}\{\rho_b < \rho_{b0}\}$

$\rho_b$ : Signal/average noise ratio

$\rho_{b0}$ : Signal/reference noise ratio



Average error probability vs elevation angles

RLN channel model

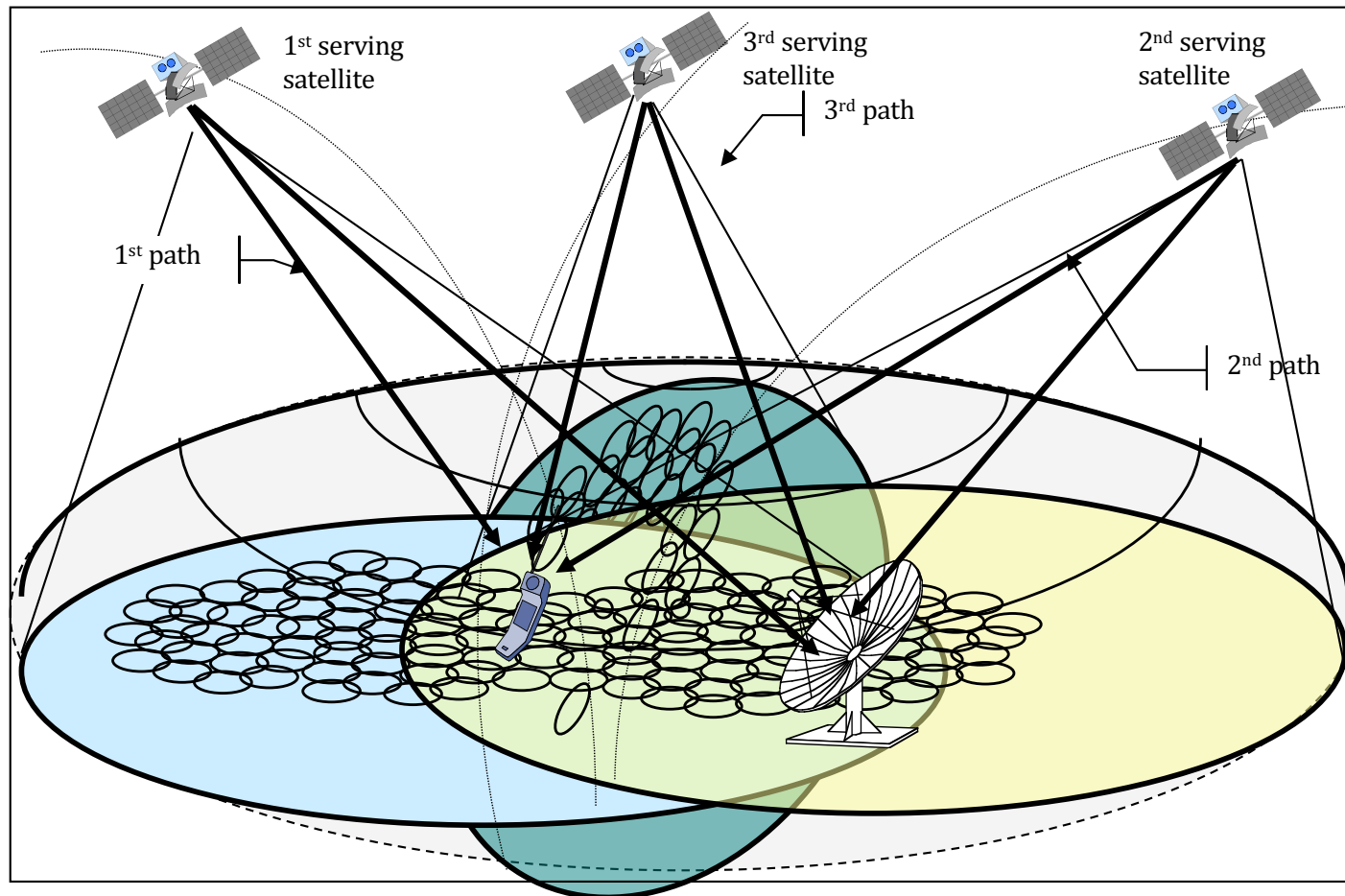
## Satellite (path) diversity: generalities

- 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)



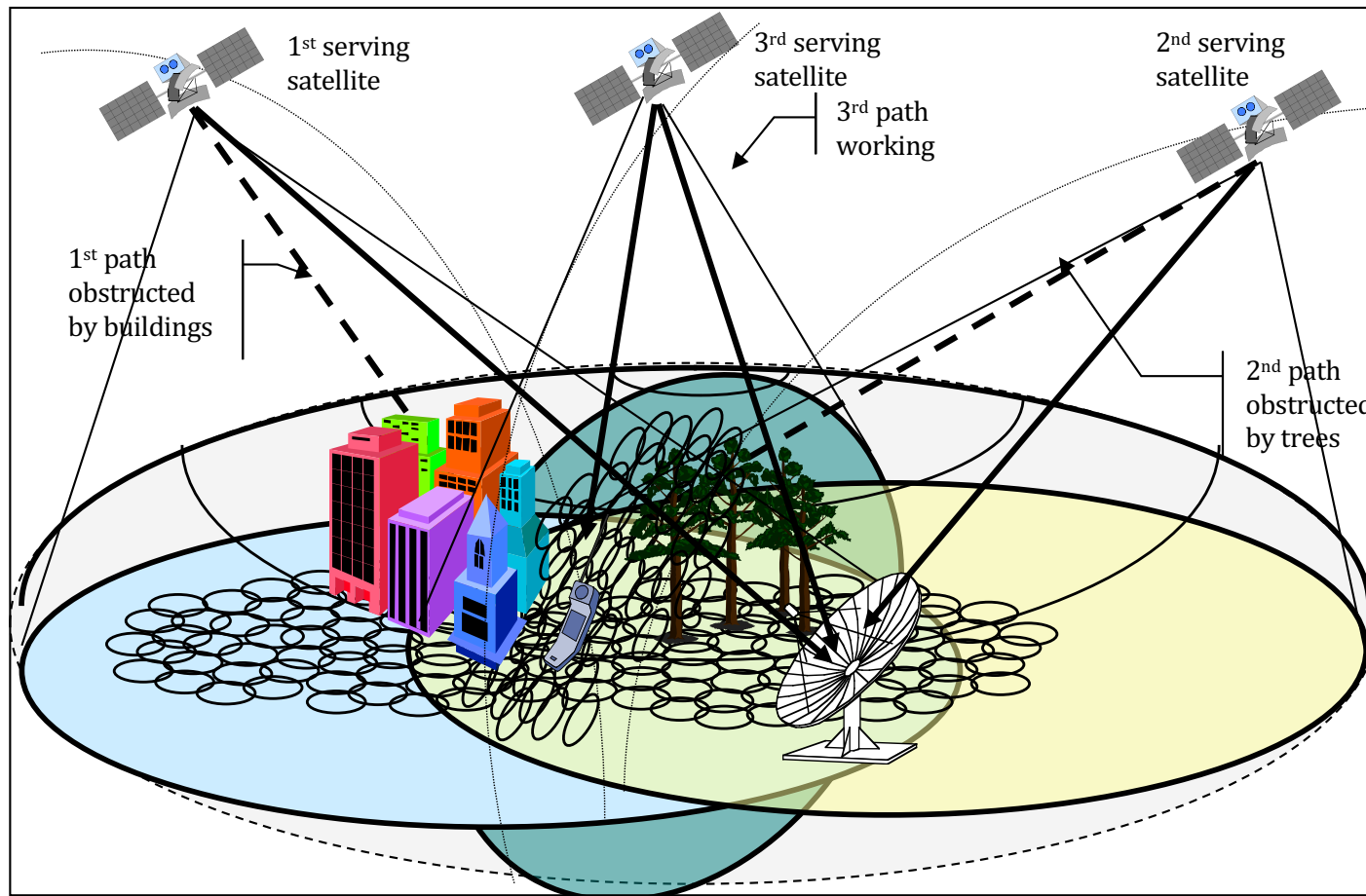
**To evaluate diversity performance a suitable channel model is needed**

# Mobile channel effects countermeasures: Satellite diversity



**Improving C/N**

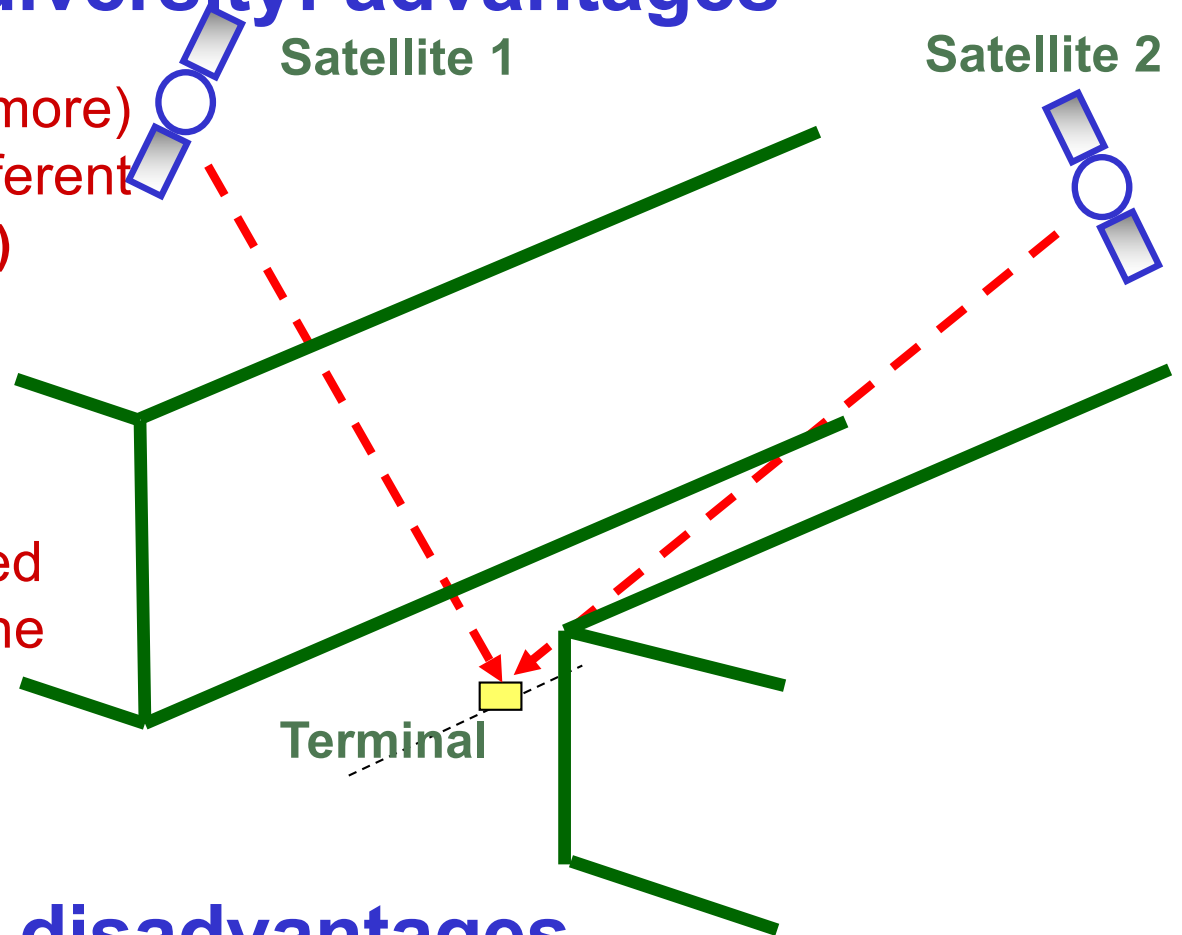
# Mobile channel effects countermeasures: Satellite diversity (2)



**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



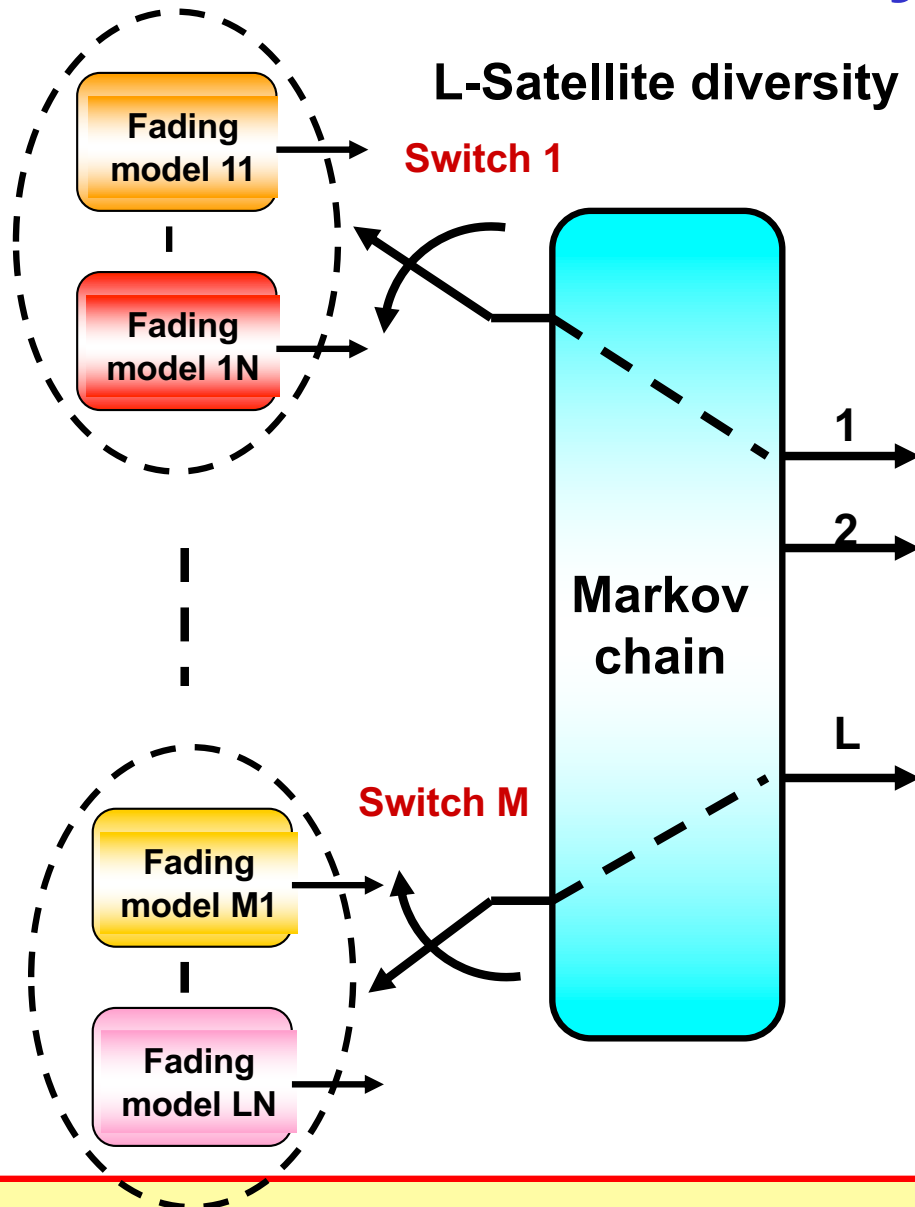
## Satellite diversity: disadvantages

- 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 states

(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

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

*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**

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

$z_i$  is RLN

# Satellite diversity: single state model assumptions

RLN hypothesis:

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

Statistical hypotheses:

- 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 is necessary to determine the shadowing statistics ( $S_1, \dots, S_L$ )

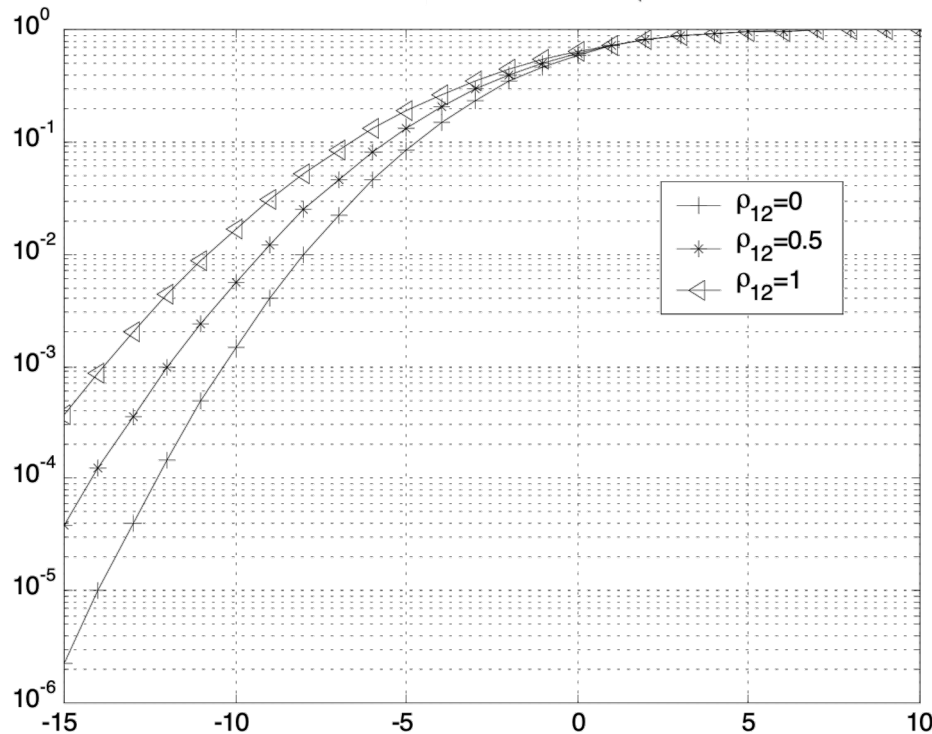


**These have been determined with suitable models**

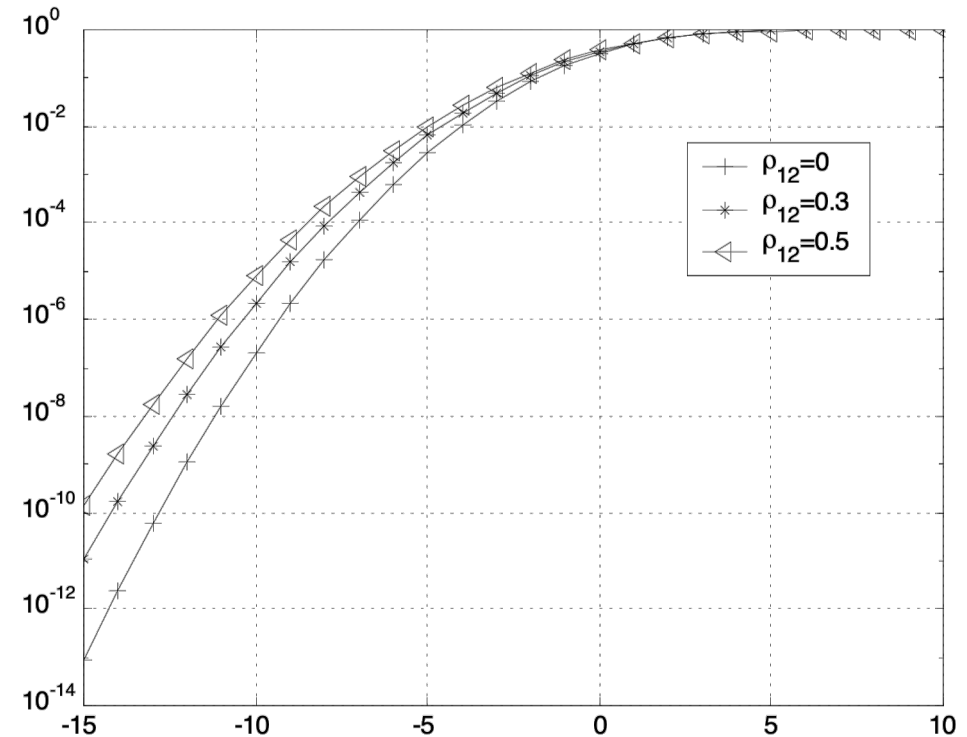
# Satellite diversity: performance

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

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



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



$\theta_1 = 20^\circ$ ,  $\theta_2 = 40^\circ$ ,  $\mu_1 = -4.5$  dB,  $\mu_2 = -1$  dB,  
 $\sigma_1 = 4$  dB,  $\sigma_2 = 2$  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

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

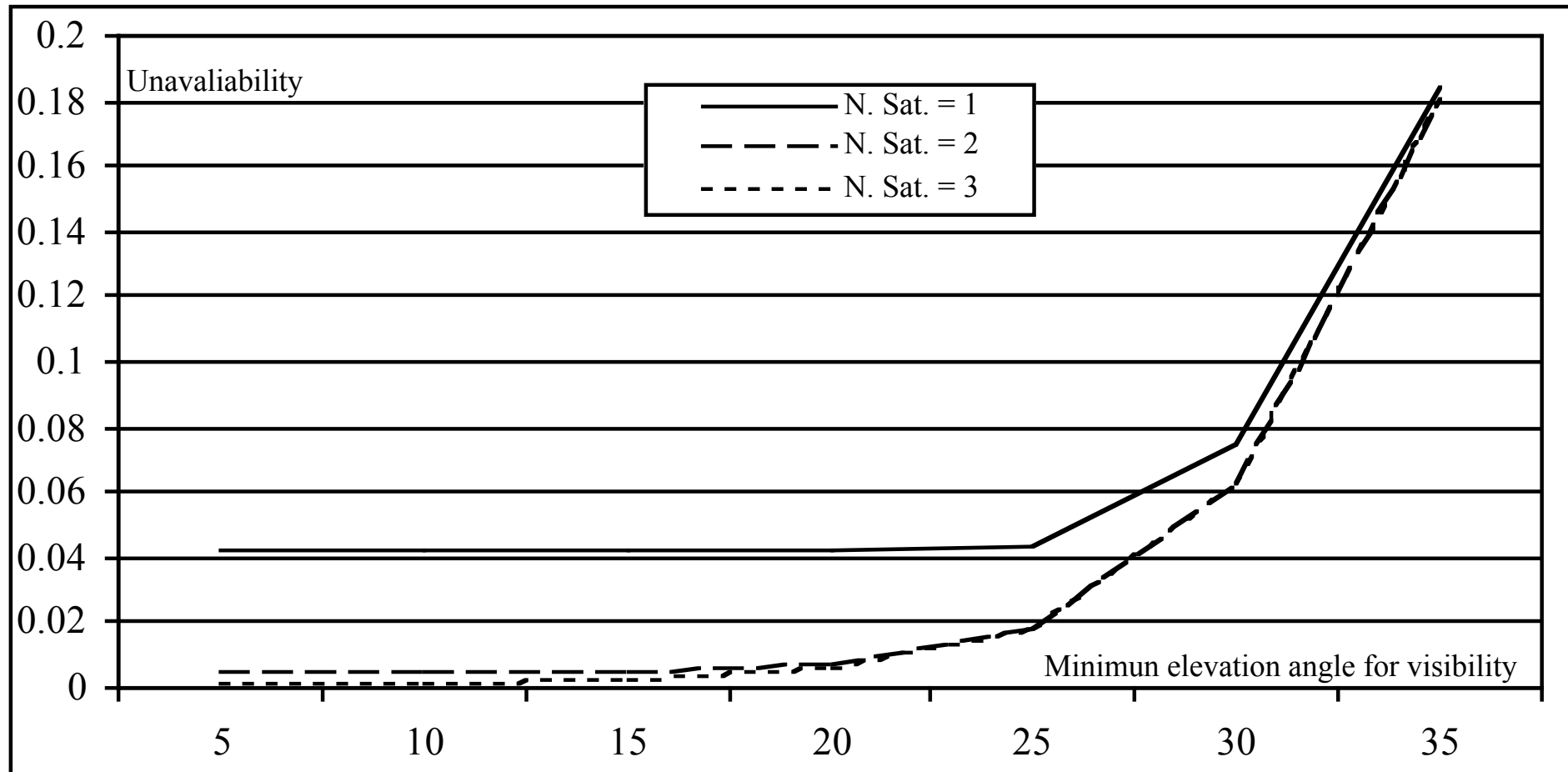
- Maximal Ratio Combining

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

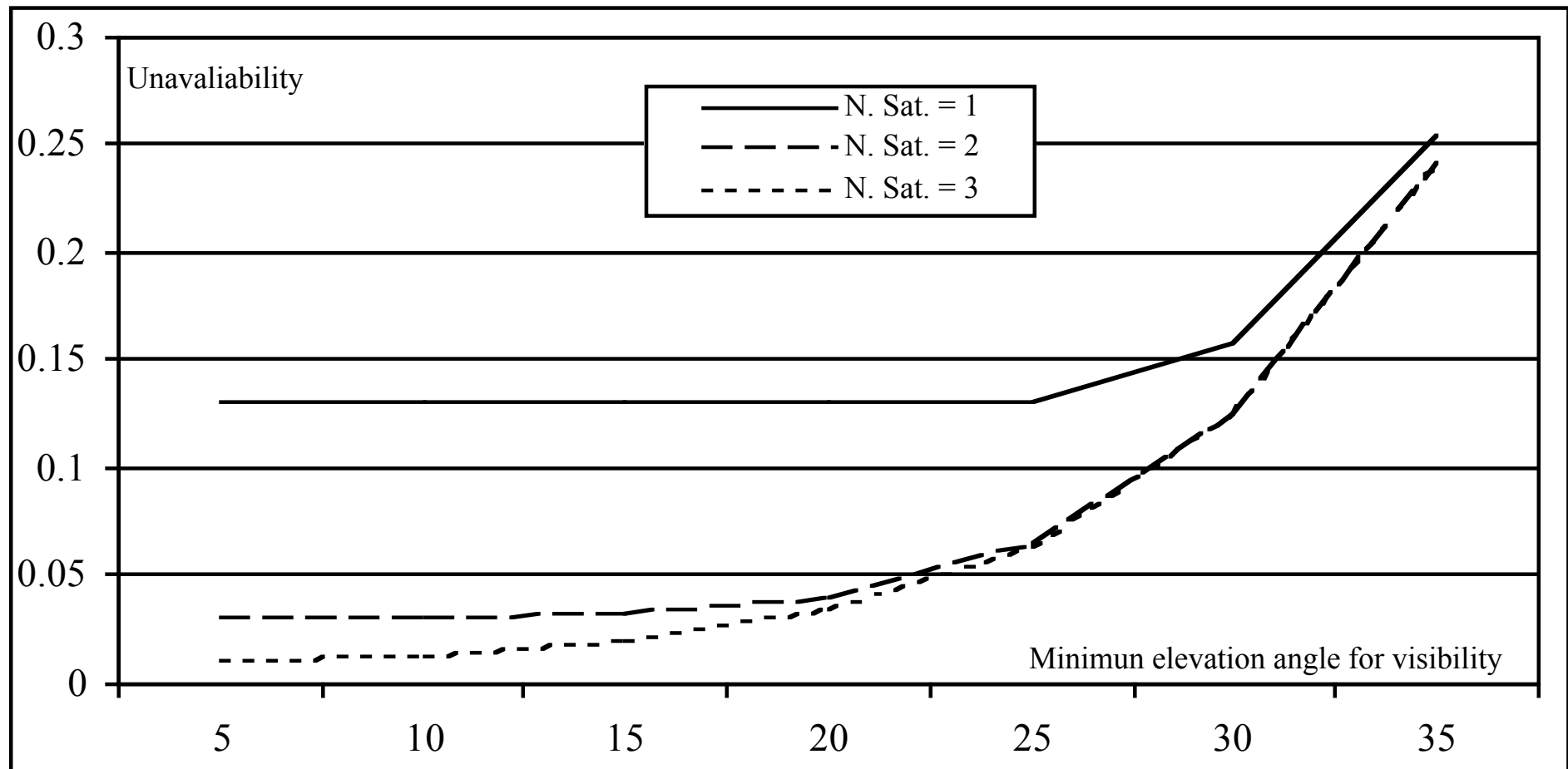
$c_k$  = complex conjugate of the impulse  
response coefficients of the  $k^{\text{th}}$  path

$n_k$  is the noise plus interference signal

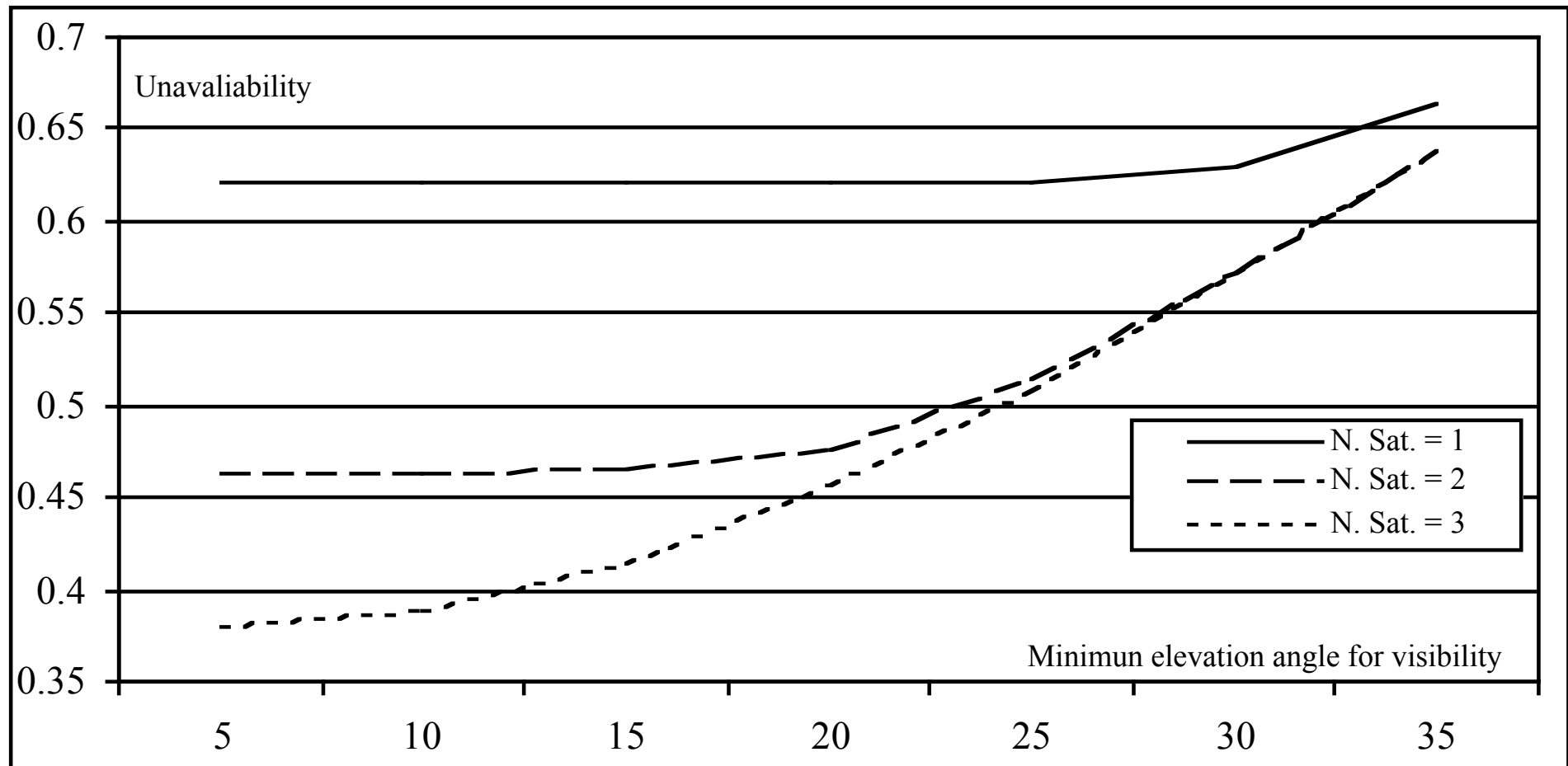
## Diversity advantage in rural environment



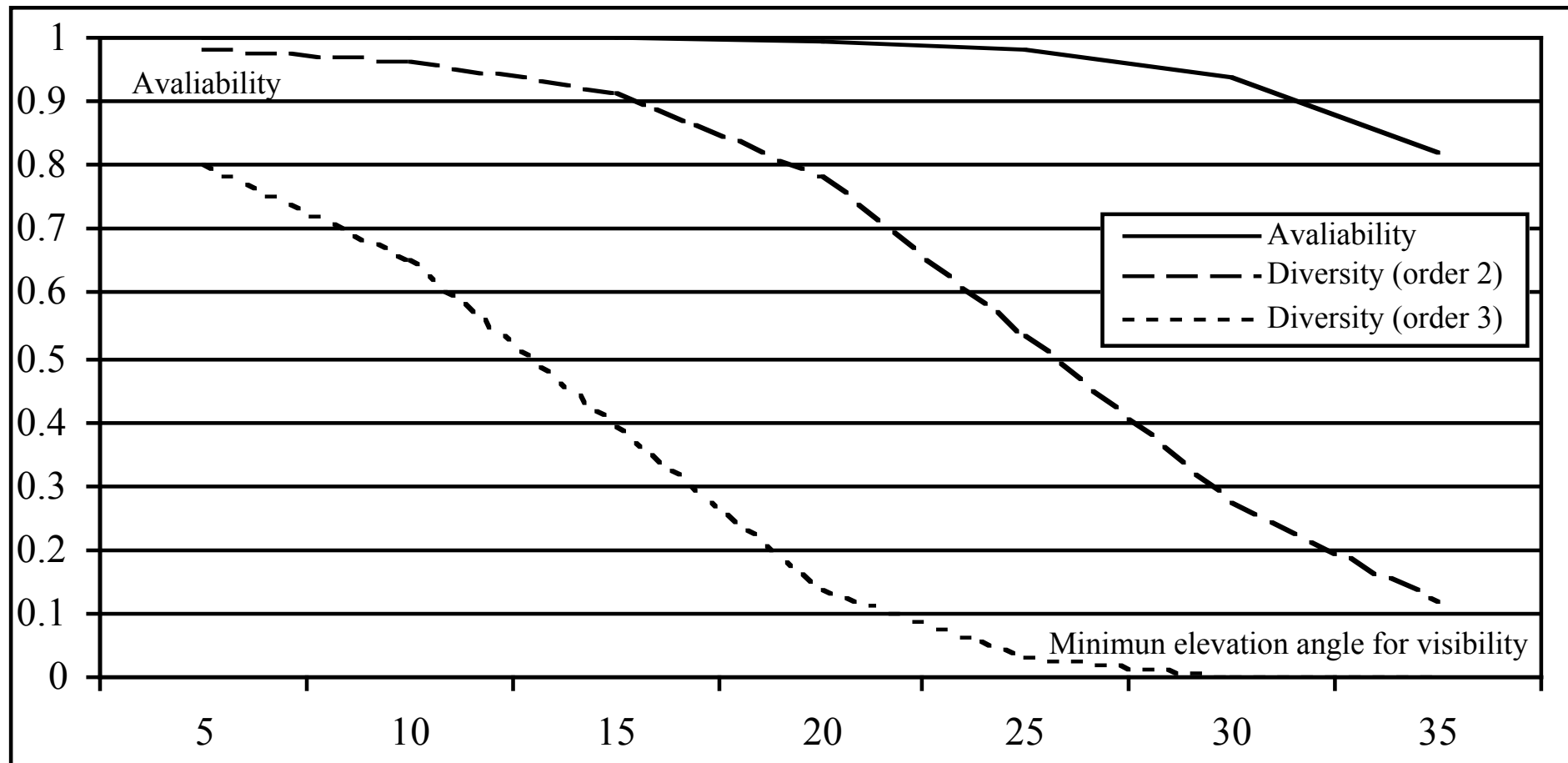
## Diversity advantage in suburban environment



## Diversity advantage in urban environment

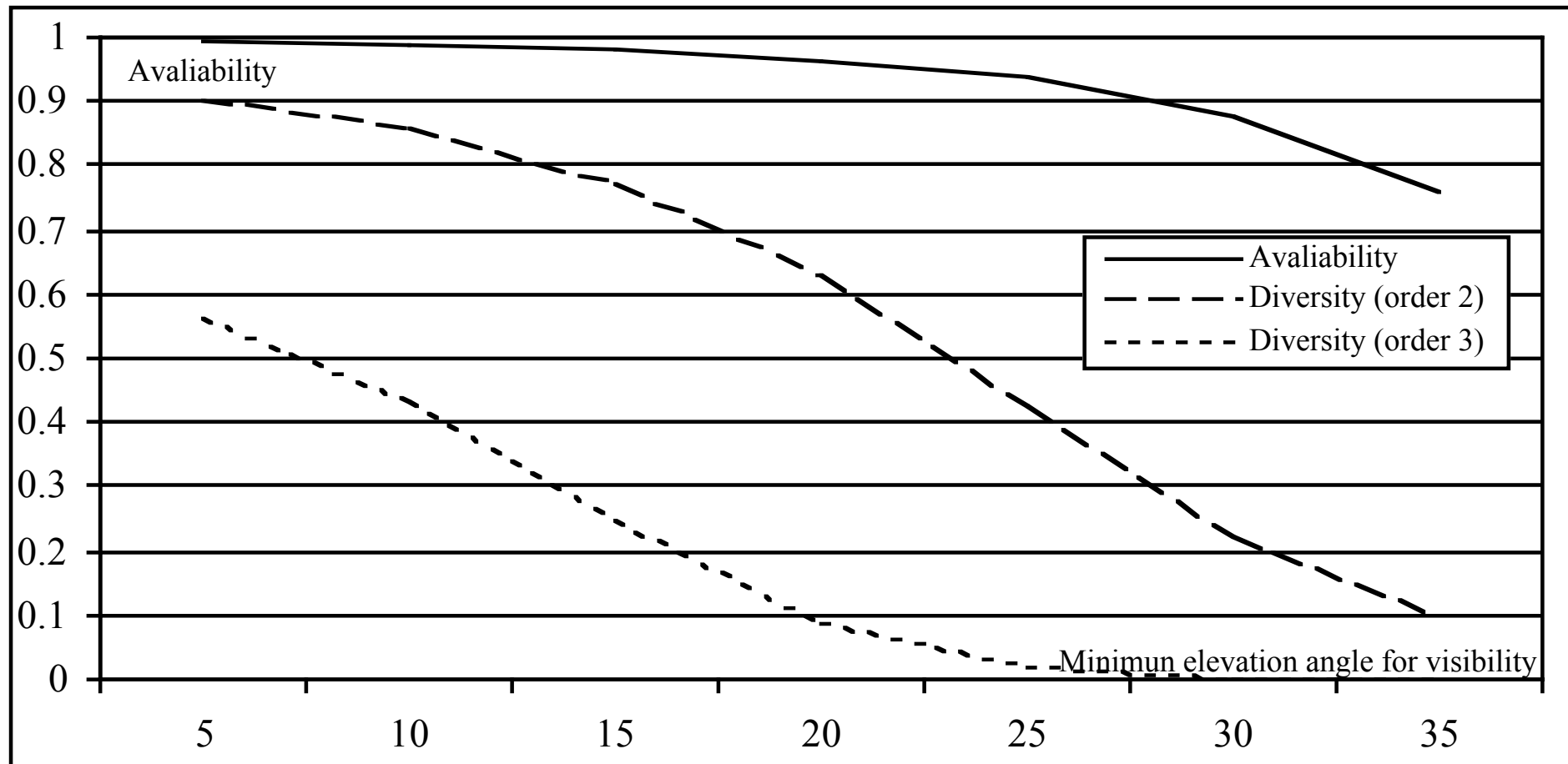


## Diversity probability in rural environment

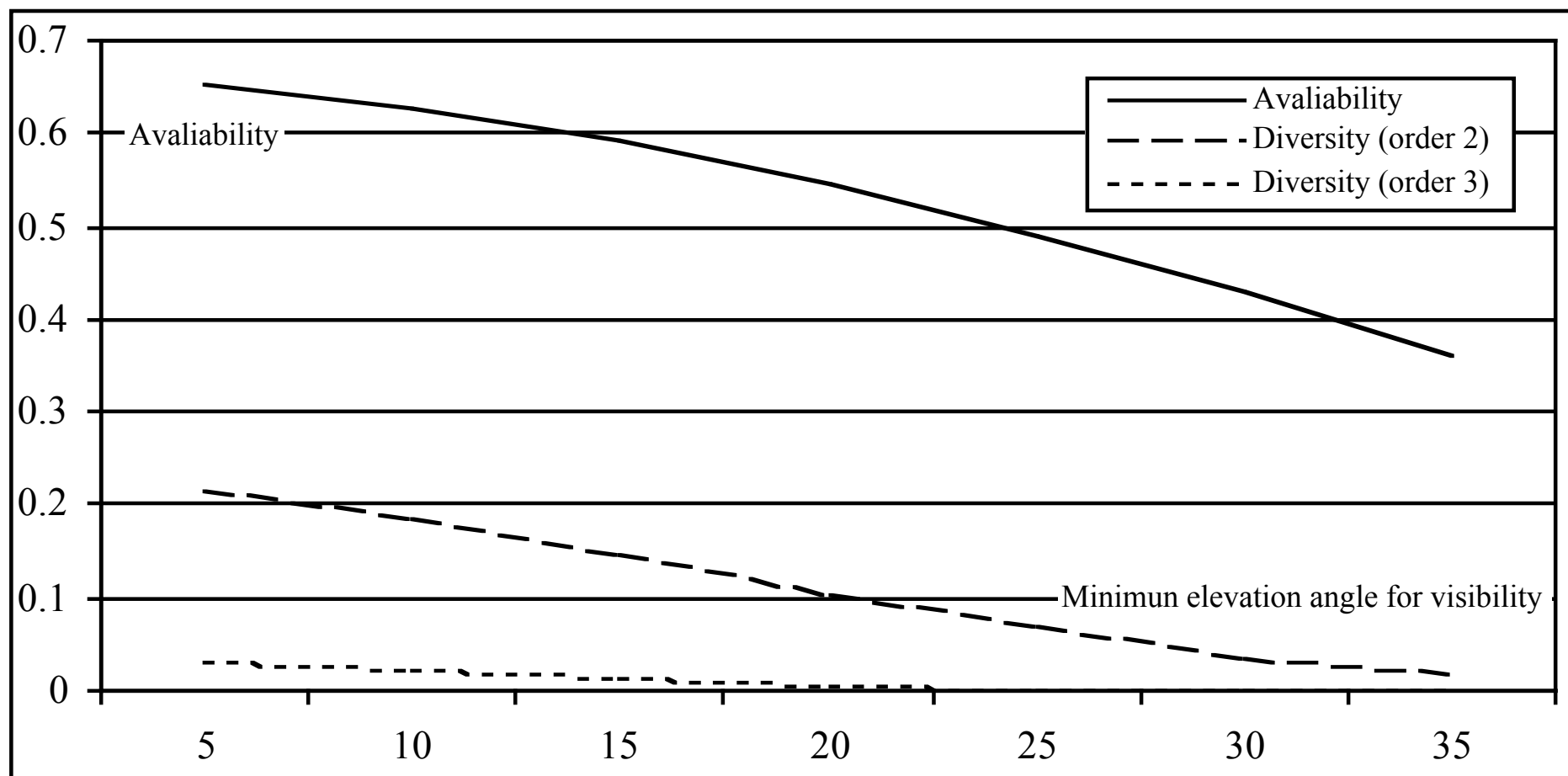




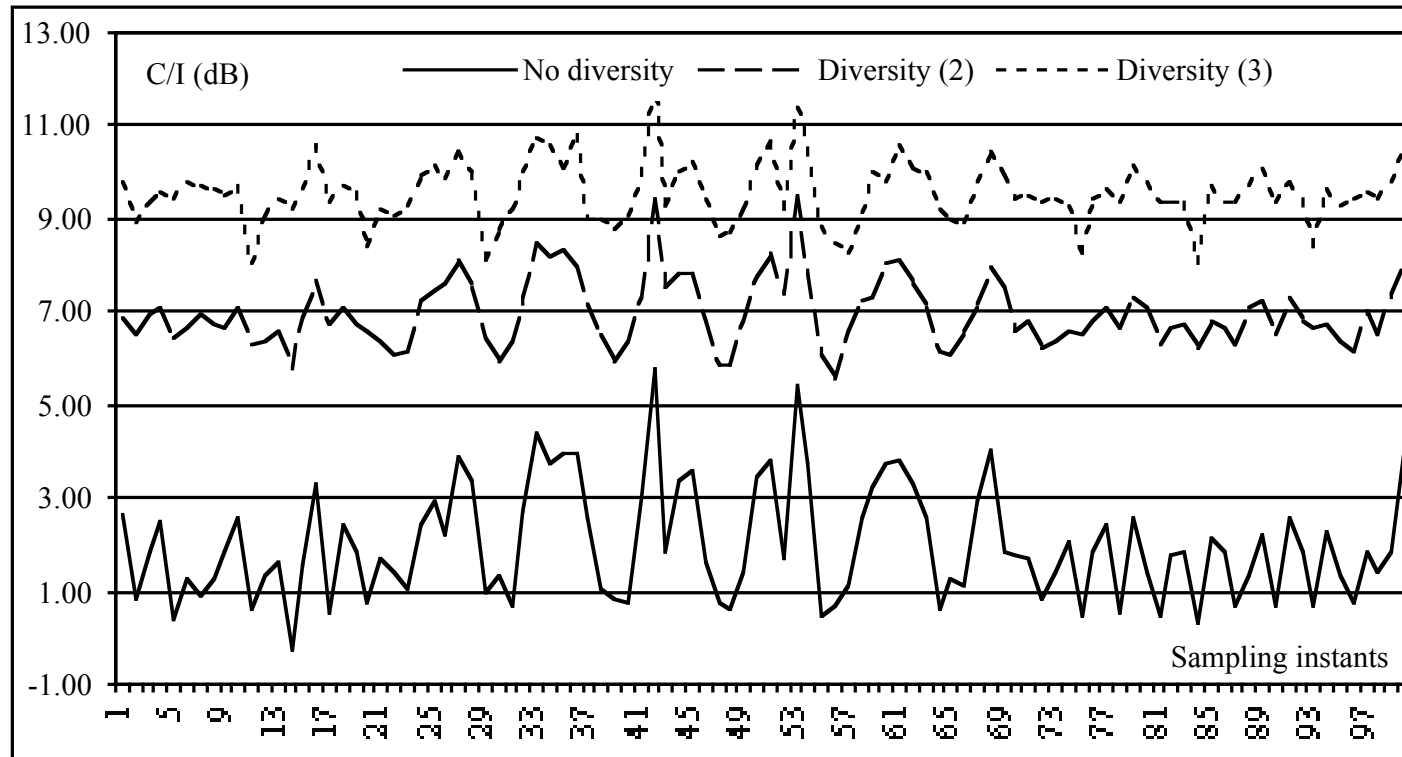
## Diversity probability in suburban environment



## Diversity probability in urban environment



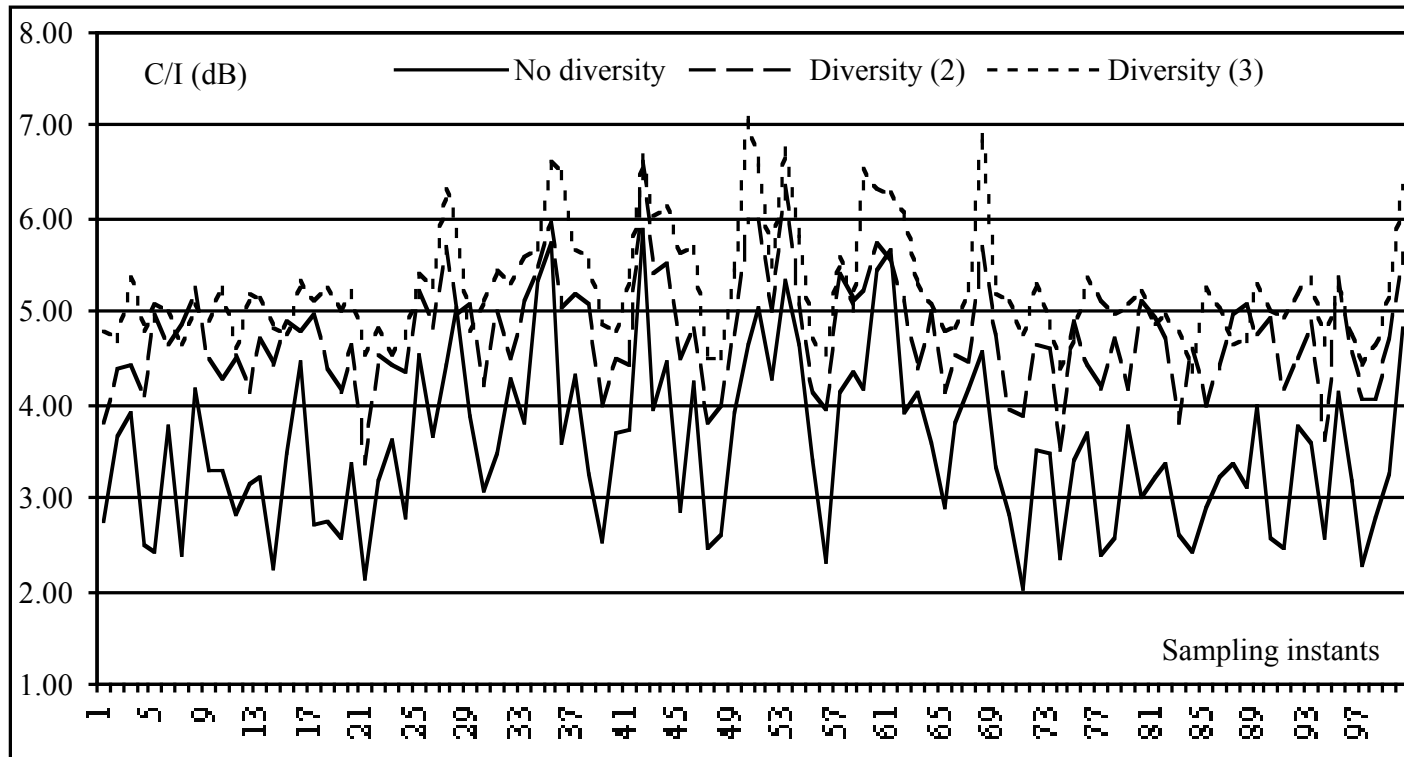
## Up link C/I time behavior



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

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
<b>minimum</b>	<b>2.03</b>	<b>3.36</b>	<b>4.35</b>
<b>average</b>	<b>3.54</b>	<b>4.73</b>	<b>5.26</b>

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:**

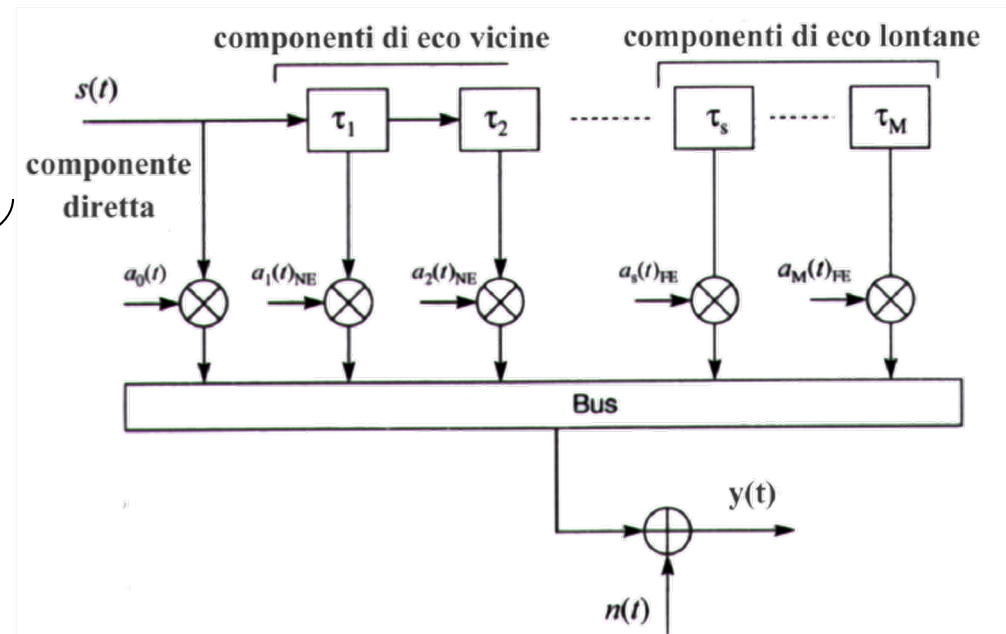
- satellite channel wide sense stationary
- signals associated to different delays are independent

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

$$a_k(t) = r_k(t) e^{j\phi_k(t)} \quad \text{Total attenuation}$$

$$\tau_k(t) \quad \text{Total delay}$$

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  $\lambda_{FE}$  and  $\lambda_{NE}$
- Total envelope:
  - Direct component  $\Rightarrow$  Lutz model
  - Far Echo  $\Rightarrow$  Rayleigh
  - Near Echo  $\Rightarrow$  exponential