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FOURTH ICTP-URSI-ITU(BDT) COLLEGE ON RADIOPROPAGATION:
Propagation, Informatics and Radiocommunication System Planning

30 January - 3 March 1995

Miramare - Trieste, Italy

Cellular Rdio Network Design

with Emphasis on CDMA IS 95

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CELLULAR RADIO NETWORK DESIGN WITH EMPHASIS ON CDMA IS 95

A short course

by

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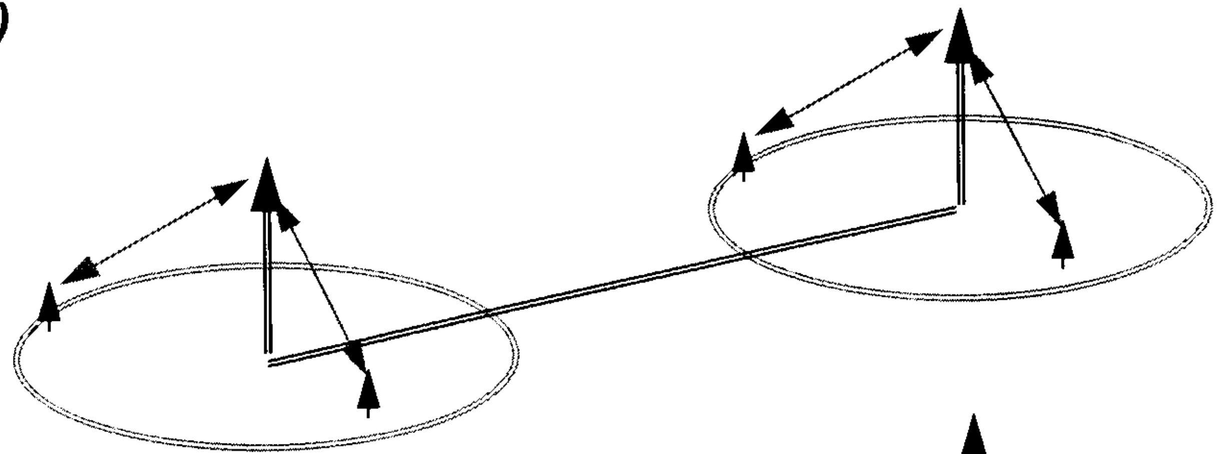
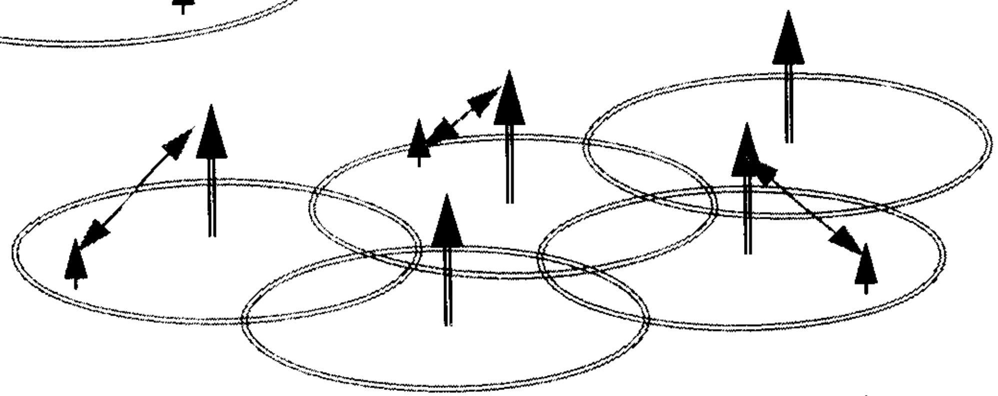
INTRODUCTION
MOBILE RADIO EVOLUTION

Two-way radios
(Walkie talkie, CB radios)

Trunked mobile radio



Cellular radio



THE MOBILE RADIO SERVICE

- **Communication to a mobile platform**
  - Equipment has to be compact
  - Durable power source
  - Transmission is non directional (or otherwise intricately tracking)
  - The path-loss has to be tolerable through the service area
- **Service objectives**
  - From broadcast to two-way communications
  - Voice (preferable full duplex)
  - Data (short messages, telemetry, and into sessions)
  - Video (a look to the future)

FUTURE EVOLUTION

CELLULAR

DIGITAL CELLULAR - *Higher capacity and quality, added features*

PCS - *Higher capacity, lower cost, pedestrian use, personalized*

"THIRD GENERATION" - *layered, fully connected network*

FPLMTS - *Future Public Land Mobile Telecommunication System. Global standards, multitude of systems, ubiquitous service.*

Satellite cellular networks - *Global coverage. Interconnected to the terrestrial networks*

VOLUME

	TODAY	YEAR 2000
CELLULAR	25 M	60 M
PCS	100 M	
Satcomm		6 M

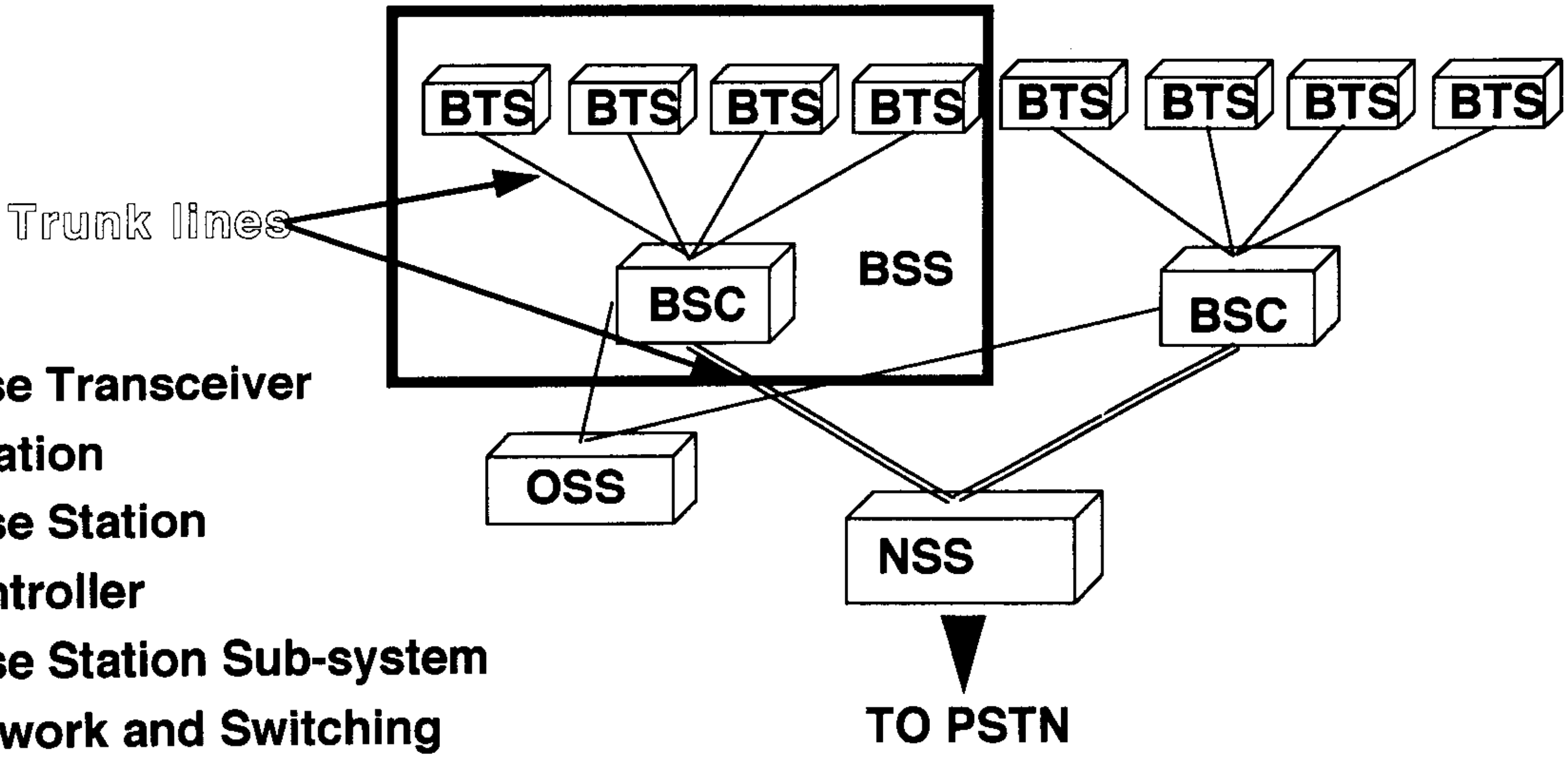
THE CELLULAR RADIO

THE CELLULAR RADIO SYSTEMS RELY ON SPATIAL ISOLATION IN ORDER TO LOCALLY REUSE TELETRAFFIC CAPACITY.

THAT IS ACHIEVED BY:

- **PROPAGATION CONTROL - site and antenna location**
- **DIRECTIVITY CONTROL - antenna pattern (sectorization, tilting)**
- **CELL CLUSTER PLANNING - frequency reuse patterns**
- **POWER CONTROL - for coverage and for interference reduction**
- **NETWORK CONTROL - channel assignments, handoffs**

CELLULAR NETWORK ARCHITECTURE (GSM EXAMPLE)



BTS	Base Transceiver Station
BSC	Base Station Controller
BSS	Base Station Sub-system
NSS	Network and Switching Sub-system
OSS	Operation Sub-system

TELETRAFFICS

- The GRADE OF SERVICE is defined by the PROBABILITY OF BLOCKED CALL (P_b) ON A FIRST ATTEMPT
  - The cellular standard is 2% during the busy hours
- Each user has an access to the circuits available on the air interface of a single BTS
- The circuit efficiency increases with the number of circuits per BTS (per trunk line)
- The unit to measure teletraffic is ERLANG
- P_b is calculated by ERLANG B formula blocked calls cleared - LCC).
- Less common in the cellular is ERLANG C formula (blocked calls held). More pessimistic.

CIRCUIT EFFICIENCY

Erlang:

one circuit in use for one hour

BLOCKING PROBABILITY Pb:

Probability of calls that fail at first trial (lost calls)

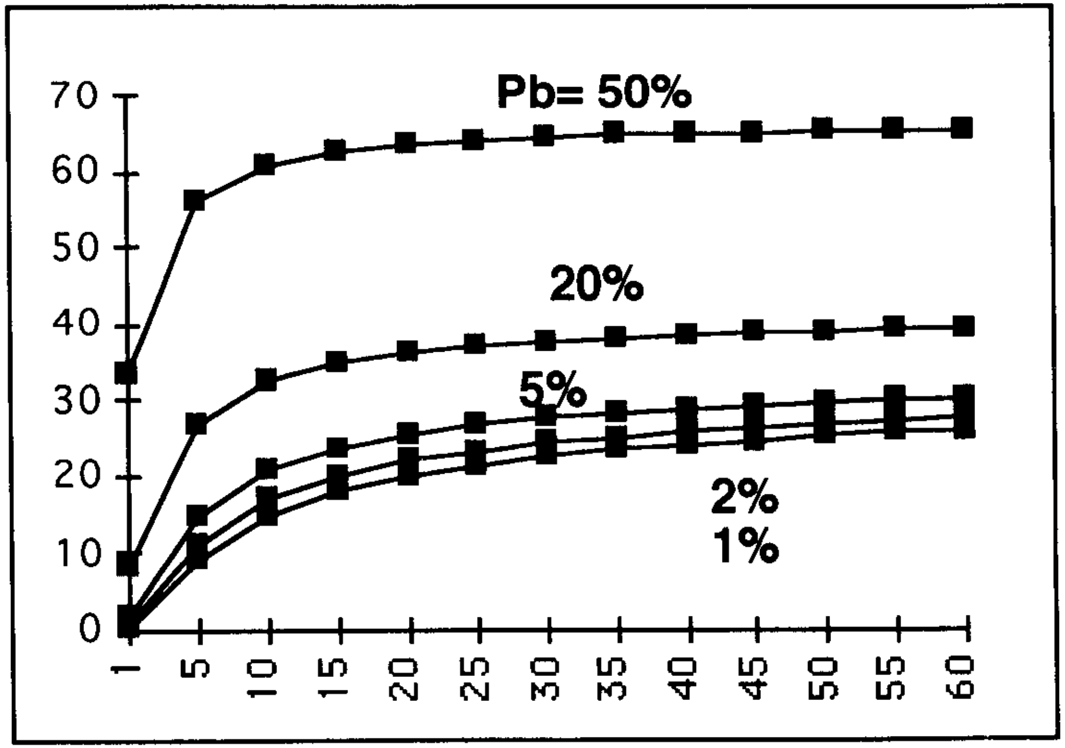
ERLANG B FORMULA

$$P_b = \frac{\frac{A^n}{n!}}{\sum_{i=0}^{n} \frac{A^i}{i!}}$$

A mean of the offered traffic (Erlangs)

n number of circuits (traffic channels) available

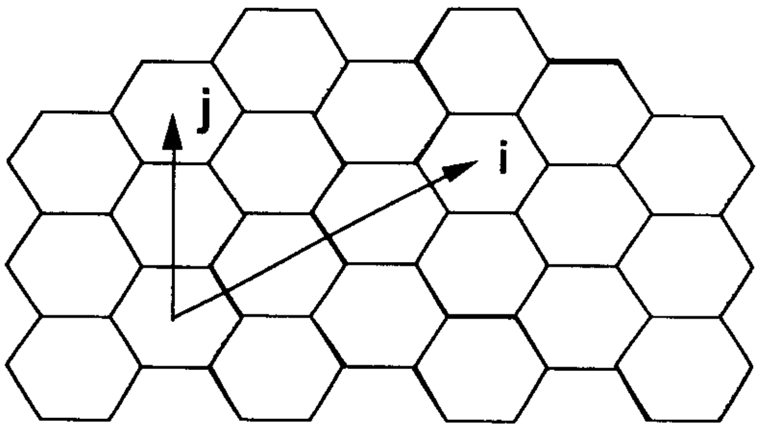
Number of subscribers per traffic channel (.03 Erlang / subscriber)



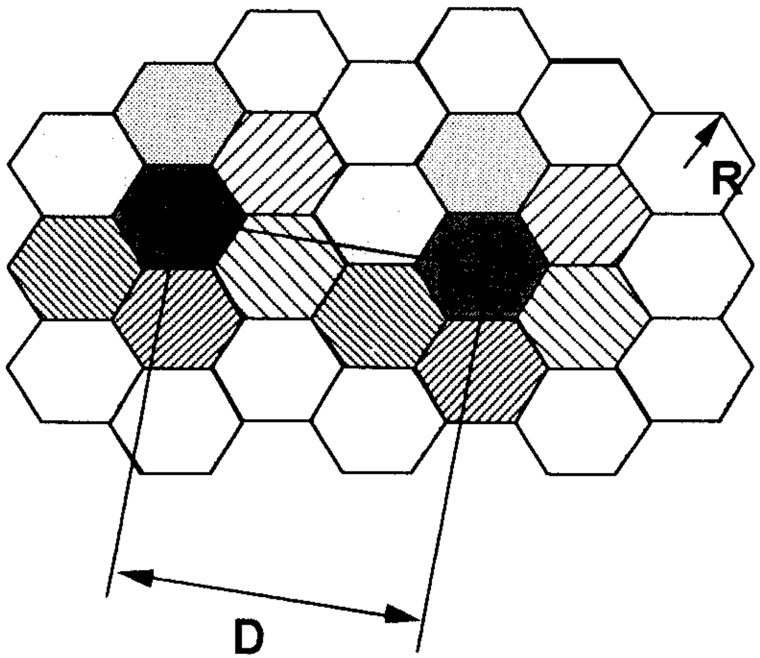
Number of traffic channels

THE REUSE PATTERN

The reuse pattern In the hexagonal grid $K=i^2+ij+j^2$



Reuse pattern K=7



THE CELLULAR GRID: THE REUSE FACTOR K

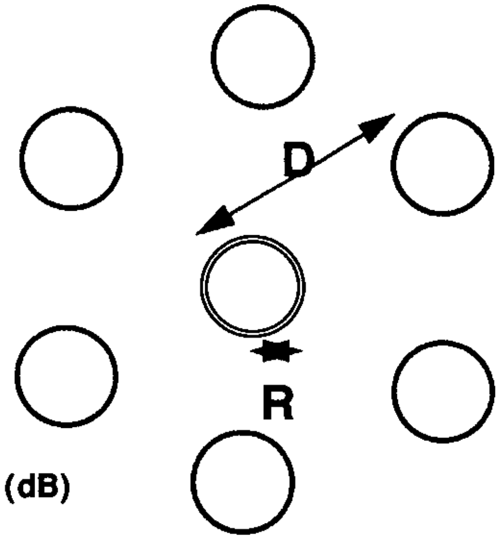
PERIODICITY IN A HEXAGONAL GRID: $K = I^2 + IJ + J^2$

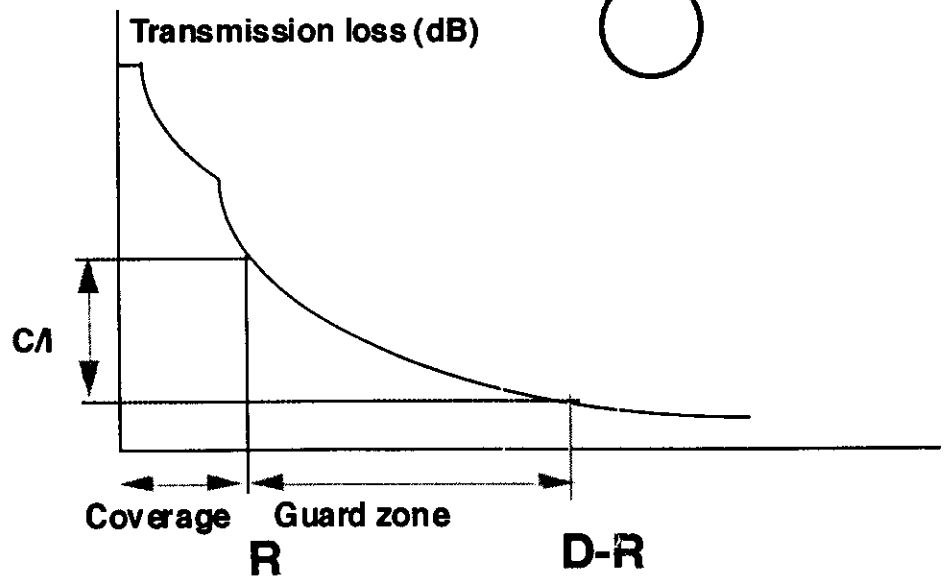
$D = \sqrt{3K}\, R$

q= D/R	K
3.46	4
4.6	7
6	12
7.55	19

$$\frac{C}{I} = \frac{R^{-\alpha}}{\sum_{k=1}^{k_I} D_k^{-\alpha}} \cong \frac{1}{\sum_{k=1}^{k_I} q_k^{-\alpha}} \cong \frac{q^{\alpha}}{6}$$

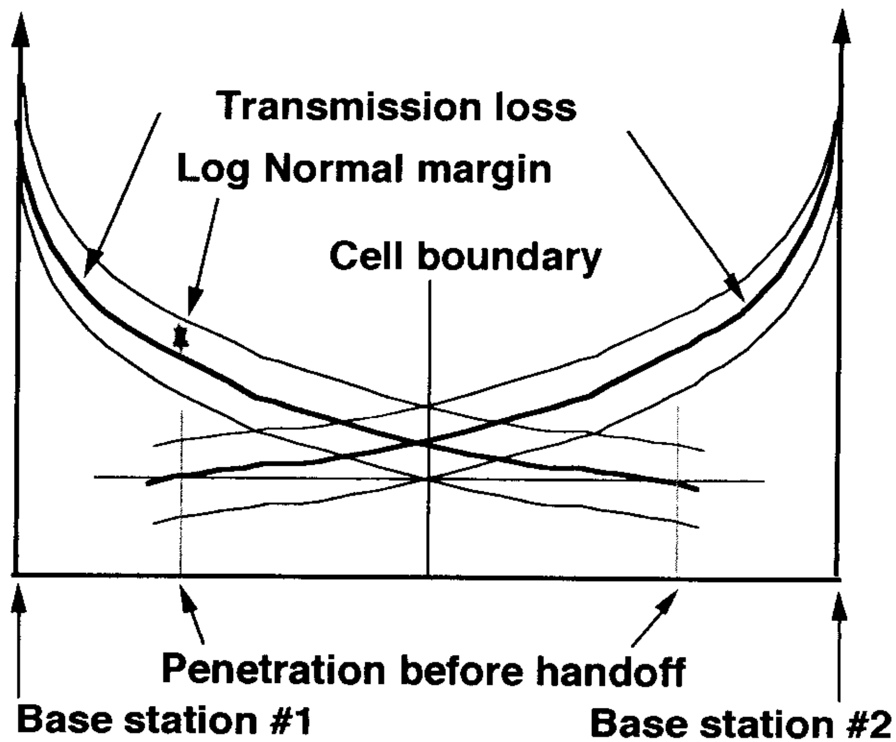
$$K = \frac{1}{3}\left(6\frac{C}{I}\right)^{\frac{2}{\alpha}}$$





HARD HANDOFF MARGIN

- $r^{-\alpha}$ with LogNormal variation
  - A penetration margin is required to limit the probability of call dropping. 11 to 15 dB
- Measured transmission loss
  - The coverage overlap cannot be tailored to follow all "transmission holes" . Margin is required to guarantee performance.
- Mobile assisted handoff
  - If the handoff is instantaneous - this acts as a selective diversity
  - Actual handoff is delayed, not to overload the switch. A margin is required.



SOFT HANDOFF

- Link is maintained with both base stations, and the best link is selected every frame.
- This requires two simultaneous channels. It is now applicable only in the CDMA system, where the same frequency is used throughout the network.
- A much smaller margin is required - to allow for ONE OF THE LINKS to be maintained at every time. Margin advantage of 4 to 8 dB.

CELLULAR SYSTEMS SPECIFICATIONS

	SYSTEM	ACCESS	CHANNEL	TIME SLOT	VOCODER	BAND
ANALOG	AMPS	FDMA	30 KHz	N/A	N/A	800
	NAMPS	FDMA	10 KHz	N/A	N/A	800
	TACS	FDMA	25 KHz	N/A	N/A	900
	NTACS	FDMA	12.5 KHz	N/A	N/A	900
	NMT	FDMA	20 KHz	N/A	N/A	450
						450
	IS 95	CDMA	1230	N/A	8 K(VAR)	800
DIGITAL	GSM	TDMA	200	8	13.2 K	900
	DCS-1800	TDMA	200	8	13.2 K	1800
	IS 54	TDMA	30	3	8 K	800
	JDC	TDMA	25	3	8 K	1500
	ETDMA	TDMA	30	6	4 K	800

CHARACTERIZATION OF THE MOBILE CHANNEL

THE TERRESTRIAL MOBILE CHANNEL:
COVERAGE AND SIGNAL QUALITY

Propagation of total power

Loss = Exponent of the distance
Log Normal distribution
Shadowing

Forward propagation processes. Frequency insensitive.

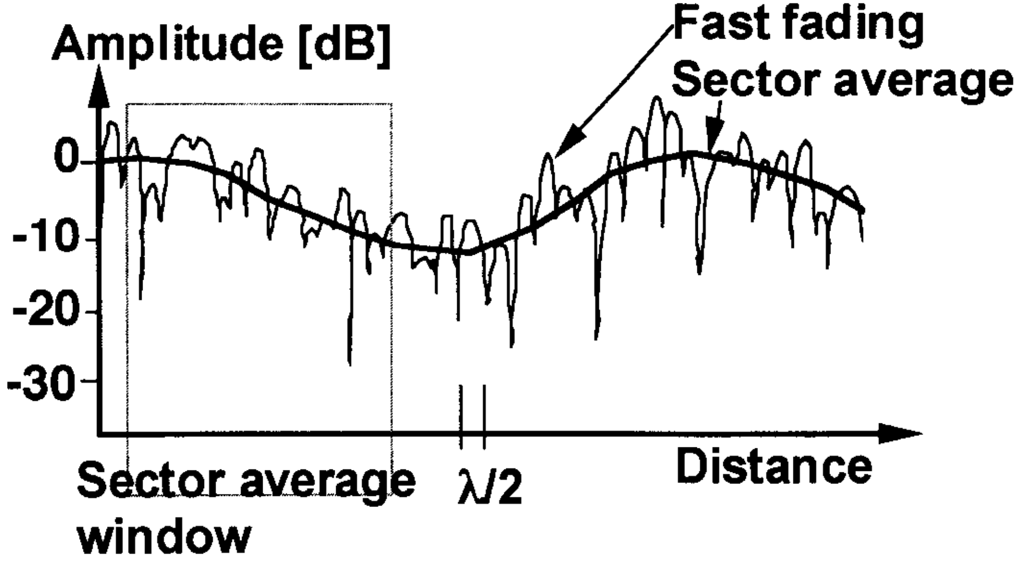
Channel quality: the impulse response

Fading: flat, frequency selective
Delay spread
Coherence bandwidth

Scattering and interference Processes. Frequency dependent.

NARROW BAND SIGNAL

- **The fast fading is a result of multipath interference**
  - **Its rate of change is bound by** $|f_D| \leq \frac{V}{\lambda}$
  - **Its rate statistics is described by the Power Spectrum**
  - **Its amplitude obeys the Rayleigh statistical distribution**
  - **The fast fadings are highly frequency dependent**
- **The slow change is a result of forward propagation:**
  - **Shadowing**
  - **Forward scattering**
  - **It rarely changes faster than 1 dB/λ.**
  - **Its statistics is Log Normal**
  - **It is frequency independent**
- **To separate**
  - **Average in a window 20-40λ, or**
  - **Low pass filter**



RAYLEIGH FADINGS

- **Rayleigh pdf $p(R) = 2R \exp(-R^2)$**
  - **R = amplitude / RMS amplitude**

- **Nakagami pdf**

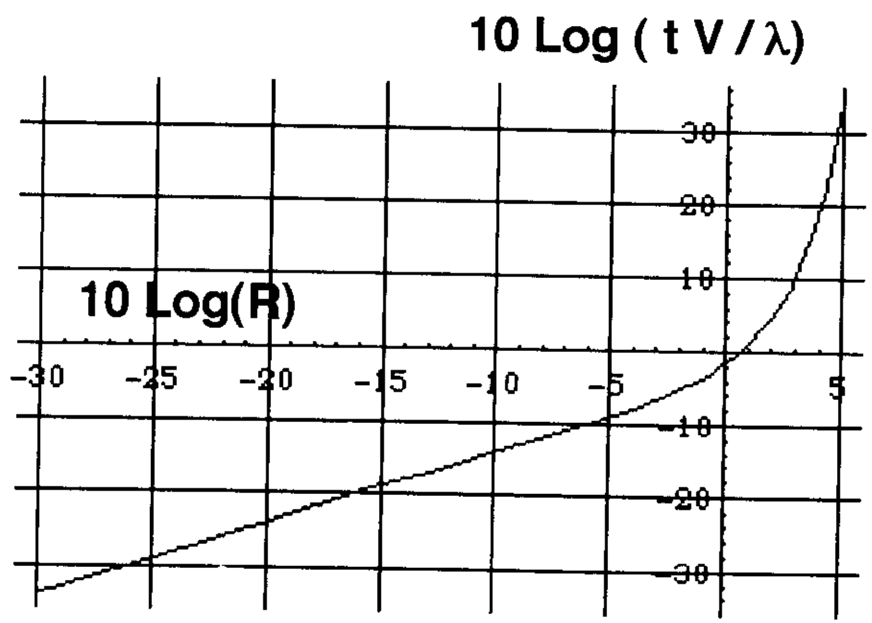
$$\mathrm{pdf}(r) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m r^{2m-1} e^{-\frac{m}{\Omega}r^2}$$

is an approximation to partially phase-correlated waves (Rician)

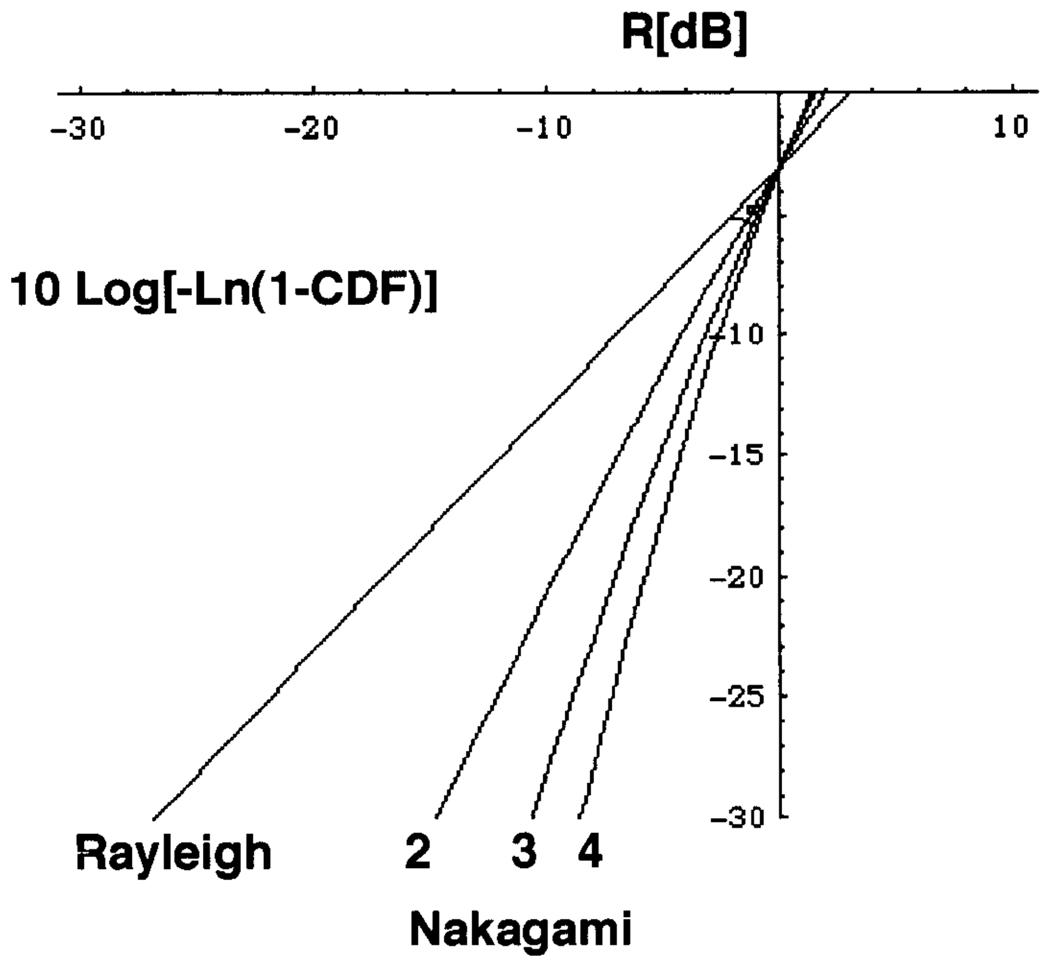
$$m = \frac{\langle r^2 \rangle^2}{\langle (r^2 - \langle r^2 \rangle)^2 \rangle}$$

$$\Omega = \langle r^2 \rangle$$

Mean duration of fadings



THE RAYLEIGH PAPER



THE DISPERSIVE CHANNEL

- **Coherence bandwidth B_c**

  $B_c \tau_{max} < 1$, where τ_{max} is the max excess delay of the channel

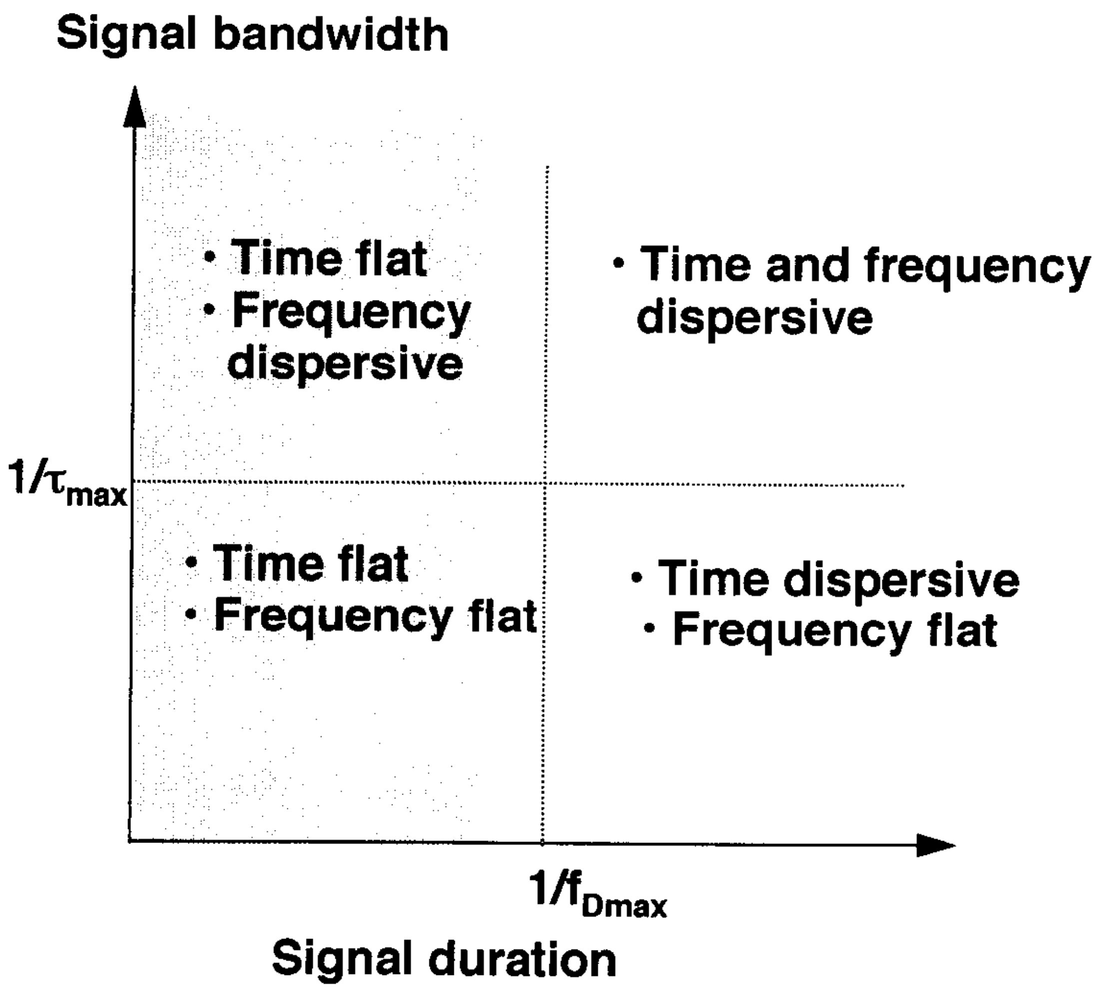
  Signal narrower than the coherence bandwidth is not spectrally distorted but fades.

- **Coherence time T_c**

  $T_c f_{Dmax} < 1$, where f_{Dmax} is the max Doppler of the channel

  Signal shorter than the coherence time is not time distorted.

- **Terrestrial mobile comm is mostly in the shaded area**



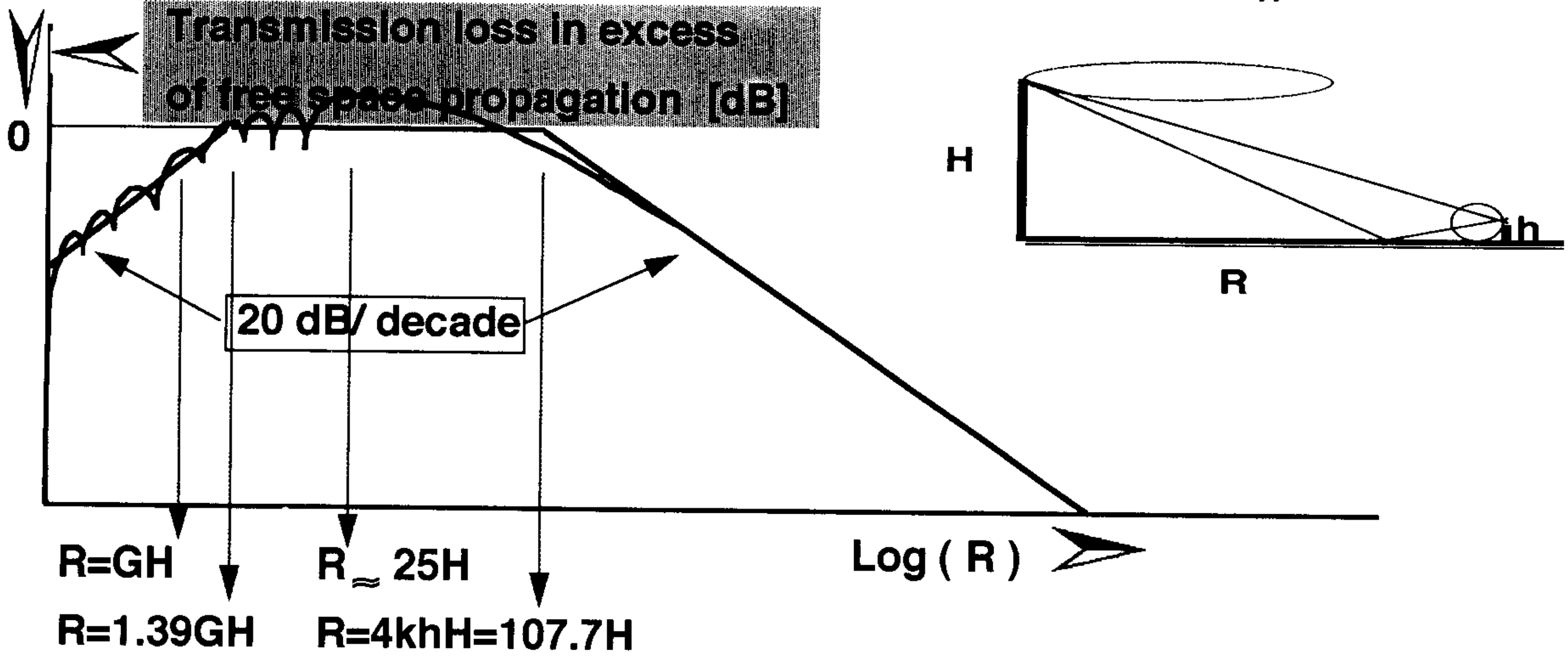
PATH-LOSS - THE FORWARD PROPAGATION MECHANISMS AND MODELS

THE TWO-RAY, FLAT EARTH MODEL

Free space L[dB]=20 Log (R[m]) - g(cell) - g(mobile) + 31.6

Multipath L[dB]=40 Log (R) - g(cell) - g(mobile) - 20 Log (H) - 20 Log (2h) - C

Earth curvature correction C= 20 Log (1 - R^2/(17H*1,000,000))



R - Base-to-mobile distance

H - Base antenna height

h - Mobile antenna height

G=GMv*GCv

GMv (GCv) - Vertical gain of mobile (base) antenna

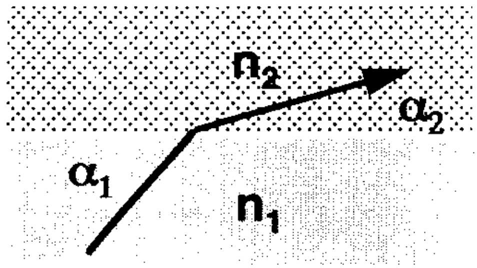
k=6.28/(wavelength)

Wavelength - .35 m

h = 1.5m

SPHERICAL EARTH AND THE DUCT

- **Ray refraction - Snell's law** $\frac{\cos(\alpha_1)}{\cos(\alpha_2)} = \frac{n_2}{n_1}$
  - **n - the refraction coefficient**



- **The refraction of the atmosphere is proportional to the air density and humidity**

  $n-1 = (n_0-1)e^{-\alpha h}$; Define $N = (n-1)\,10^6$

At low elevation $N \cong N_0(1-\alpha h)$; $\alpha = -\frac{dN}{dh}10^{-6}$

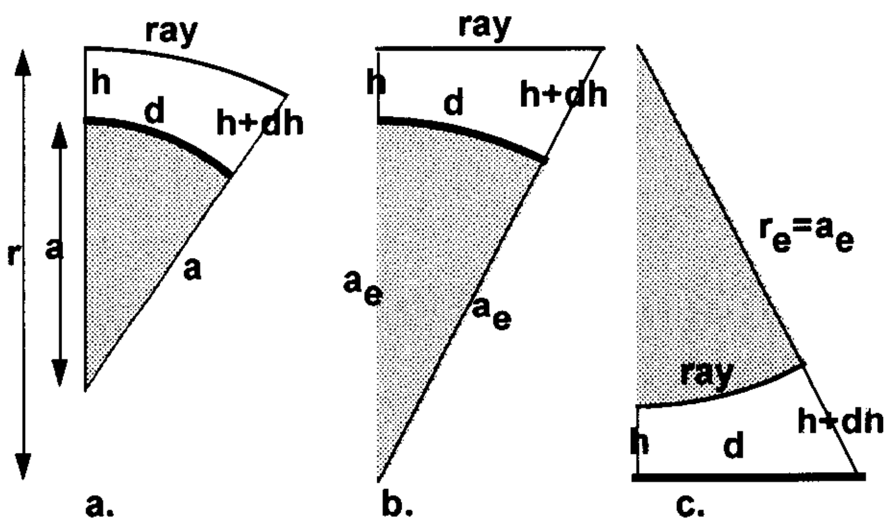
- **The radius transformation**

  $K = \frac{a_e}{a} = \left(1+10^{-6}a\frac{dN}{dh}\right)^{-1} = \left(1+\frac{dN}{dh}/157\right)^{-1}$

  presents a straight ray (b.) or a flat Earth (c.).
- **Standard Atmosphere**

  $N_s=301$, $dN/dh=-39$, $K=4/3$
- **The radio horizon**

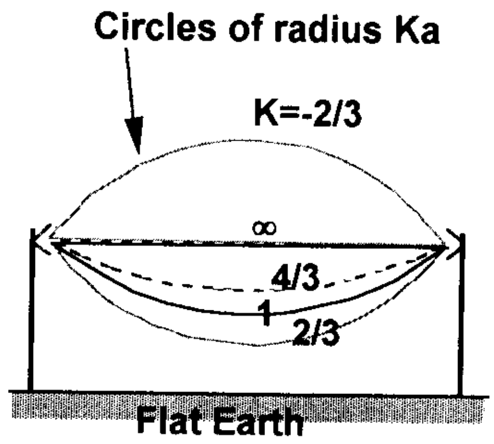
  $d=\sqrt{2haK}$, $d[km]=3.57\sqrt{Kh[m]}$
- **Grazing distance between two points** $d[km]=3.57\sqrt{K}\left(\sqrt{h_1[m]}+\sqrt{h_2[m]}\right)$



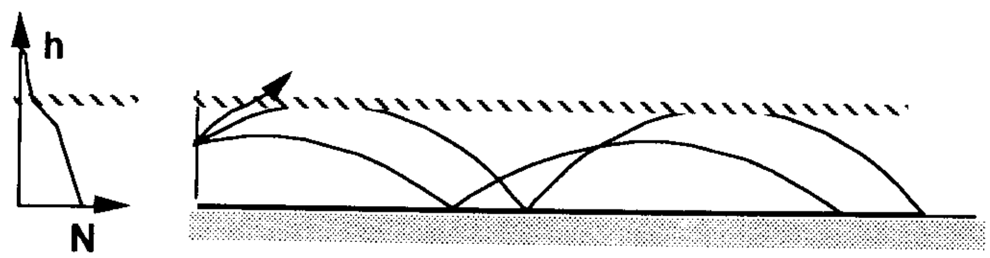
PROPAGATION DUCTS

- **Abnormal conditions**

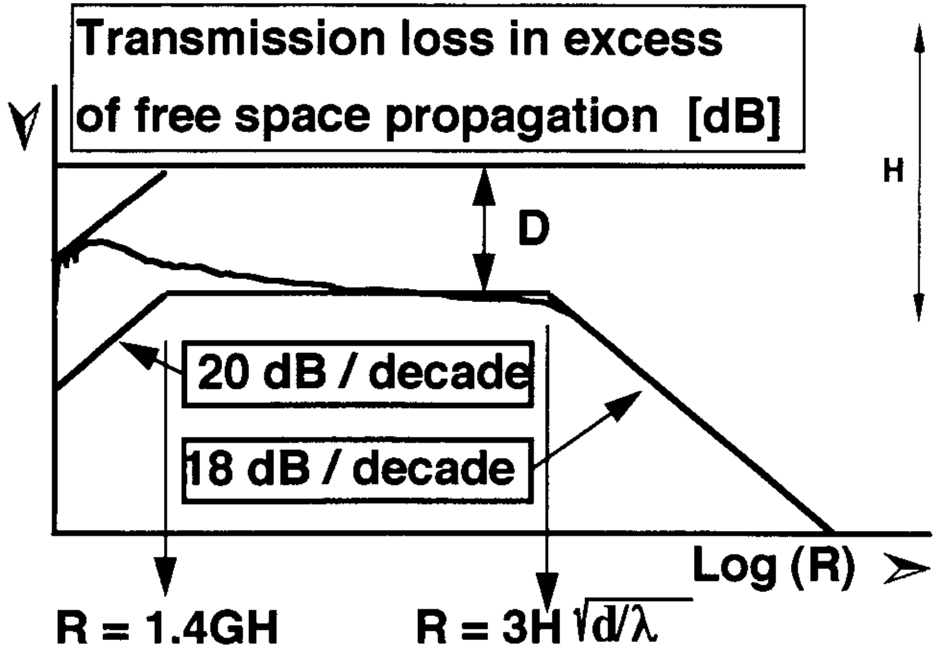
Condition	dN/dh	K
Standard	-39	4/3
Super-refractive	-157	∞
Ducting	-393	-2/3
Constant Atm.	0	1
Sub-refractiuve	79	2/3

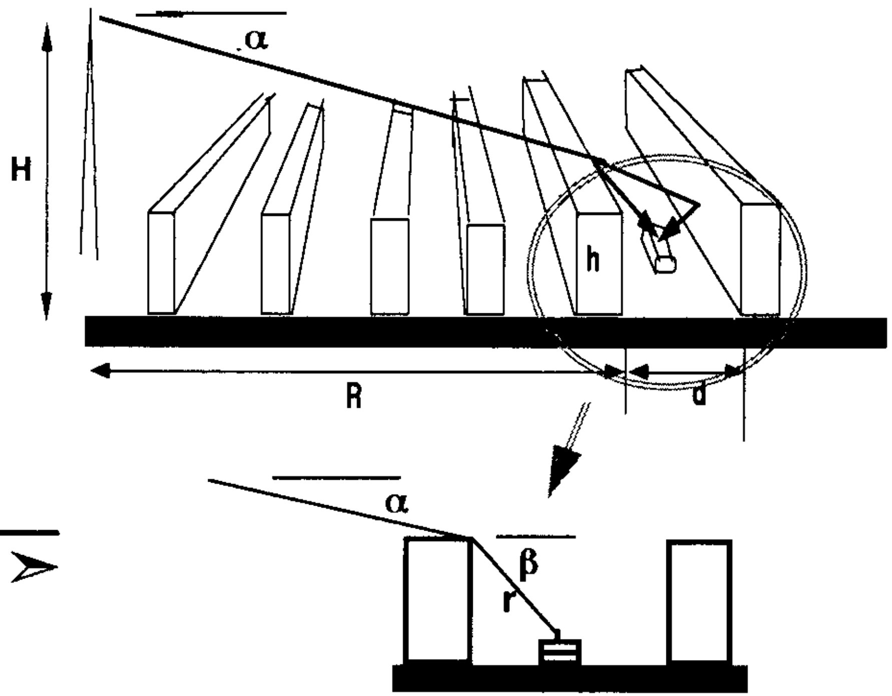


- **Surface ducts prevail over water bodies**



OVER THE ROOF PROPAGATION



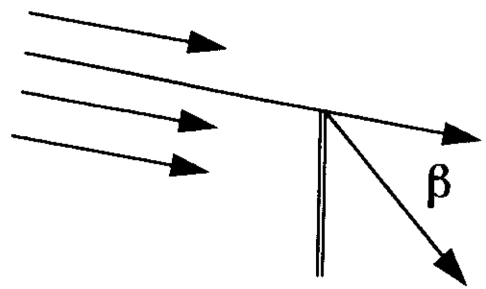


Diffraction over multiple screens

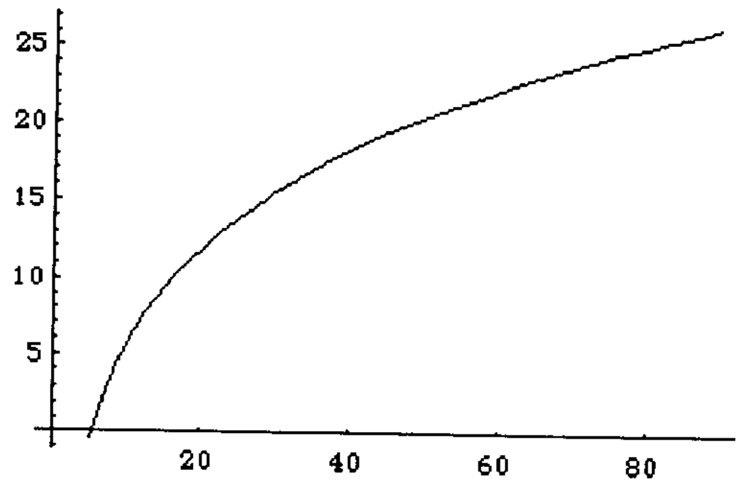
$$L = 38 \, \mathrm{Log}(R) - 18 \, \mathrm{Log}(H-h) - 10 \, \mathrm{Log}(d/\lambda) + D - C$$

$$D = \text{edge diffraction loss} = 16 + 10 \, \mathrm{Log}(r/\lambda) - 20 \, \mathrm{Log}\left| \frac{1}{2\pi + \beta - \alpha} - \frac{1}{\beta - \alpha} \right|$$

EDGE DIFFRACTION



- **Absorbing screen is a good representation of diffraction by non metallic buildings**
- **Diffraction loss at 1 m from the edge, 850 Mhz**



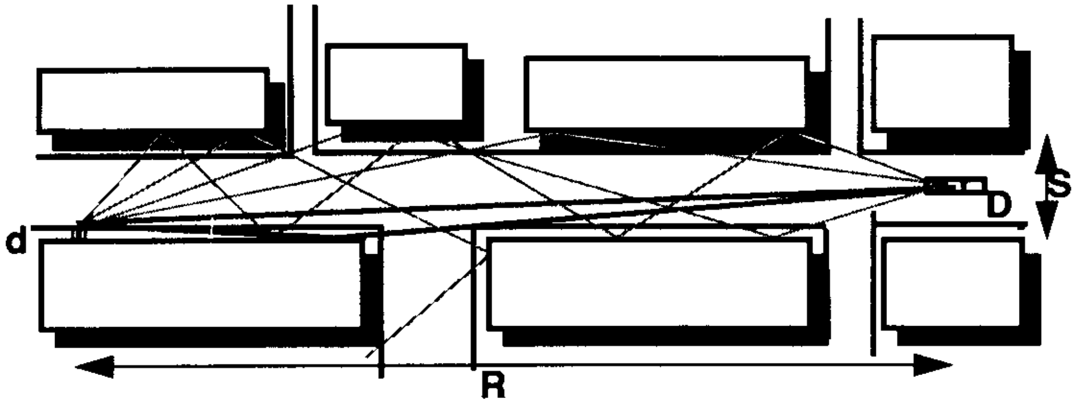
D^2[dB]=20.5- 20 Log[1/β-1/(2π+β)]

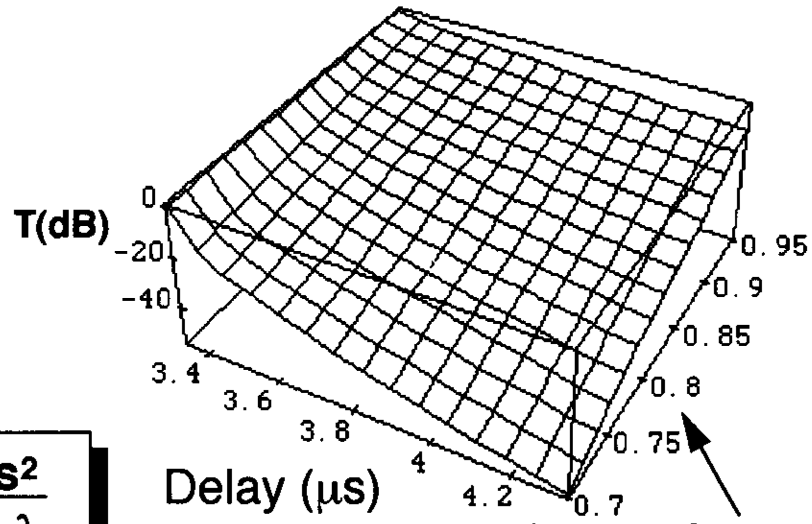
where β in radians

- **Loss at r [m] (from the incident field on the edge)**

L[dB] = D^2[dB] + 10 Log[r]

PROPAGATION IN THE STREET CANYON





Direct path (free space) - to the 1st Fresnell zone. Beyond that - attenuated by

- **Building walls discontinuities**
- **Multiple reflections**

$$R \cong \frac{S^2}{2\lambda}$$

T(dB) = 20 Log(R) - 20 Log (Cos(θ)) - (2R Tan(θ)/s)Log(r) + 25.6

R = 1 km
S = 50 m

Only few rays, near grazing angles, persist for a long distance.

Multiply reflected rays penetrate only to first few corners.

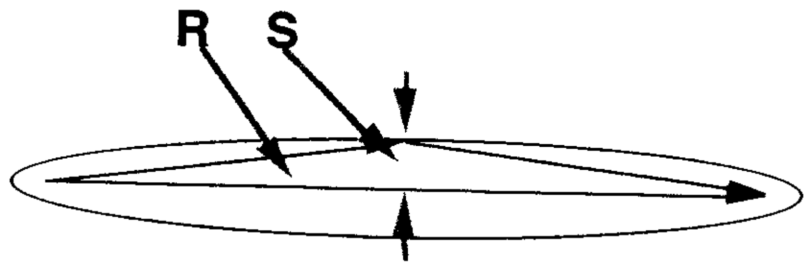
FORWARD SCATTERING - THE (FIRST) FRESNELL ZONE

Path difference $< \frac{\lambda}{2}$

(phase $< 180^0$)

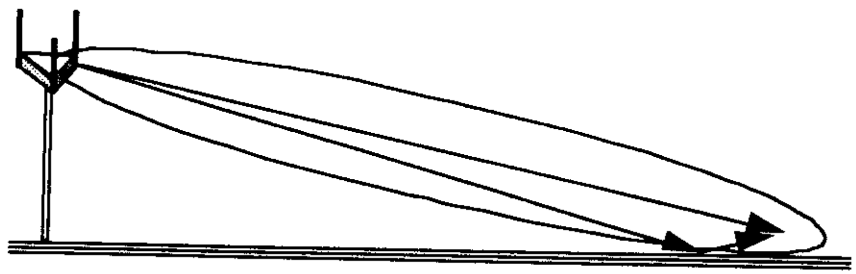
Minor axis of ellipse $s = \frac{1}{2}\sqrt{R\lambda}$

For $\lambda = .35$ m, $S[m] = .3\sqrt{R[m]}$



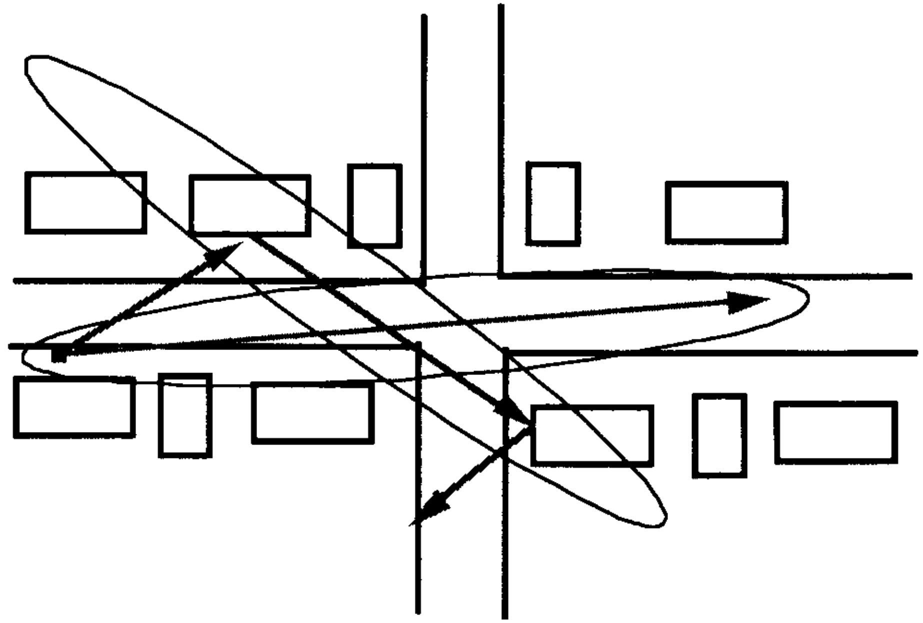
Two-ray multipath:

The break point occurs when the reflection point enters the Fresnell ellipse

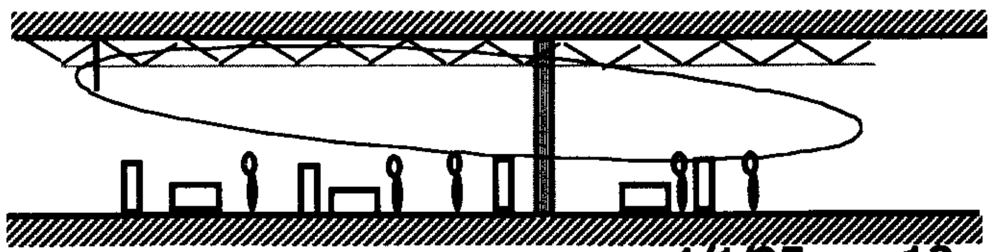


FRESNELL ZONE (CONT.)

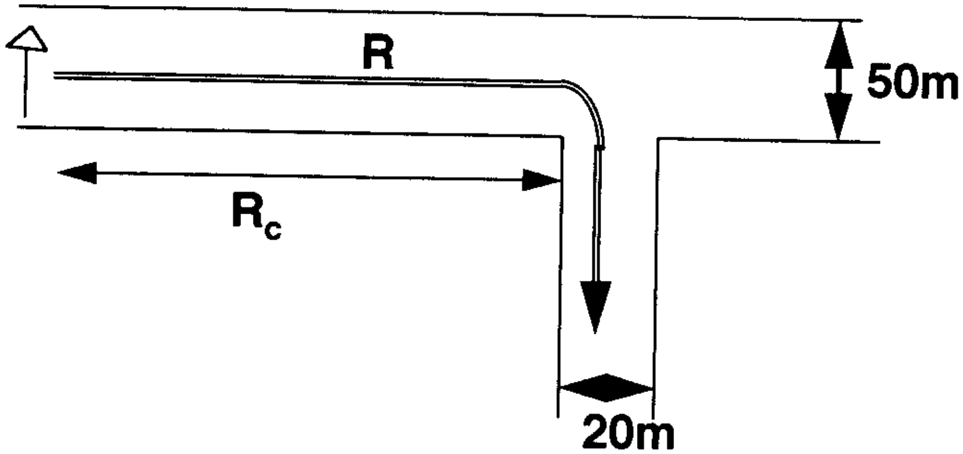
- **STREET PROPAGATION is not disturbed until the Fresnell ellipse hits the buildings or side obstructions.**
- **Reflections are attenuated when the reflectors are smaller than the Fresnell ellipse.**
- **Reflection into the cross street is dominant only for corners near the source.**

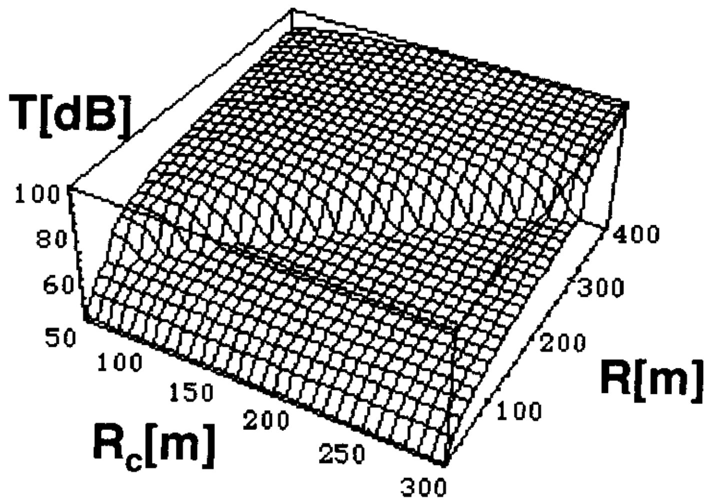


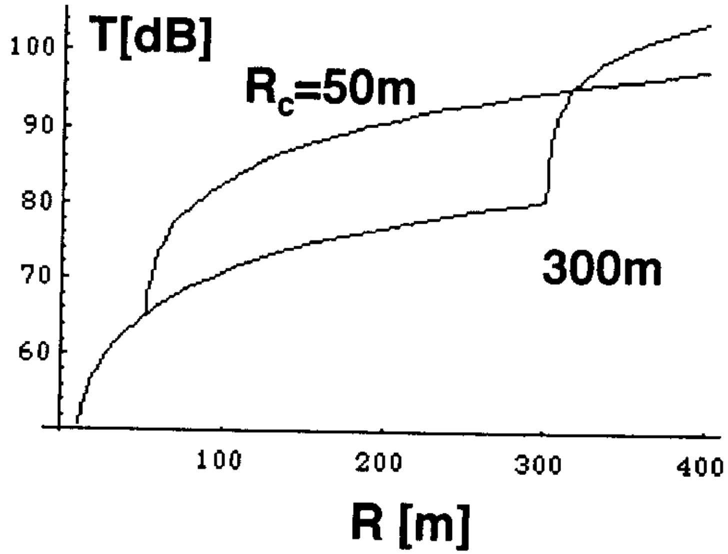
- **INDOORS PROPAGATION is not disturbed until the Fresnell ellipse hits the obstruction layers, and decays exponentially thereafter.**



STREET CORNER LOSS

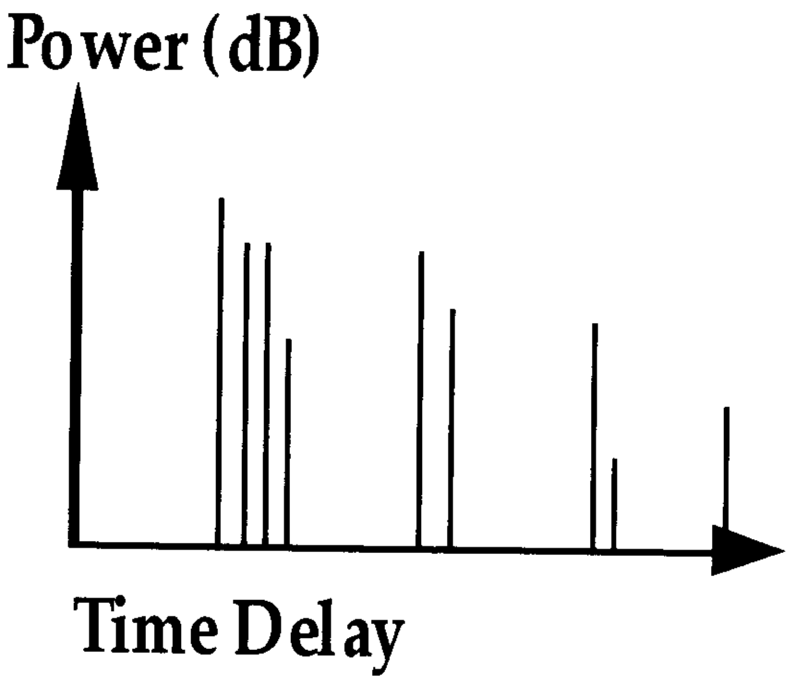




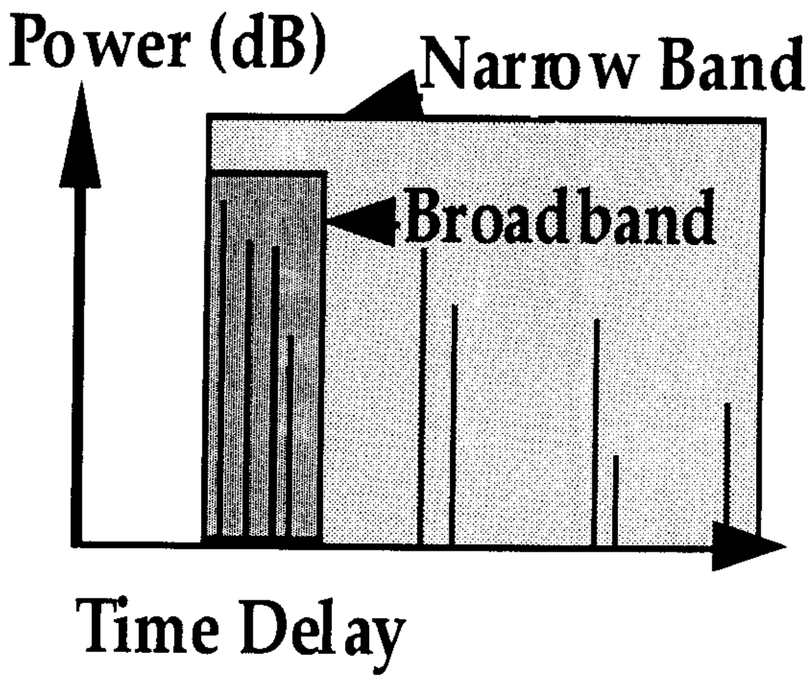


THE SCATTERING ENVIRONMENT, MULTIPATH AND DELAY PROFILE

A TYPICAL DELAY PROFILE

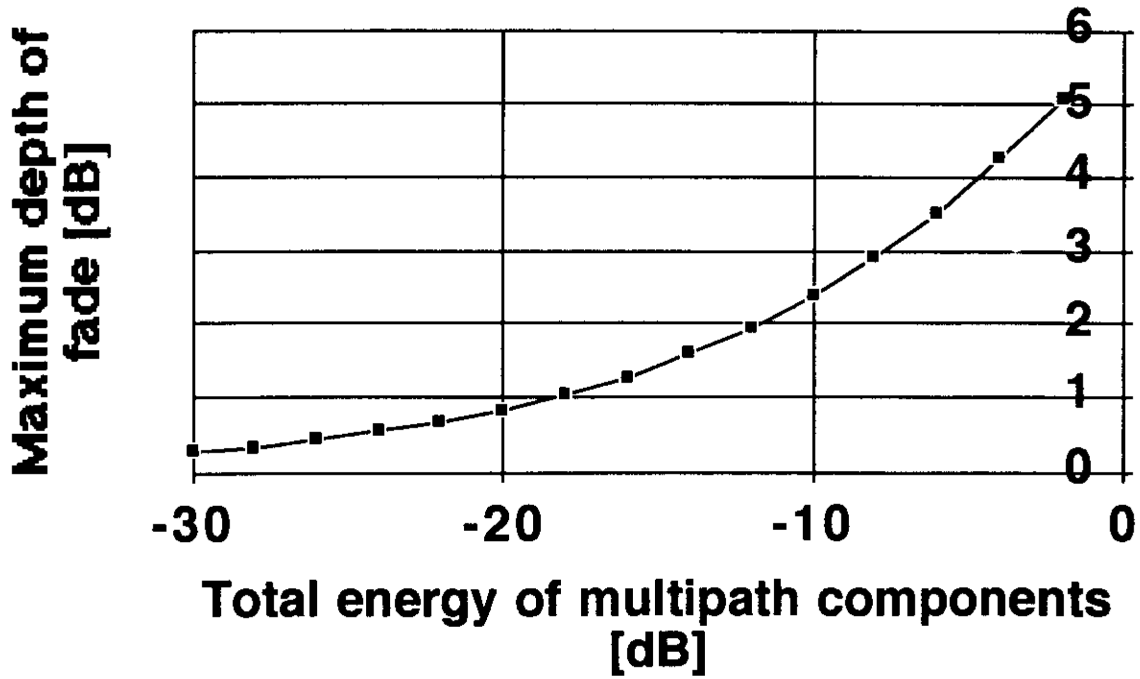


Impulse response



Correlation windows

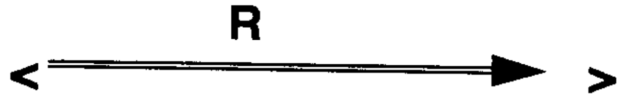
MULTIPATH FADING DEPTH



THE RADAR EQUATION

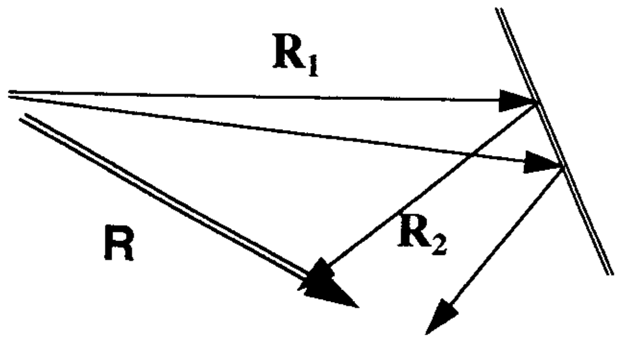
The transmission equation

$$\frac{P_d}{P_t} = \frac{G_t A_r}{4\pi R^2} \; ; \quad A \equiv \frac{G\lambda^2}{4\pi}$$



The reflection equation

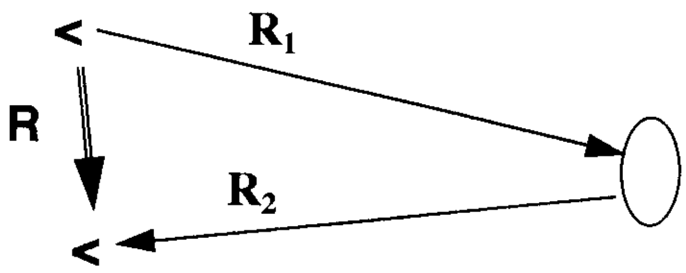
$$\frac{P_r}{P_t} = \frac{G_t G_r \lambda^2}{(4\pi)^2 (R_1+R_2)^2} \; ; \quad \frac{P_r}{P_d} = \frac{R^2}{(R_1+R_2)^2}$$



The Radar equation

$$\frac{P_s}{P_t} = \frac{G_{t1} A_{r2}}{4\pi R_1^2} \cdot \frac{G_{t2} A_{r3}}{4\pi R_3^2} \quad ; GA \equiv \sigma$$

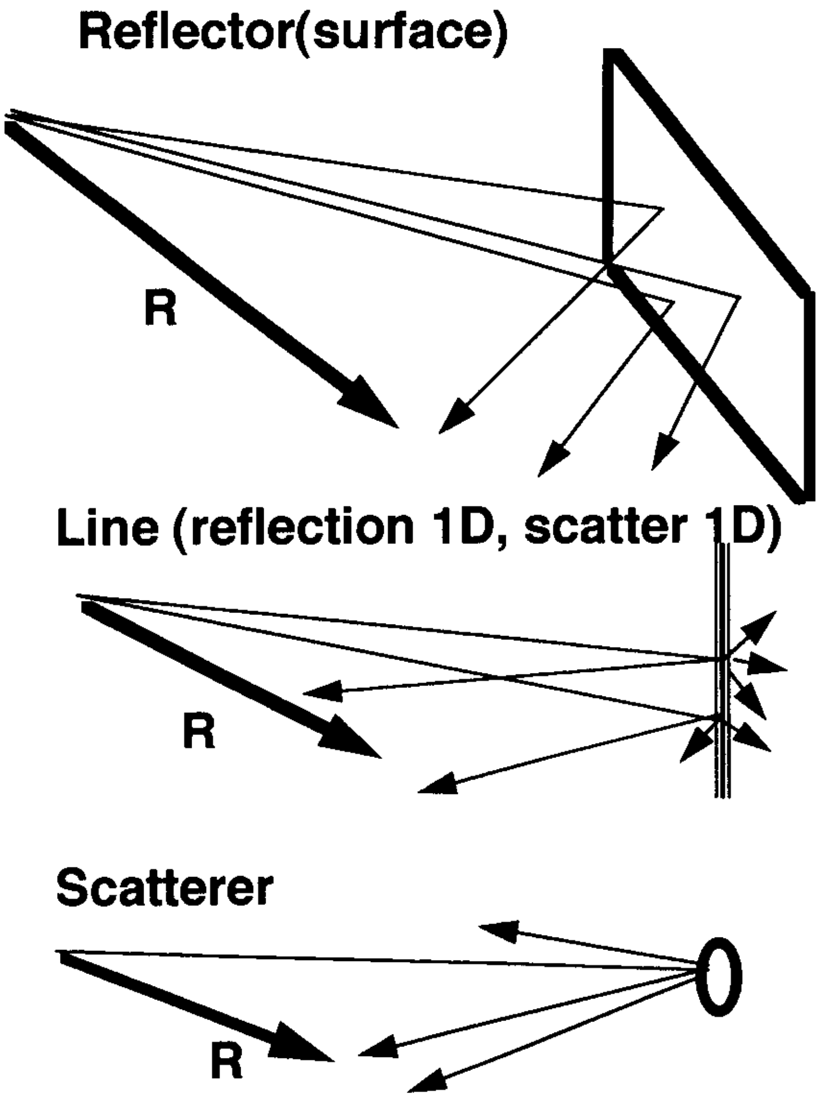
$$\frac{P_s}{P_t} = \frac{G_t G_r \lambda^2}{(4\pi)^3 (R_1 R_2)^2} \sigma$$

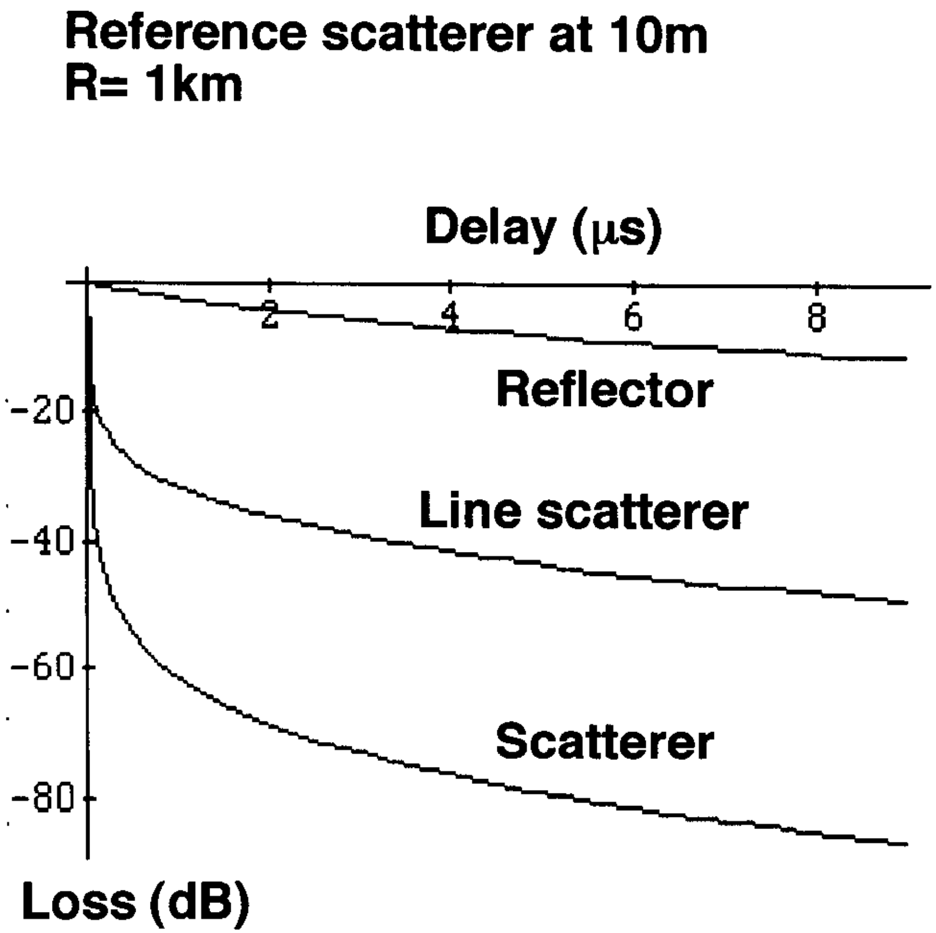


When $R_1 \approx R_2$

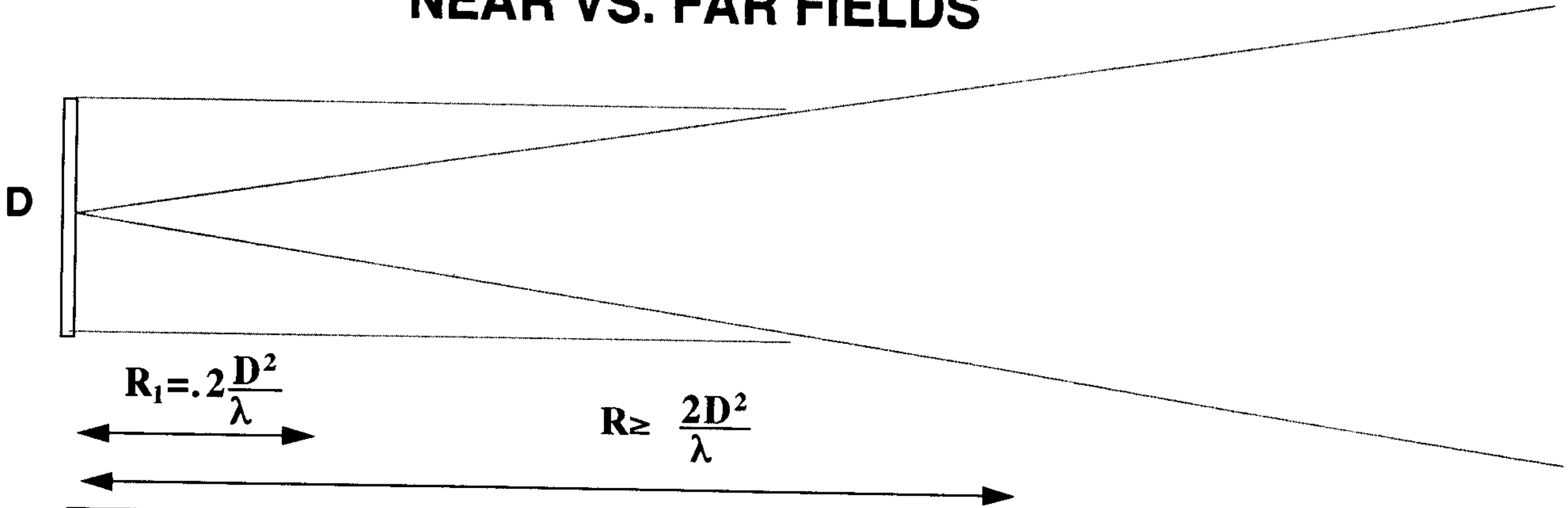
$$\frac{P_s}{P_d} \approx \frac{\sigma}{4\pi R_2^2}$$

Relative Delay Profiles For Reflection and For Scattering



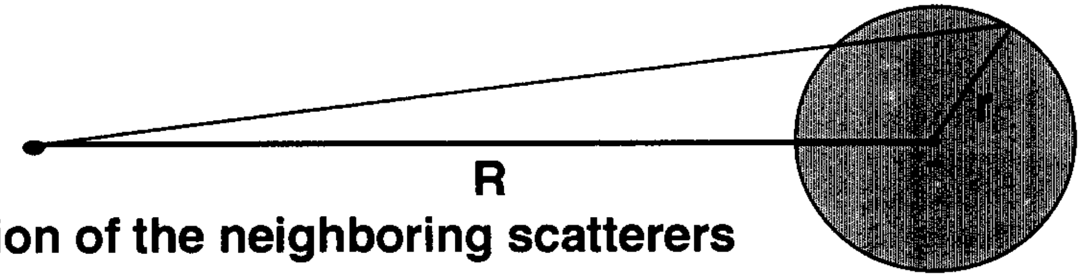


NEAR VS. FAR FIELDS



Examples D[m]	λ =.35 m R1[m]	R[m]
10	57	570
50	1430	14,300
100	5714	57,140

THE SCATTERING NEIGHBORHOOD - HOW BIG ARE THE SCATTERERS



The multipath contribution of the neighboring scatterers decrease away from the mobile as

$$\frac{S_{scattered}}{S_{direct}} = \frac{\sigma}{4\pi r^2}$$

- The delay profile has a r^{-2} slope
- At $r = 10$ m, $\sigma = 1\ m^2$ $\quad \frac{S_{scattered}}{S_{direct}} = -31$ dB m^2

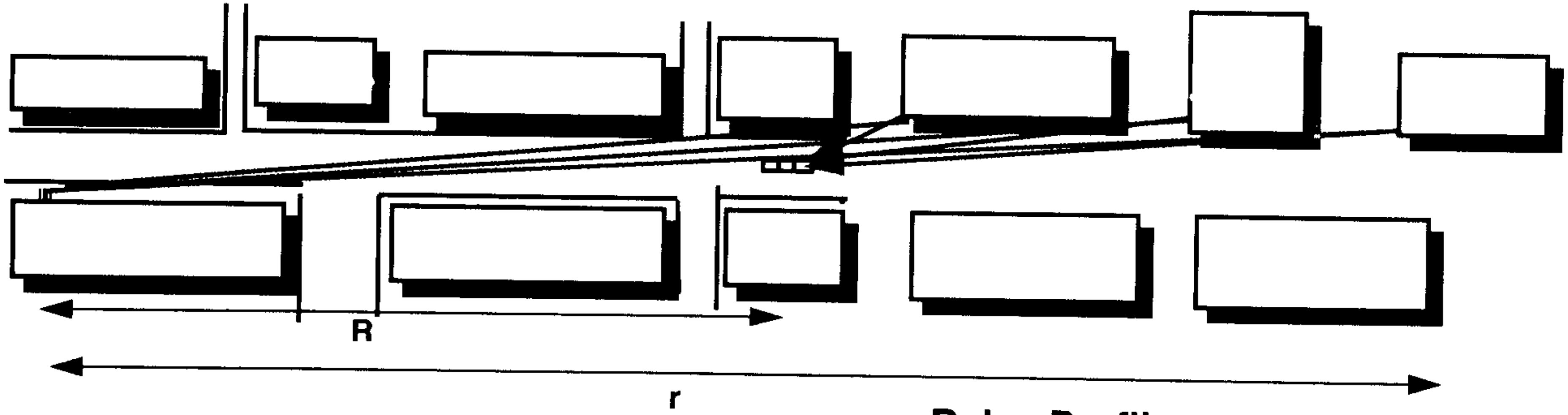
Representative scattering cross sections

- Elementary dipole $\sigma = -16.6$ dB m^2
- A typical car $\sigma =$ 1 to 10 dB m^2

In order for a multipath from a car, 10 m away from the mobile, to match the direct path, it has to be illuminated 20 to 30 dB stronger. Such an illumination gradient is not likely

The outdoors scattering neighborhood consists of a small number of large scatterers

PROPAGATION IN THE STREET CANYON : BACK REFLECTIONS



REFLECTION FROM PLANAR VERTICAL SURFACES

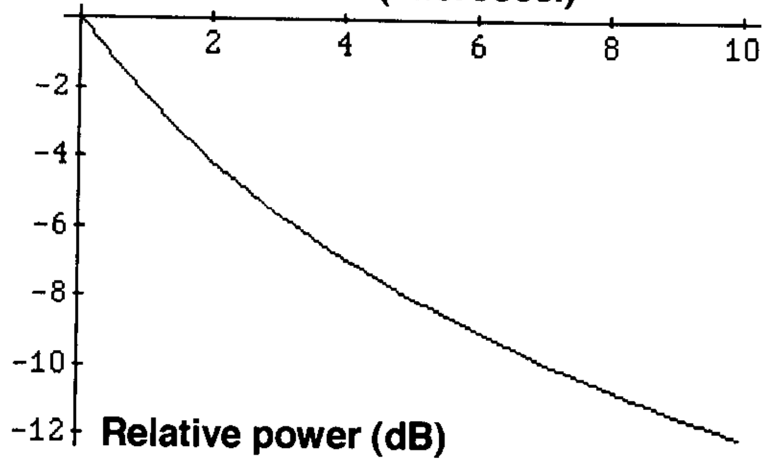
$l\ (dB) \sim 20 \text{ Log } (2r-R) = 20\text{Log } (R + ct)$

t - excess time delay

Multiple forward reflections are attenuated in most cases.

Back reflections dominate the delay profile

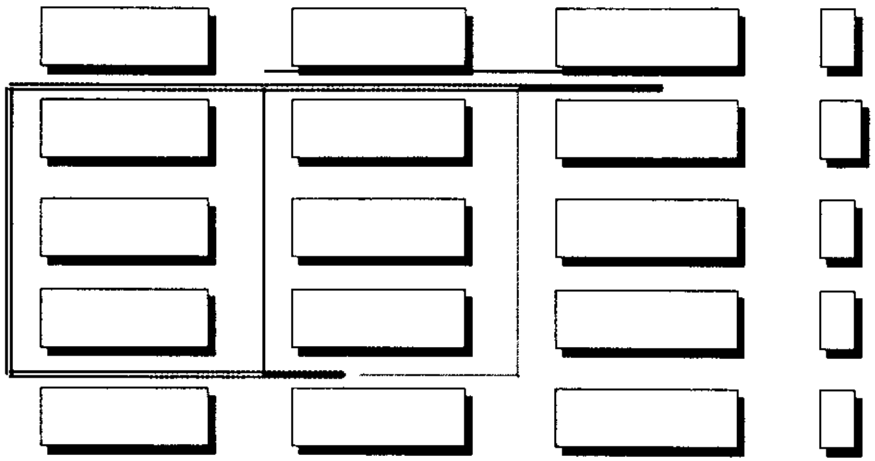
Delay Profile



FIRST ORDER PROPAGATION IN THE MAZE

$$t_j=\frac{1}{c}\sum_{i}^{n} R_i$$

$$T_j=G_tG_rK\frac{D^{n-1}}{\prod_{i}^{n} R_i\left(\sum_{i}^{n} R_i\right)^{\alpha-1}}$$



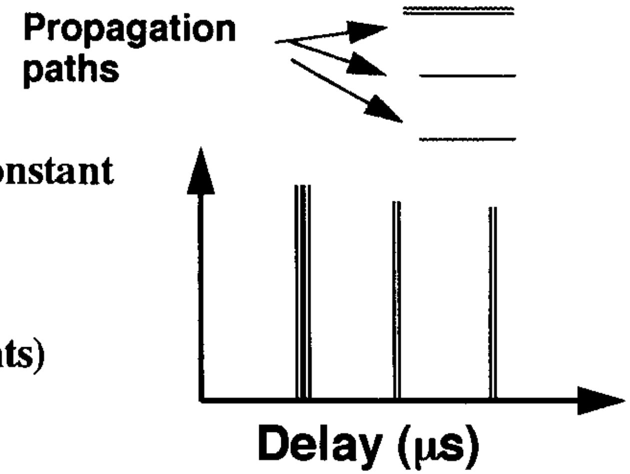
G_t	Gain of transmit antenna
G_r	Gain of receive antenna
λ	Wavelength
D	Compound corner diffraction
R_i	Length of each sector
α	Propagation-loss exponent
j	Index of the propagation path
τ	Time delay for the path
T	Transmission-loss for the path
c	Speed of light

K is a propagation constant

$$K=\left(\frac{\lambda}{4\pi}\right)^2 ;\alpha=2$$

$$K=(2hH)^2 ;\alpha=4$$

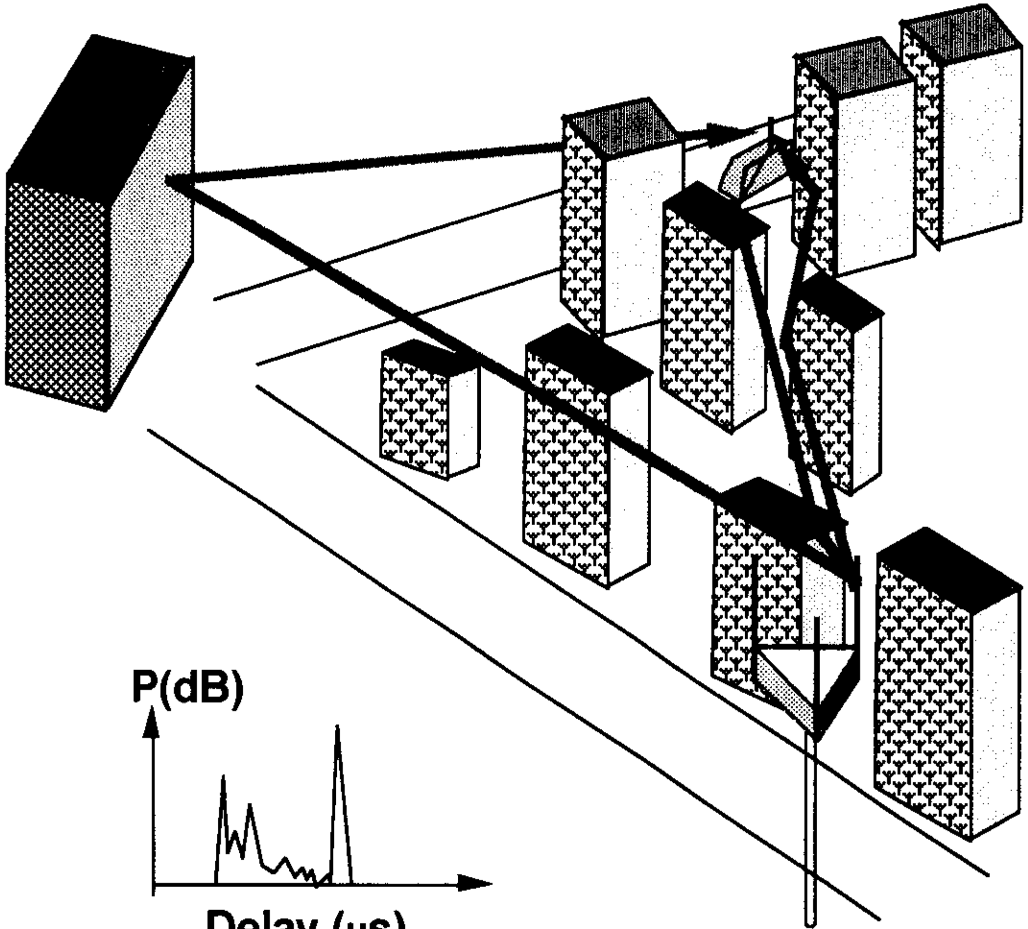
(h,H-antenna heights)



PROPAGATION IN THE MAZE (cont.)

- Both BS and MS antennas are far below the buildings height
- Buildings are dense and the cross streets are the only significant openings (other additional openings allow additional rays)
- The diffraction from all corners is lumped into one parameter D
- Multiple reflections along the street walls may affect the cross street only for corners near the BS (large angles). These affect only short distance along the cross street.
- The ray develops as a series of diffractions in corners in the horizontal plane, and free-space or empirical attenuation factor α-1 in the vertical plane.
- The number of corners that a ray passes determines its strength. The length of the pass determines the delay.
- Path ordering is therefore by [n], the number of corners.
- Lower buildings, or openings between the building, may by-pass this order, mainly for high [n].
- Many delayed peaks are possible for a path with high [n].

THE WASHINGTON DC CASE

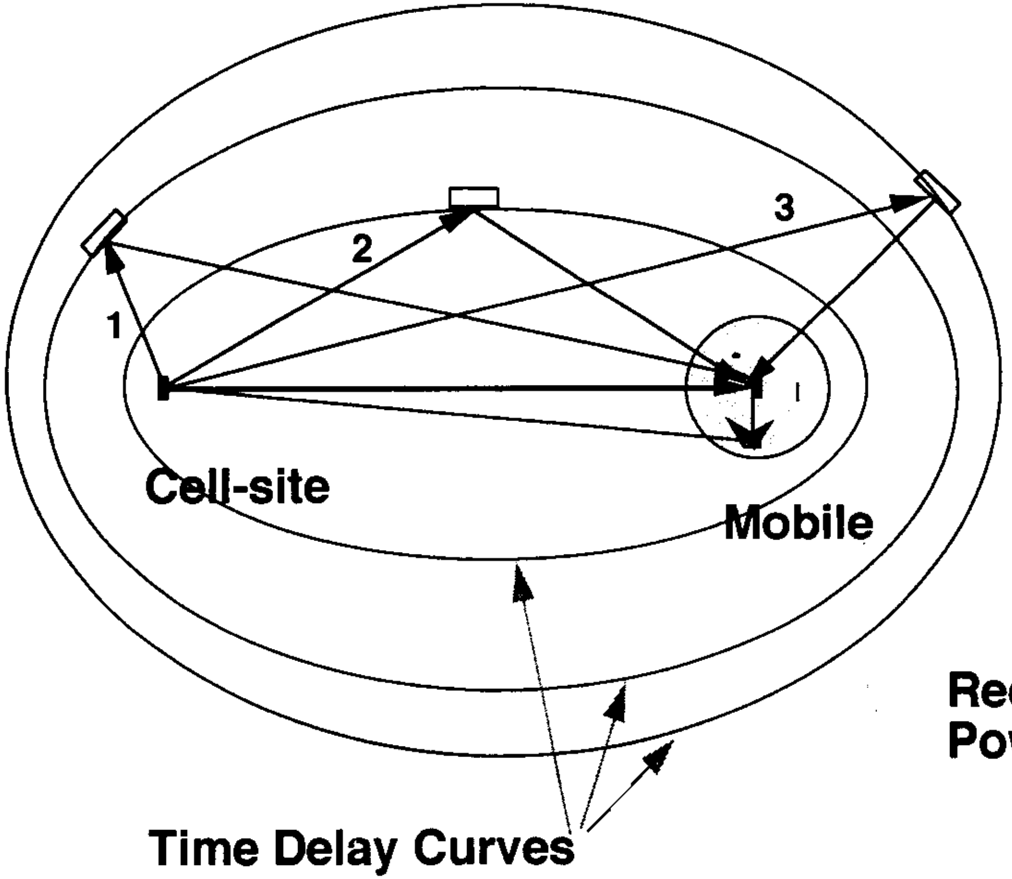


Reflection from the White House is stronger than the direct NLOS path

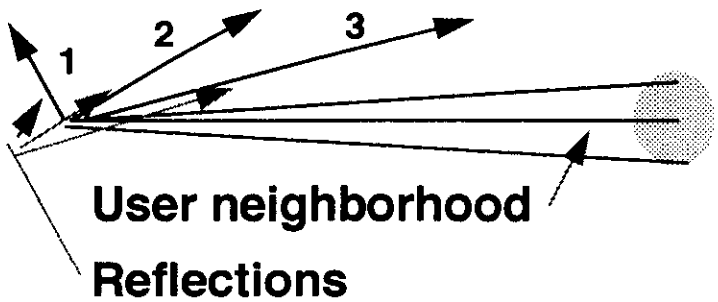
DELAY PROFILE - SUMMARY

- A short cluster resulting from neighborhood scattering
- Longer delays resulting from large reflectors
- The delay profile of reflectors extends further with the Tr-Rc distance
- The delay profile is longer when the delayed paths have a propagation advantage compared to the direct path (direct path is NLOS)
- The short delay cluster, that causes Rayleigh fades in a limited bandwidth signals, is longer when the path is NLOS, due to non uniform illumination.
- The longer delays have a shorter cluster, because they have to have a visibility advantage, and then LOS to the mobile. The have less fades (no Rayleigh fades).
- The short cluster in the outdoors is dominated by a small number of LARGE scatterers. It decays as τ^{-2} for uniform distribution of scatterers.
- In-building propagation is mostly isolated from the outside and has a short delay profile.
- The profile is clustered, according to multiple reflections. Each is surrounded by a short scattering cluster. The profile decays as exp{τ} according to the order of the multiple reflections
- The scatterers in-building are very close and a multitude of small scatterers contribute to the very short clusters (<10 ns).

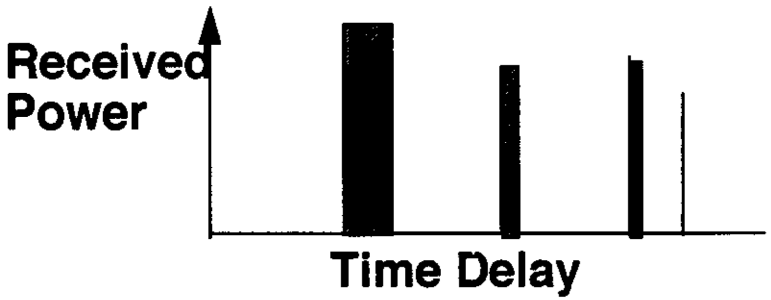
THE SCATTERING ENVIRONMENT



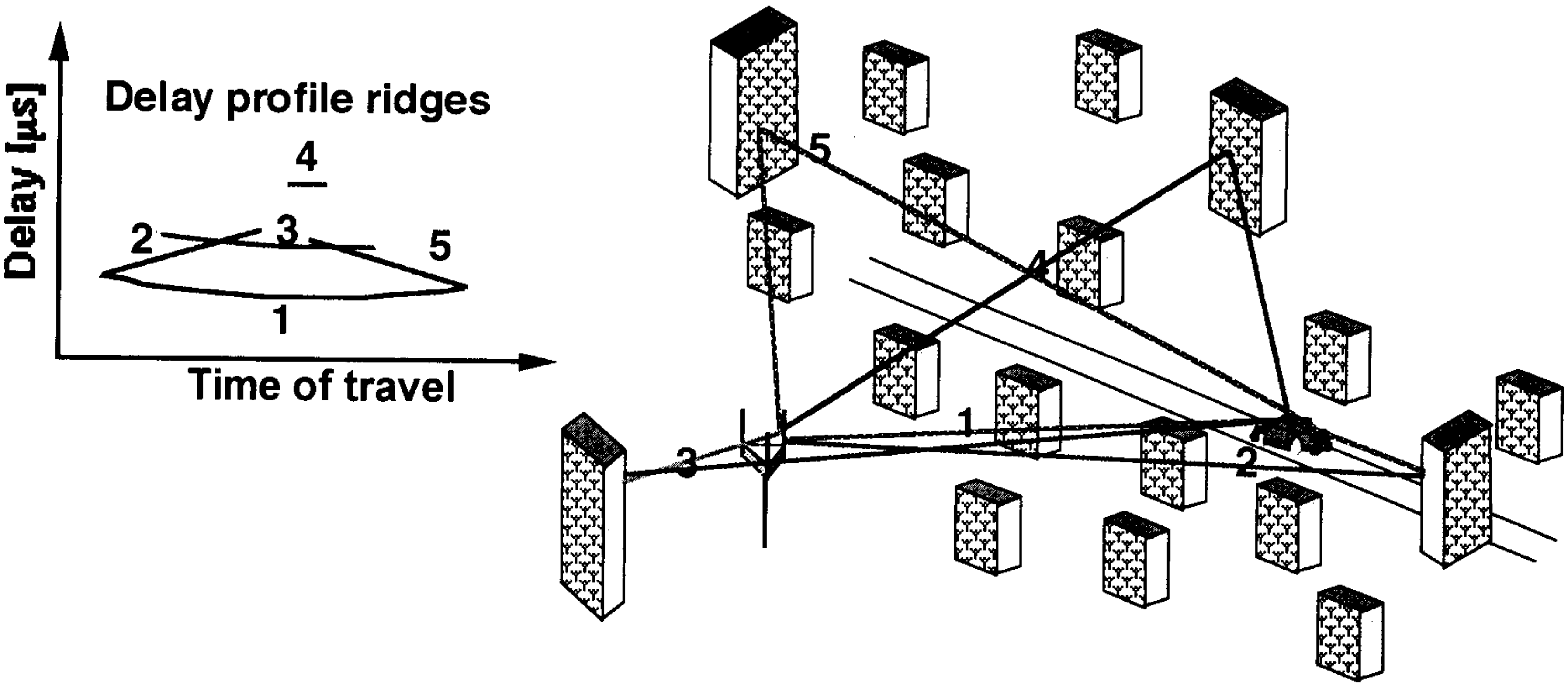
THE CELL-SITE ANGULAR SPAN



THE CELL-SITE DELAY PROFILE



TIME DEVELOPMENT OF THE OUTDOORS DELAY PROFILE

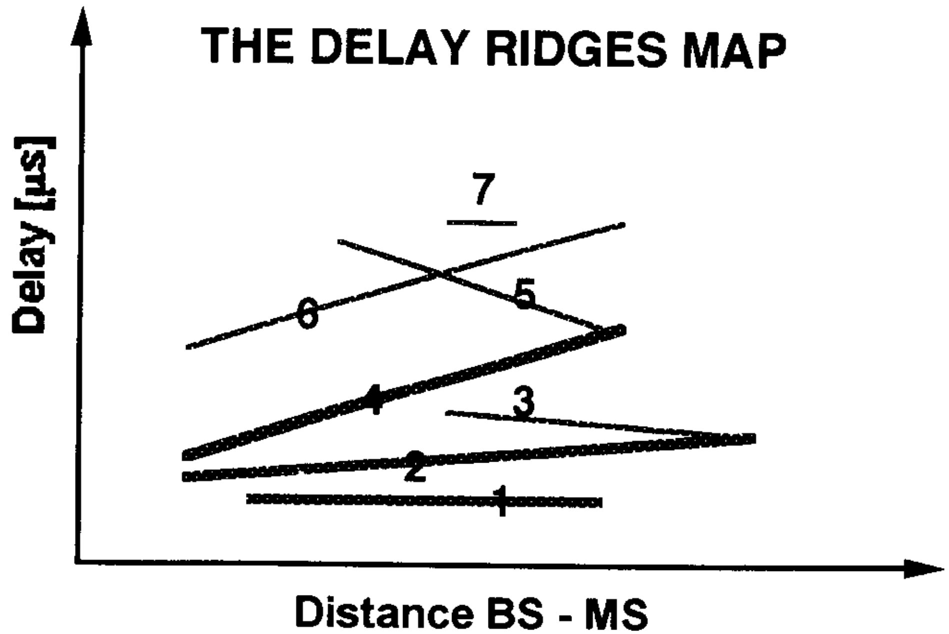


SPATIAL STRUCTURE OF THE DELAY PROFILE

- **Long delays result from reflections**
- **Both BS and the reflectors are stationary. The MS intersects a stationary illumination pattern.**

LEGEND

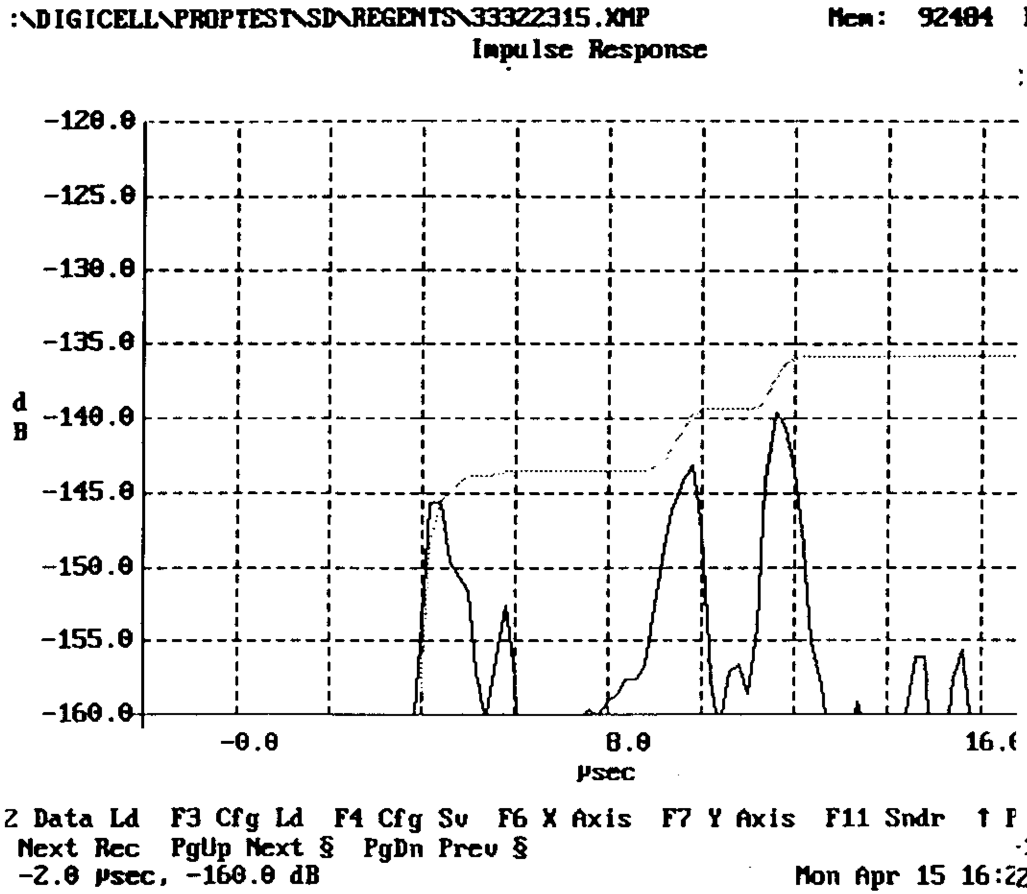
1 Direct path (DP), MS perpendicular to DP
2 DP, MS at an angle to DP
3 Reflection from a building along the MS route, away from BS
4 DP, MS route away from BS, Delay [μs] = Distance [m] /300
5 Reflection from a building along the MS route, away from BS
6 Reflection from a building behind the BS
7 Reflection from a building on the delay ellipse. The ridge is short (the MS traverses a beam).

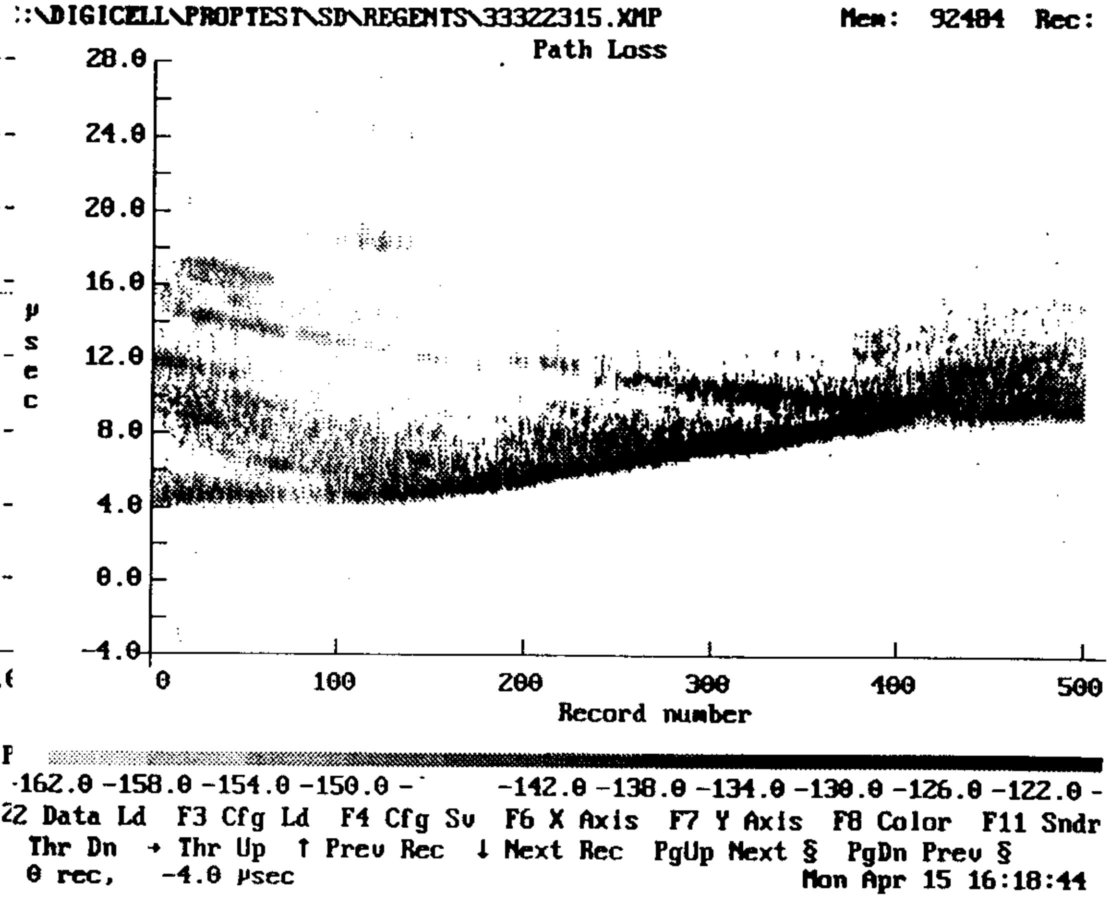


DELAY MAPS EXAMPLES

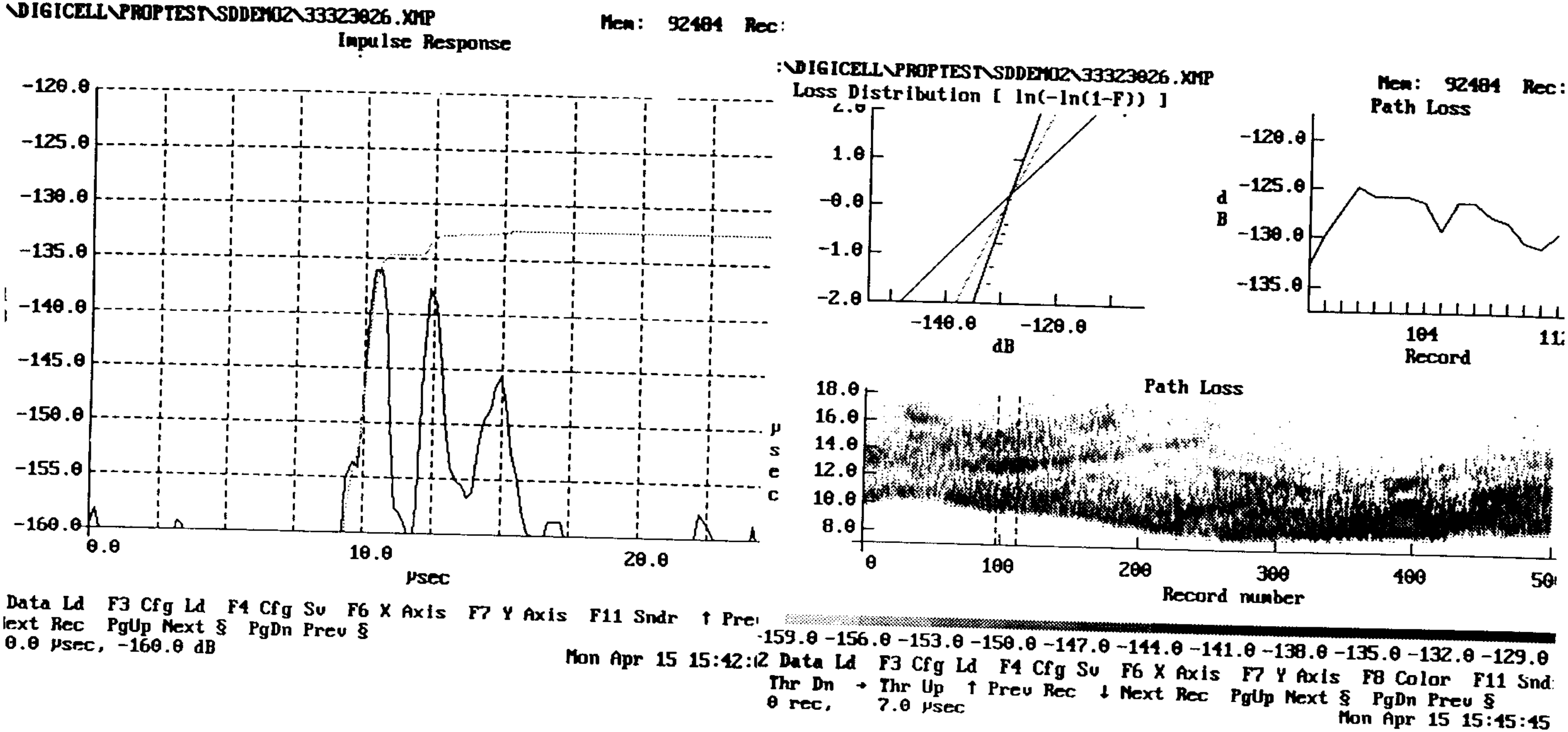
- Suburban - San Diego
- Manhattan

UNIVERSITY CITY, SAN DIEGO



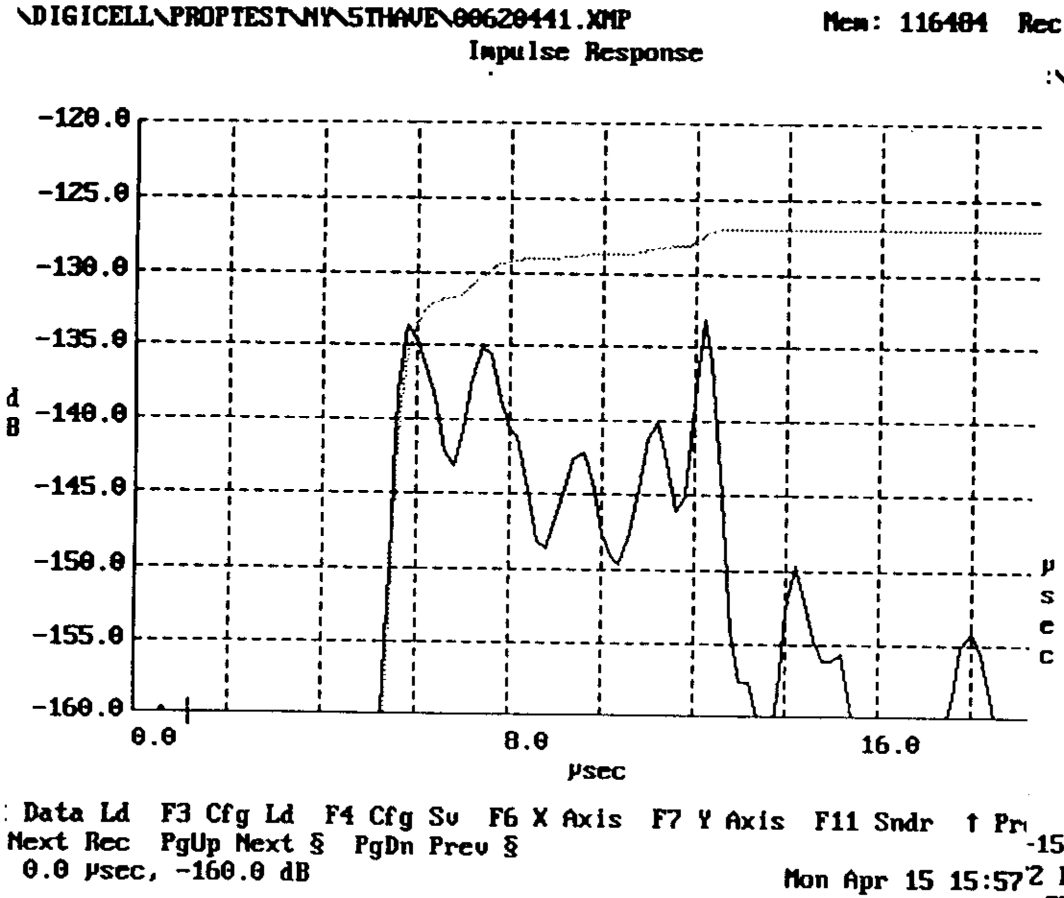


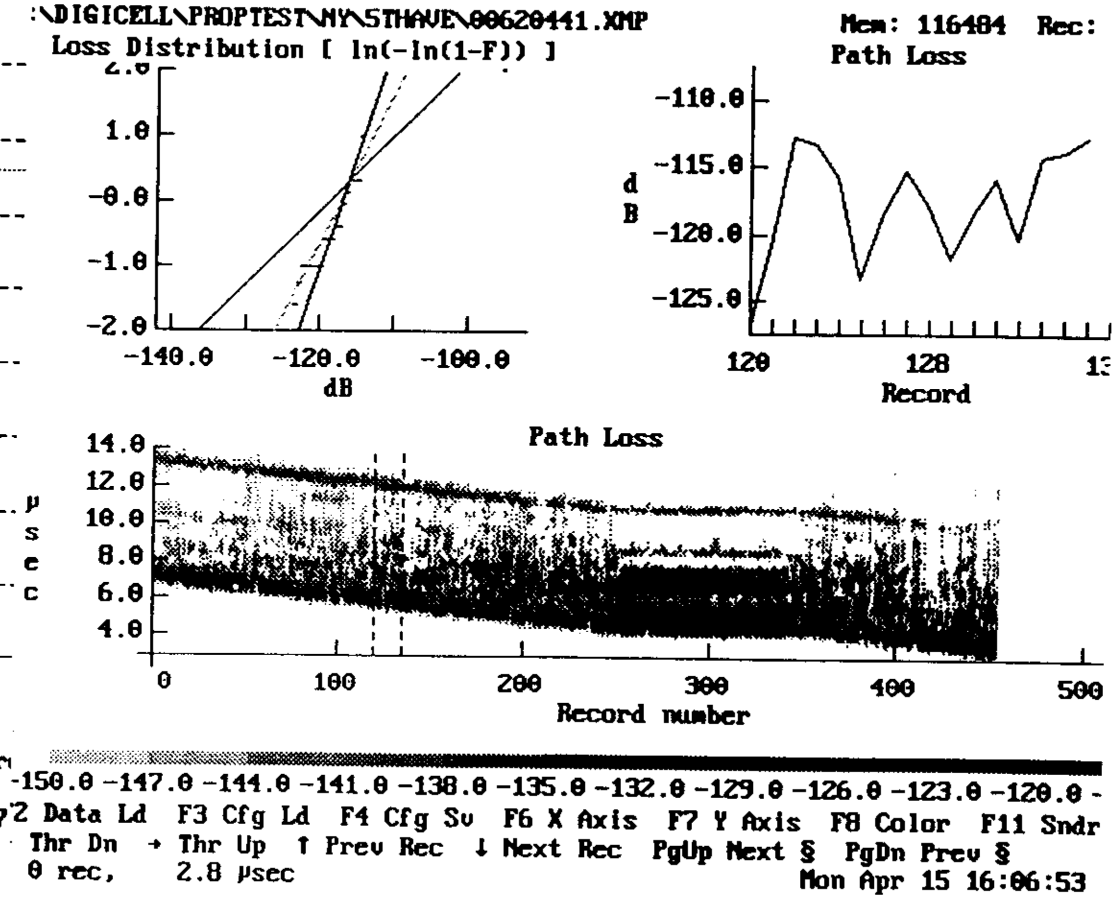
CARMEL VALLEY, SAN DIEGO



5 TH AVENUE, NEW YORK

MICROCELL. EMPIRE STATE BUILDING BEHIND THE BS



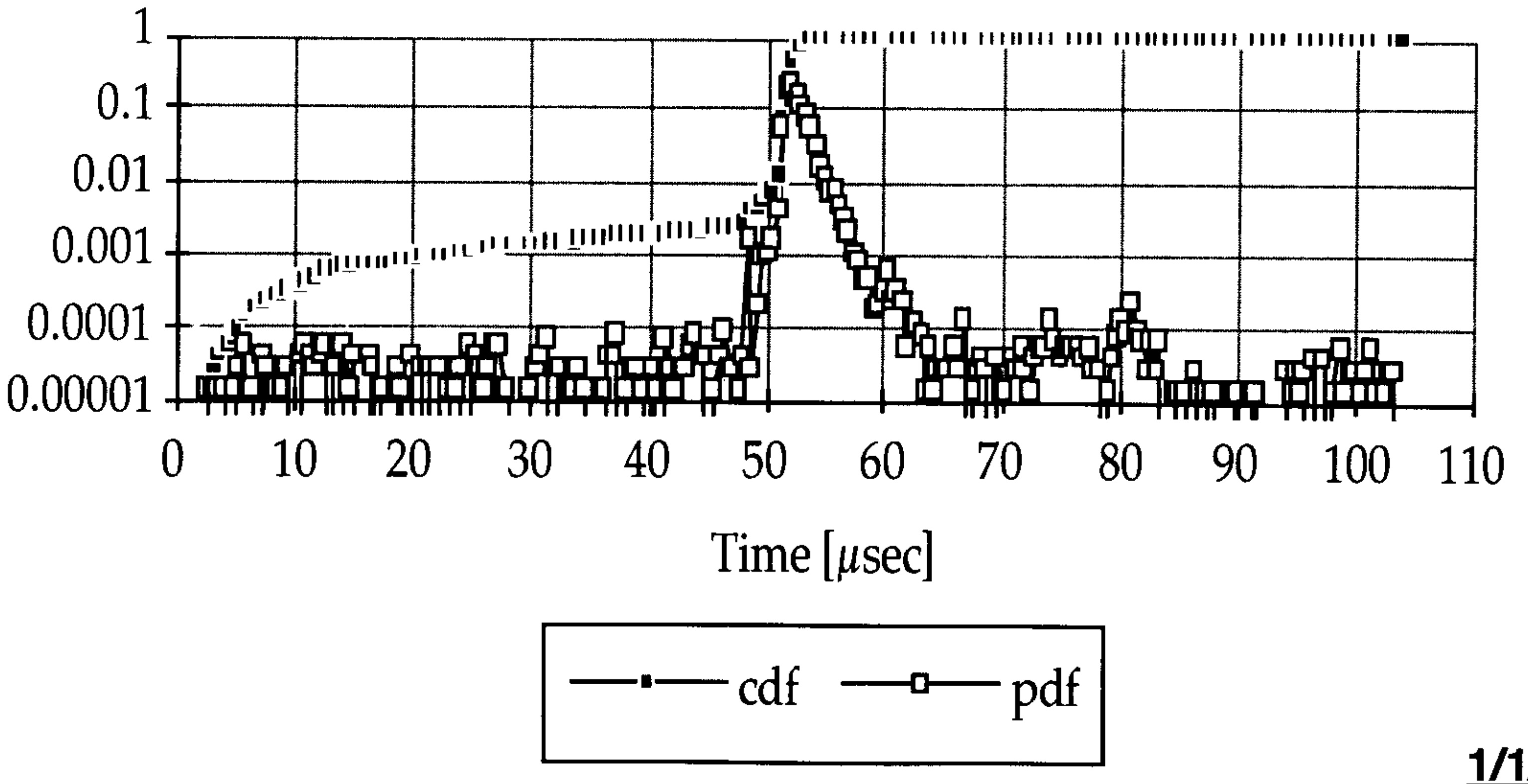


OBSERVATIONS FROM MEASUREMENTS

- The multipath spreads the signal into distinct peaks. The diffused delayed signal is much weaker.
- The delayed peaks are persistent, with lifetime from 1 to many seconds.
- Typical spreads:
  - Downtown, heavy urban - 1 to 5 μs. Up to 10 μs in extreme cases
  - Suburban,low level buildings with scattered high-rises - up to 20 μs
  - Mountainous - up to 40 μs (120 μs in Salt Lake City)
- In an are congested with scatterers and no LOS the peak is broad (diffused), 1 to 2 μs or more - and - with a 1.25MHz system, fluctuates, though less than Rayleigh. This is typical of the first peak.
- Later peaks are more stable in urban environment.

DELAY HISTOGRAM DOES NOT SHOW THE DELAY STRUCTURE

Multipath Delay Statistics
1 hr/ 80K samples Survey of 4 cells (MtAda, MValley, MBay (3 sectors), Downtown San Diego)



INDOORS PROPAGATION MECHANISMS

- **Furniture, machines, crowd, constitute a high attenuation clutter**
- **The floor space is slabbed into:**
  - Clutter layer
  - open space layer
  - ceiling clutter layer
- **Free-space propagation in the open space layer to a distance $R_F = 4 S^2 / \lambda$. Attenuation beyond that depends on the roughness of the layer boundary.**
  - Office furniture - attenuation beyond R_F reaches R^{-4}, and higher beyond $R = 8R_F$
  - Smooth concrete floor, ceiling or walls offer a guiding structure with low excess attenuation. Doors or other disturbances determine the attenuation.
- **Inner wall reflection coefficient may be as low as .5 (normal incidence). Penetration loss is 1.5 tp 5 dB**
- Reference: H. Bertoni, H. Honcharenko,L.R. Maciel, H. Xia, Proc. IEEE,Vol.82, No 9, pp.1333-1359

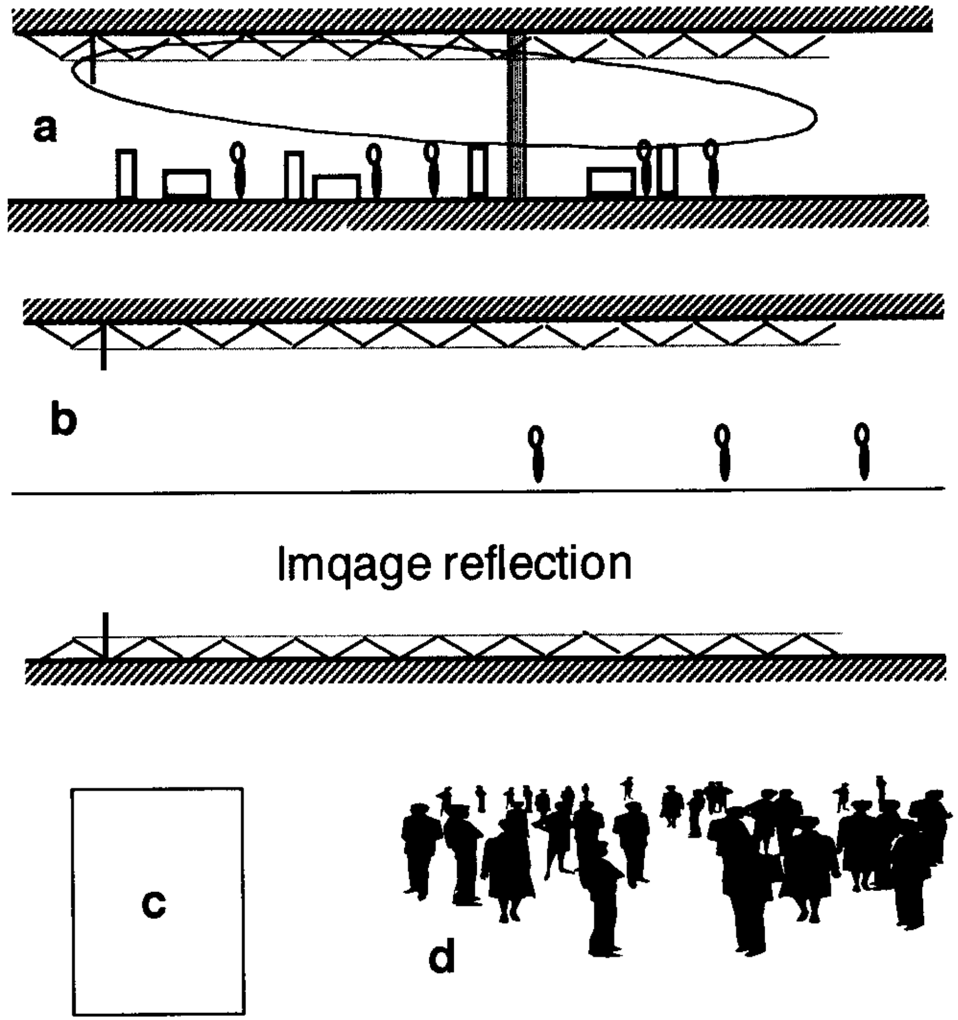
CLASSIFICATION OF THE INDOORS MEDIA

a Office space. Propagation in the open space, and attenuates beyond (exp 4). Additional loss down into the cluttered zone. Wall penetration and multiple reflections.

b Halls. The floor images the ceiling and the antenna. Long Fresnell zone. Standing wave pattern of the antenna and its image. (exp. 2.4)

c Corridors. May be a guiding structure with smooth walls (exp. 1.9). Open doors increase loss.

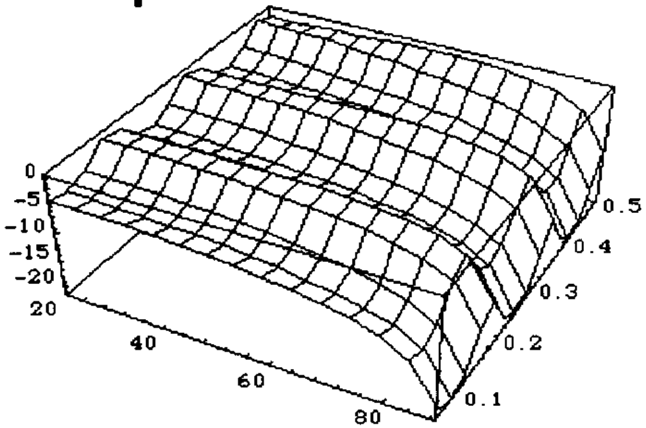
d A crown creates a clutter and moves #b to #a.

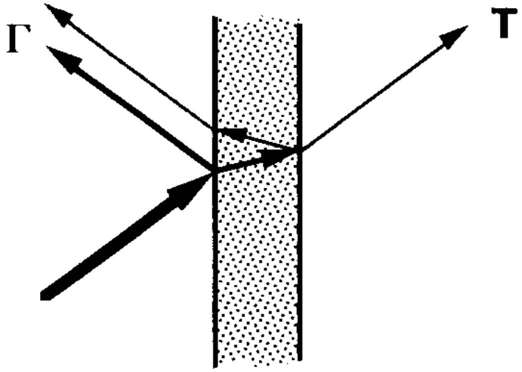


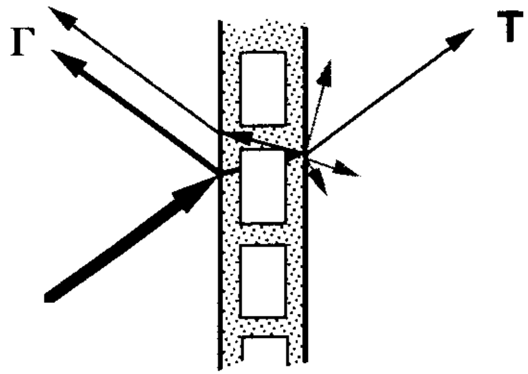
WALL PENETRATION

ε=10

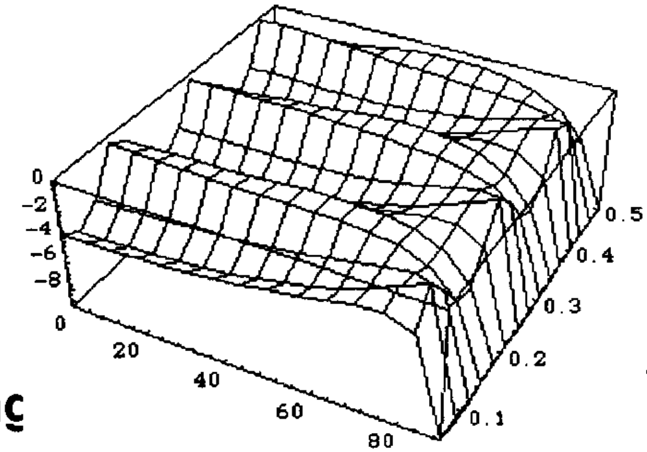
Penetration loss (dB)
Vertical polarization







Horizontal polarization



Anç
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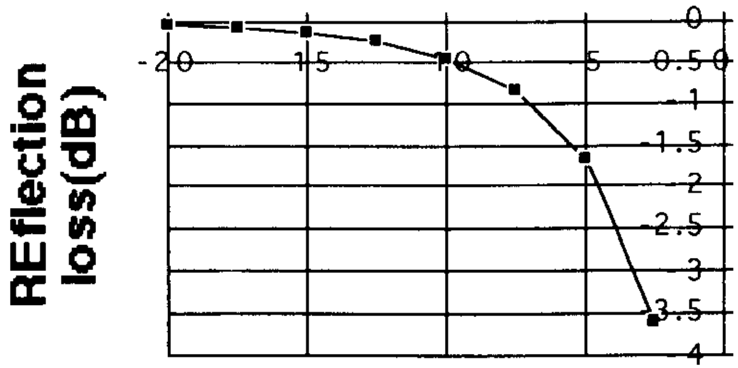
wavelengths



Penetration loss(dB)

WALL PENETRATION (CONT.)

- The wall acts as a radome
  - Not as a solid half space
  - The penetration depends on wall thickness and the angle of incidence
- Structured walls have stray penetration and reflection
  - Penetration may be higher at 1850 MHz than at 850 MHz
- Strong reflection and poor penetration near grazing
  - In LOS along streets the penetration degrades
  - In NLOS the incident radiation is mostly non directional and the penetration loss is smaller
- Penetration advantage to higher floors
  - The incident radiation is stronger

BUILDING PENETRATION LOSS

- **Service objectives - serve portables in buildings from outdoors BS**
- **BPL (Building Penetration Loss) definition**
  - AVERAGE signal level in a floor (or designated area in the floor) compared to the level OUTSIDE, AT STREET LEVEL (1.5 m)
  - Rationale - the service is to be compared with the outside level of service.
  - Difficulty - a multi-parameter definition. Depends on building configuration and structure, BS location, shadowing neighborhood, method of measurement and averaging.
- **Penetration mechanisms**
  - Wall penetration
    - » Wall structure (concrete, steel structure, hollow blocks, glass - metallic tinted or not, wood)
    - » Angle of incidence. Difference of 15dB and more between normal and grazing incidence.
    - » Wall penetration may vary between 0 dB (untinted glass wall) to 15 dB (normal incidence).
    - » Penetration through openings and hollow block is better at 1.8 GHz than at 850 MHz

BUILDING PENETRATION LOSS (cont.)

- **Wall penetration (cont.)**
  - Incident angle
    - » Penetration degrades toward grazing angles (e.g along streets)
    - » A reflection into normal incidence may compete with direct grazing.
    - » Depolarization may lead to -6 to -10 dB horizontal polarization. The penetration near grazing angles may be much stronger in Horizontal polarization.

- **Shadowing and dependence on floor level**
    - » Shadowing decreases with height for BS positioned above average building height. Propagation in that case is via roof scattering or direct illumination.
    - » This is the reason for the BPL improvement with height up to a floor where shadowing does not improve (average surrounding buildings level or any other better propagation path)

BUILDING PENETRATION LOSS (cont. 2)

- Designated areas
  - » Indoors propagation - see discussion
  - » Inside walls penetration may be 5 dB per wall
  - » Note: some published data refers to hallways and corridors only

- Some published numbers:

» First floor	14 dB
» Improvement per floor	2 dB (to fifth floor)

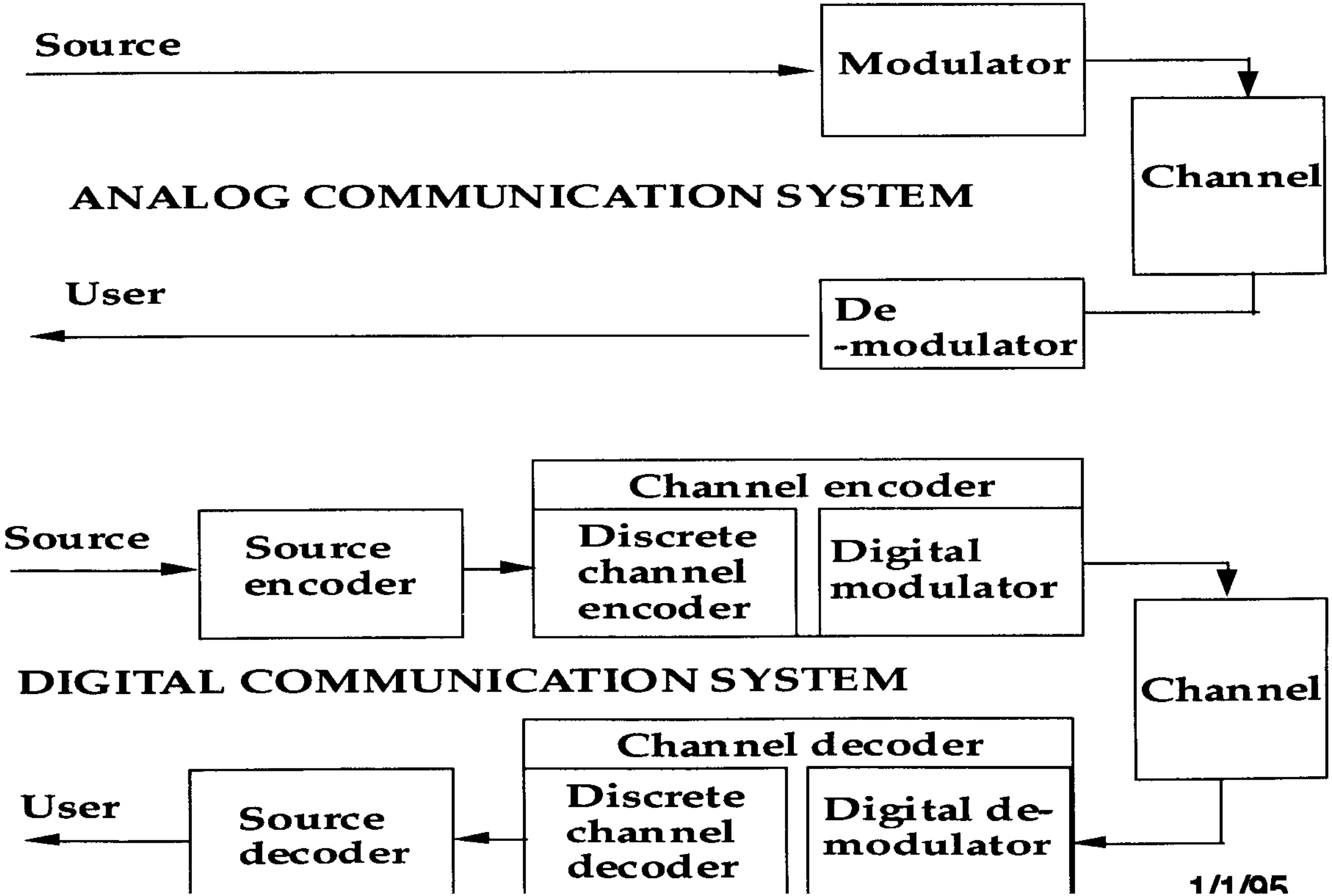
- Sample reference: W.J. Tanis, G.J. Pilato, IEEE VTC 1993, pp.206-209

PROPAGATION INSIDE A TUNNEL

- **An empty tunnel is a lossy waveguide.**
  - Signal at frequencies for which the wavelength is larger than the dimensions of the tunnel are attenuated exponentially.
    - » For tunnel width W, signal with $\lambda > 2W$ looses 100 dB in a couple of wavelengths
  - Propagation is not disturbed until the first Fresnell zone fills the tunnel ($R > 4W^2/\lambda$). Beyond that the loss depends on the loss of the walls
- **Traffic in the tunnel shrinks the uncluttered space, reduces the first Fresnell zone length and much increases the attenuation beyond that. This depends on the traffic density and vehicle size.**
- **measurements inside the Lincoln Tunnel in New York (W= 8m) yielded a R^{-4} law for f = 900MHz (Ref. W. Jakes, p.110)**
- **The entrance of the tunnel is not well coupled to the outside (corner effect).**

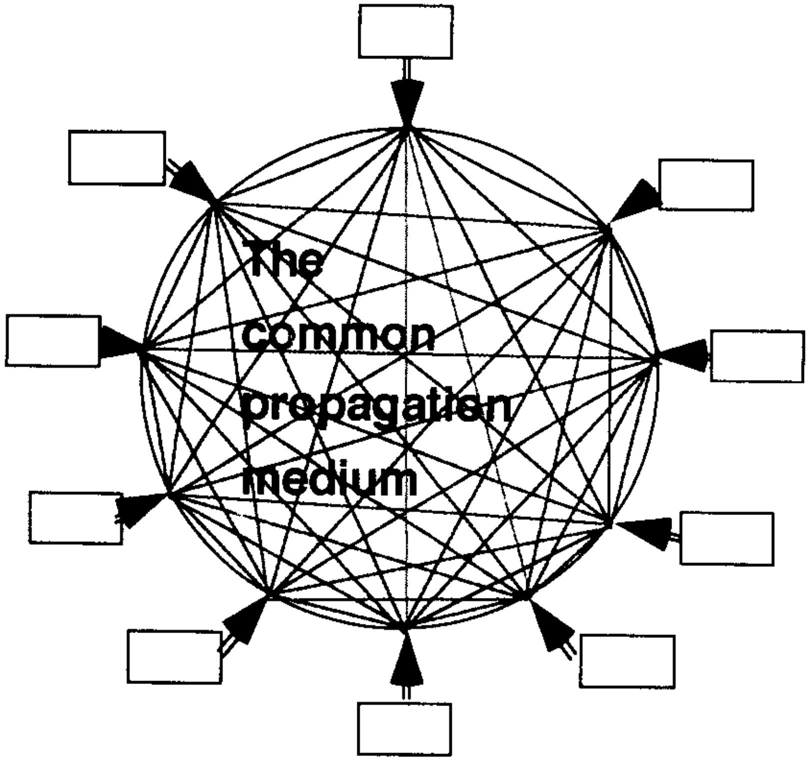
THE RADIO SYSTEM

COMMUNICATION SYSTEM BLOCK DIAGRAM



THE COMMUNICATION FILTERS

The Communication System Problem



The Communication Filters

Filter	Characteristics
Radial	Soft R^{α}
Angular	Soft θ^{α}
Polarization	Soft Cosine (θ)
Modulation	Depends on Type
Frequency	Hard (bandwidth bound)
Code	Hard (length bound)
Time	Hard (multipath bound)

THE COMMUNICATION FILTERS - MULTIPLE ACCESS SCHEMES

- **Many simultaneous users access the same medium**
- **FDMA - Frequency division multiple access**
  - Filtering is in the frequency domain:
    - » Each user has a separate band ("channel") allocated
    - » Interference is due to the frequency filters spillage and reuse of the channel beyond some distance (spatial filtering)
- **TDMA - Time division multiple access**
  - Filtering is in the time domain:
    - » Each user has a time slot
    - » The system has to be synchronized
    - » Transmission rate and peak power are multiplied, to maintain the same average data rate and E_b/N_o.
    - » TDMA may be combined with FDMA (as in IS54, GSM)
    - » Interference is due to synchronization errors, multipath and reuse of the channel beyond some distance (the higher peak power increases the reuse distance)

THE COMMUNICATION FILTERS - MULTIPLE ACCESS SCHEMES (cont.)

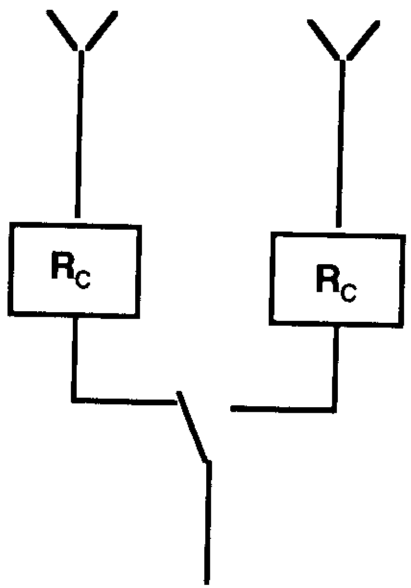
- **CDMA - Code division multiple access**
  - Each signal consists of a different binary sequence.
  - In a direct sequence (DS) the carrier is modulated, and the ("spreading") sequence spreads the spectrum of the wave form. The spreading rate is much higher than the data rate, and their ratio is the "processing gain" - the spreading code filter gain. In cellular applications the sequences are not orthogonal, because of extreme complexity of synchronizing the chips across the network. Interference is due to the transmission of all other coeds within the cell and in other cells, using the same frequency band.
  - In a frequency hopping (FH) the carrier is hopping into predetermined frequency slots (not necessarily contiguous), in a coded sequence. Codes may be orthogonal within the cell, and in a reuse pattern to avoid collision. A random code allows for some interference within the cell and between cells, due to non orthogonality of codes. The reuse pattern is reduced, however.
    - » Slow frequency hopping - when the hopping rate is lower than the data rate (more than one data bit per hop).
    - » Fast frequency hopping - when the hopping rate is faster than the data rate (more than one hop per data bit).

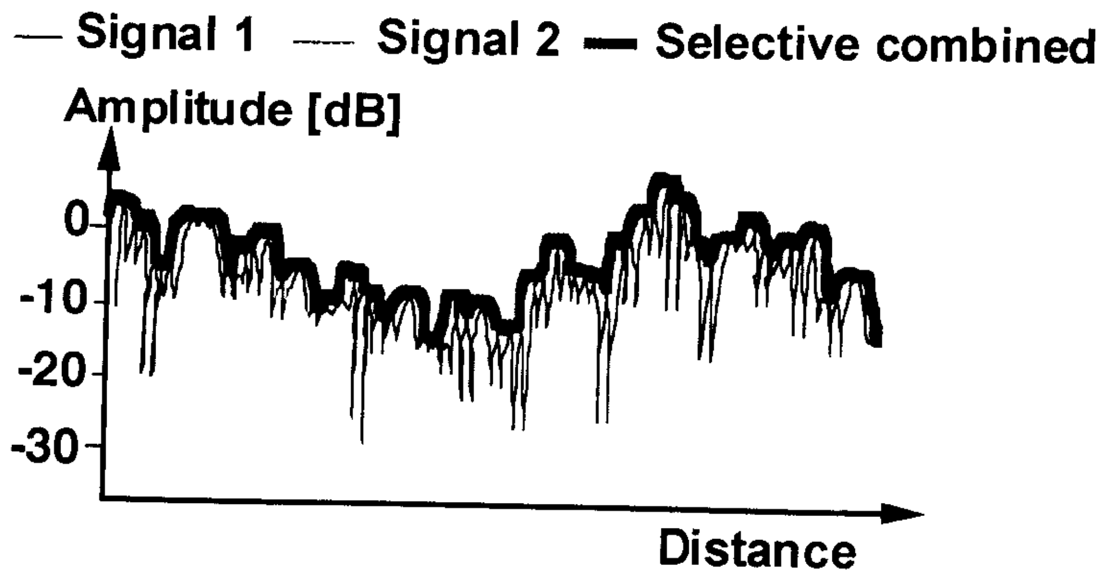
THE COMMUNICATION FILTERS - OTHER FILTERS

- **The radial filter - is a main tool in terrestrial cellular radio and determines the reuse distance**
  - Means of hardening the filter:
    - » Power control
    - » Antenna siting and vertical beam shaping
- **The angular filter- is limited by the antenna size.**
  - It is in extensive use in Point-To-Point communication (PTP).
  - Its use in the terrestrial cellular has been limited to sectorization in the BS. It has further potential for sectorization (CDMA) and in adaptive schemes for beam steering and interference nulling.
  - It is the main filter for cells reuse in cellular satellite communications.
- **Polarization**
  - The terrestrial mobile channel depolarizes the transmission, and polarization may be used as an auxiliary means only.

CHANNEL DIVERSITY

Example: selective combining of two fading channels reduces the occurrence of fades





DIVERSITIES

DIVERSITY - probing the channel at independent states

- Space diversity - space between (receive) antennas
  - Micro - for mitigating fades
  - Macro - for mitigating fades and shadowing

  Uses the unused spatial dispersion of the radiation
- Angle - different antenna patterns
  - Analog to micro - space diversity
- Time - different delays - the RAKE receiver
  - Requires bandwidth
- Time (macro) - the bit interleaver
  - Increases the processing delay
- Frequency - in FH, in wideband systems (beyond coherent BW)
  - Requires additional frequency slots
- Phase - the equalizer (reconstruction in the spectral domain)
- Polarization - needs a highly depolarizing medium, or a loss of 3 dB

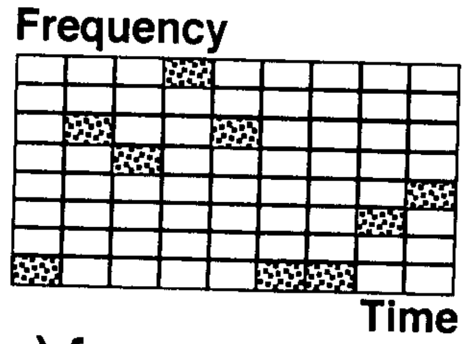
DIVERSITY (cont.)

- **The terrestrial mobile communication channel is mostly time-flat**
  - The signal deterioration is due to low SNR during fades
  - The noise (and the resulting errors) come in bursts during fades
  - Frequency dispersion adds interference to broad-band signals due to time stretching (ISI).
- **OBJECTIVES OF DIVERSITY RECEPTION**
  - Reduce the duration of each fade (spread the errors and make them manageable for corrections)
  - Reduce the total duration of fades and improve the average SNR
  - Reduce the frequency selective interference/ distortion by correcting the frequency dispersion in broadband systems.
- **KEY TO EFFICIENT DIVERSITY RECEPTION**
  - The diversity channels fade independently
  - The measure is by the correlation of the channels over the coherent source ensemble.

DIVERSITY (cont. 2)

- **Fast (Rayleigh) fading result from phase difference of the multipath components. Local diversity schemes apply.**
- **Slow (LogNormal) fading is a forward propagation mechanism and requires an amplitude difference. Macro diversity(path diversity) is required. The fade is slow and selective diversity combining is effective.**

FREQUENCY HOPPING



- The allocated frequency band is sliced into (narrow) frequency slots. The transmission hops between the frequency slots.
- Frequency hopping may be used as an additional means of diversity, to average the interference sources beyond the reuse distance (" interferer diversity"), and to limit the duration of long, frequency dependent fades (effective in slow user motion). This is the usage in GSM. Hops are slower than the bit rate.
- In a slow FHMA each hop has the duration of a code symbol. The narrow frequency slot is modulated by the coded information. The hopping sequence is coded in order to isolate the multiple access users.
- FH codes may be orthogonal, to eliminate in-cell interference, or random, which allows a reuse pattern of one, or mixed (orthogonal in-cell and random intercell).

FAST FREQUENCY HOPPING

- In a fast FHMA the hop is much shorter than the information bit and is similar to the chip in the Direct Sequence MA.
- FFH also provides frequency diversity when hopping beyond the coherence bandwidth.
- Fast FH is not technically practical.

Dr. Joseph Shapira

THE IS 95 CDMA CELLULAR SYSTEM

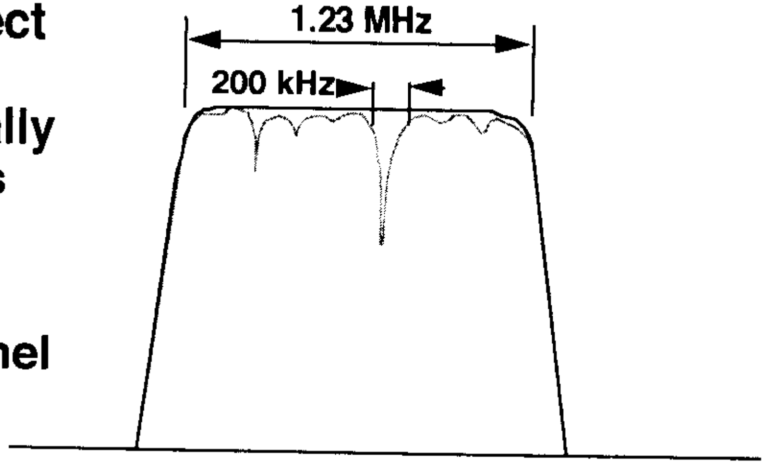
SYSTEM ATTRIBUTES

- Direct sequence Spread Spectrum system
- All users share the same band (reuse factor of 1)
- Bandwidth - 1.23 MHz per channel
- Processing gain (1230/9600) = 128 (= 21dB)
- Power control of the reverse link to within 1 dB accuracy over
- 80 dB dynamic range
- Power allocation in the forward link
- Soft handoff between cells
- Variable rate vocoder
- Rake receiver with 4 delay-searching fingers (one dedicated to searching another pilot - in the MS)

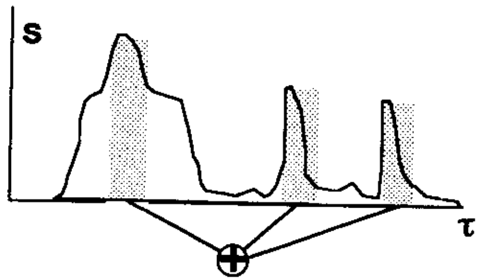
DIVERSITIES IN THE IS 95 CDMA

- **Frequency diversity**
  - Notches in the DS spectrum have little effect in terms of pulse dispersion and in interference as long as they are substantially narrower than the wave spectrum (notches may be considered as interference with reverse polarity. See the jamming test)
  - The coherence band of the outdoors channel is typically 200kHz
  - The SD wave shape provides frequency diversity

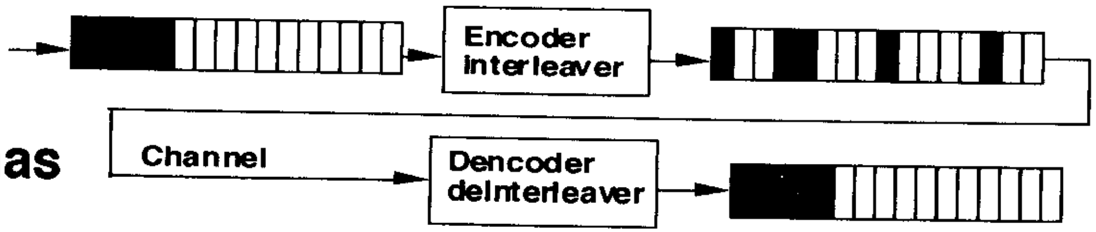
The CDMA spectrum



- **Delay diversity**
  - The wave shape resolves .8 μs. Resolvable delayed responses are detected by the "fingers" of the rake and optimally combined.



- **Time diversity**
  - Encoder & interleaver



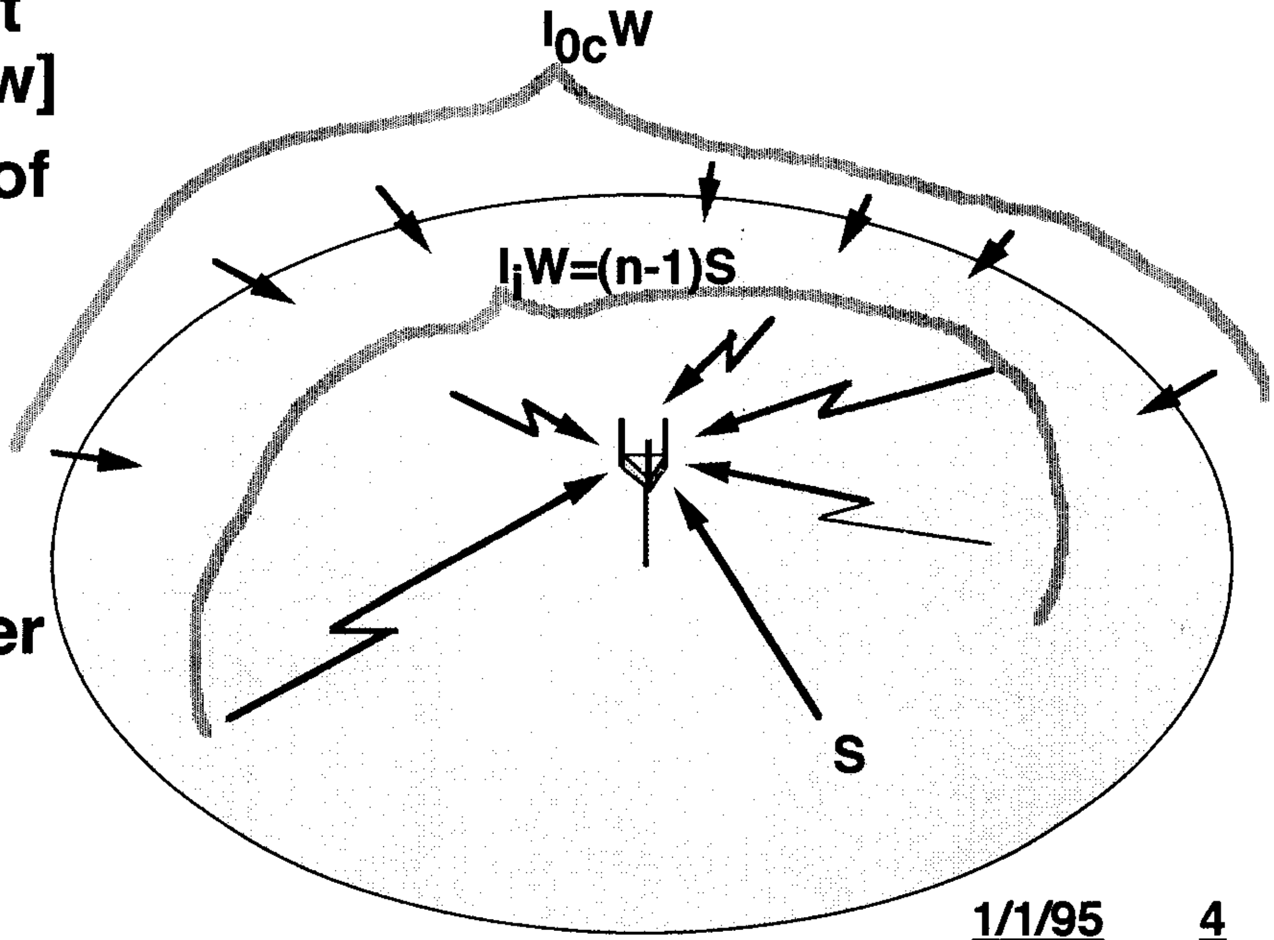
- **Space diversity - BS antennas**
- **Path diversity - soft handoff**

REVERSE LINK - SIGNAL AND INTERFERENCE

S Signal received at the base station [w]

I_i Spectral density of interference from all other users in the cell [w/Hz]

I_{oc} Spectral density of interference from users in other cells [w/Hz]



REVERSE LINK - CAPACITY EQUATION

I_o = Total spectral interference plus noise density

$$I_o = N_o + I_{oc} + I_i = N_o + I_{oc} + (n-1)S/W$$

W CDMA bandwidth

n Number of active calls

N_o Thermal noise spectral density at the input to the receiver LNA [w/Hz]

S Power received at the base station from each user [w]

C/I Signal (carrier) to noise and interference ratio

$$C/I = \frac{S}{I_o W} = \frac{S}{\left(N_o + (n-1)\frac{S}{W} + I_{oc}\right)W} = \left(\frac{E_b}{I_o}\right)\left(\frac{R_b}{W}\right)$$

$E_b = \frac{S}{R_b}$ Energy per bit of data

R_b The data rate (bit rate)

$\frac{E_b}{I_o} = \left(\frac{C}{I}\right)\left(\frac{W}{R_b}\right)$ Figure of merit of a digital modem

REVERSE LINK - CAPACITY EQUATION (CONT.)

I_{oc} The spectral density of the interference from other cells. Depends on the power control set of the other cells, their load, size and topography

v The voice activity factor: the fraction of time that a voice is transmitted in a telephone call. About 40%.

$I_i = (n-1)v \cdot S/W$ The spectral density of the interference from other users in the same cell.

$F = \frac{I_i}{I_i + I_{oc}}$ The frequency reuse factor. Note that

$$F = \frac{n\frac{S}{W}v}{n\frac{S}{W}v + I_{oc}} \text{ instead of } \frac{(n-1)\frac{S}{W}v}{(n-1)\frac{S}{W}v + I_{oc}}$$

to take care of the fact that all n users in other cells interfere

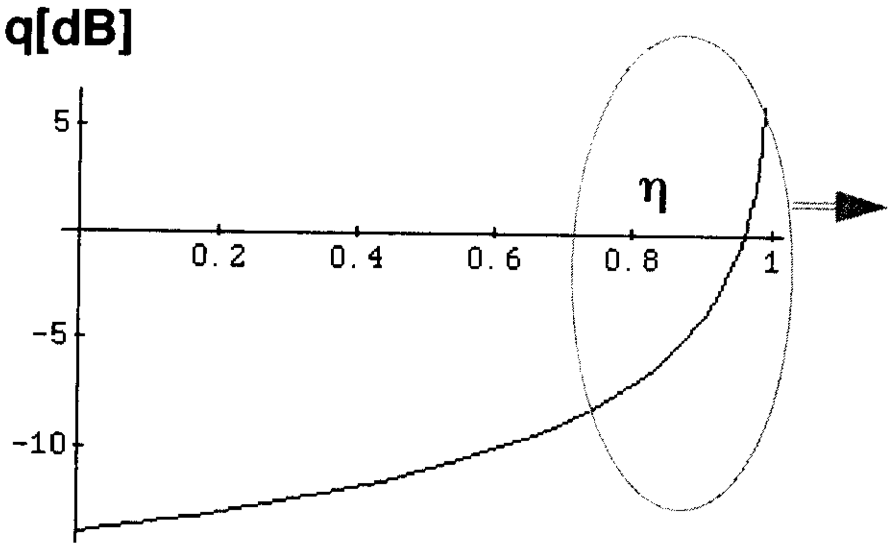
$$\frac{E_b}{I_o} = \frac{\left(\frac{S}{N_o W}\right)\left(\frac{W}{R_b}\right)}{1 + \left(\frac{n}{F} - 1\right)\left(\frac{S}{N_o W}\right)v}$$

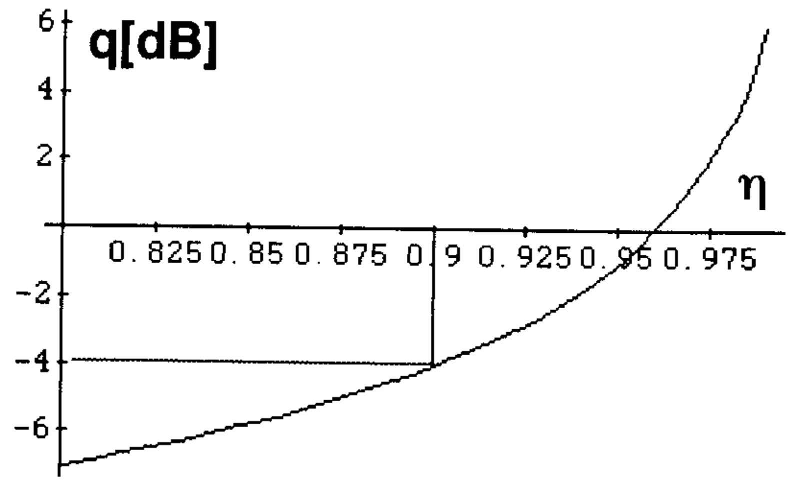
REVERSE LINK - THE LOAD EQUATION

$$q = \left(\frac{S}{N_o W}\right) = \frac{1}{\left(\frac{W}{R_b}\right) \cdot \frac{I_0}{E_b} - \left(\frac{n}{F} - 1\right) v} = \frac{\left(\frac{E_b}{I_o}\right) / \left(\frac{W}{R_b}\right)}{(1 - \eta)} = \frac{C/I}{1 - \eta} \qquad \eta = \left(\frac{n}{F} - 1\right) v \left(\frac{E_b}{I_o}\right) / \left(\frac{W}{R_b}\right)$$

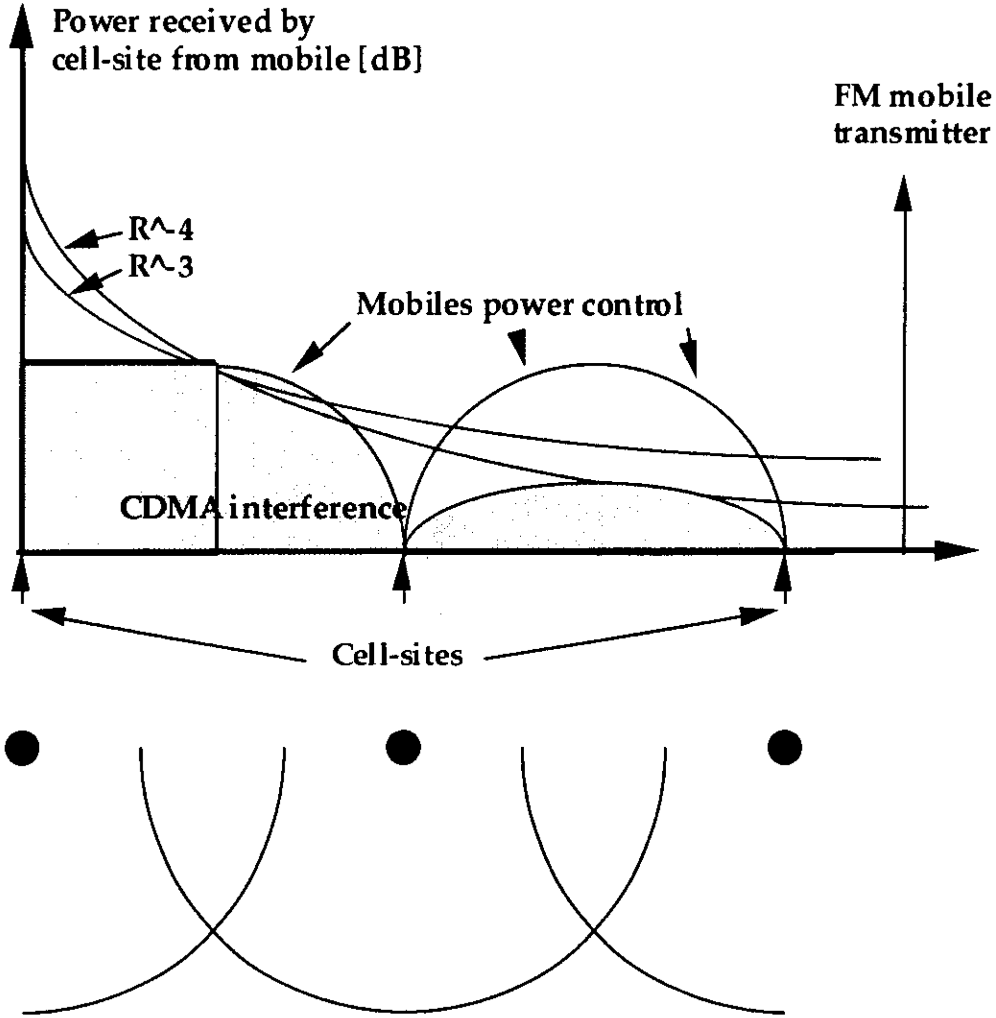
Example:

$$\frac{W}{R_b} = \frac{1{,}228{,}800}{9600} = 128 \; (= 21.07 \text{ dB}) \quad ; \frac{E_b}{I_0} = 5 \; (= 7\text{dB})$$





THE CELL NEIGHBORHOOD: DEPENDENCE ON THE PROPAGATION POWER LAW



CELL RADIUS VS. CAPACITY

UNIFORM CELL CLUSTER

$$q = \frac{1}{\frac{W}{R_b \varepsilon}\{1-\eta\}} = \frac{P_{max}}{N_0 W} L$$

$$L = A\,R^{-\alpha}$$

$$\left(\frac{R}{R_0}\right)^{\alpha} = \frac{1-\eta}{1-\eta_0}$$

L - cell radius

propagation exponent

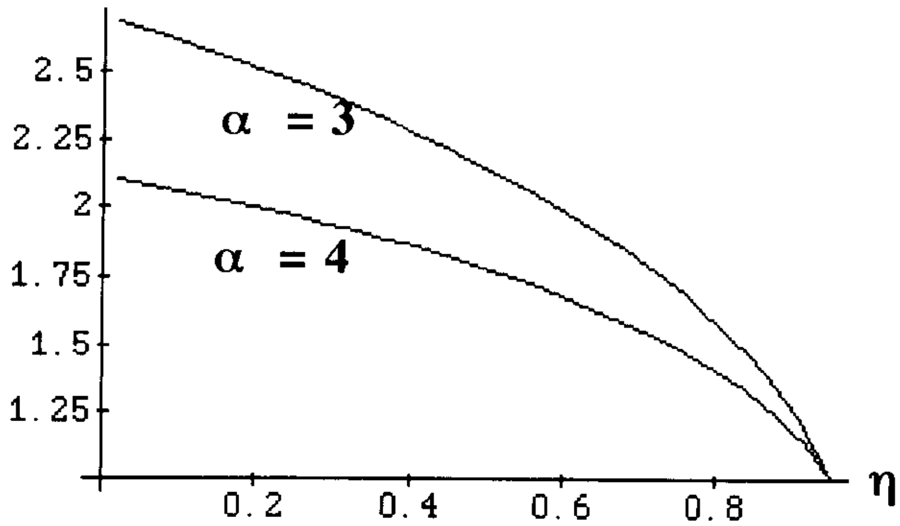
A - propagation constant

Ro - cell radius at nominal capacity

η - normalized capacity

η_0 =.95- nominal capacity (40 users)

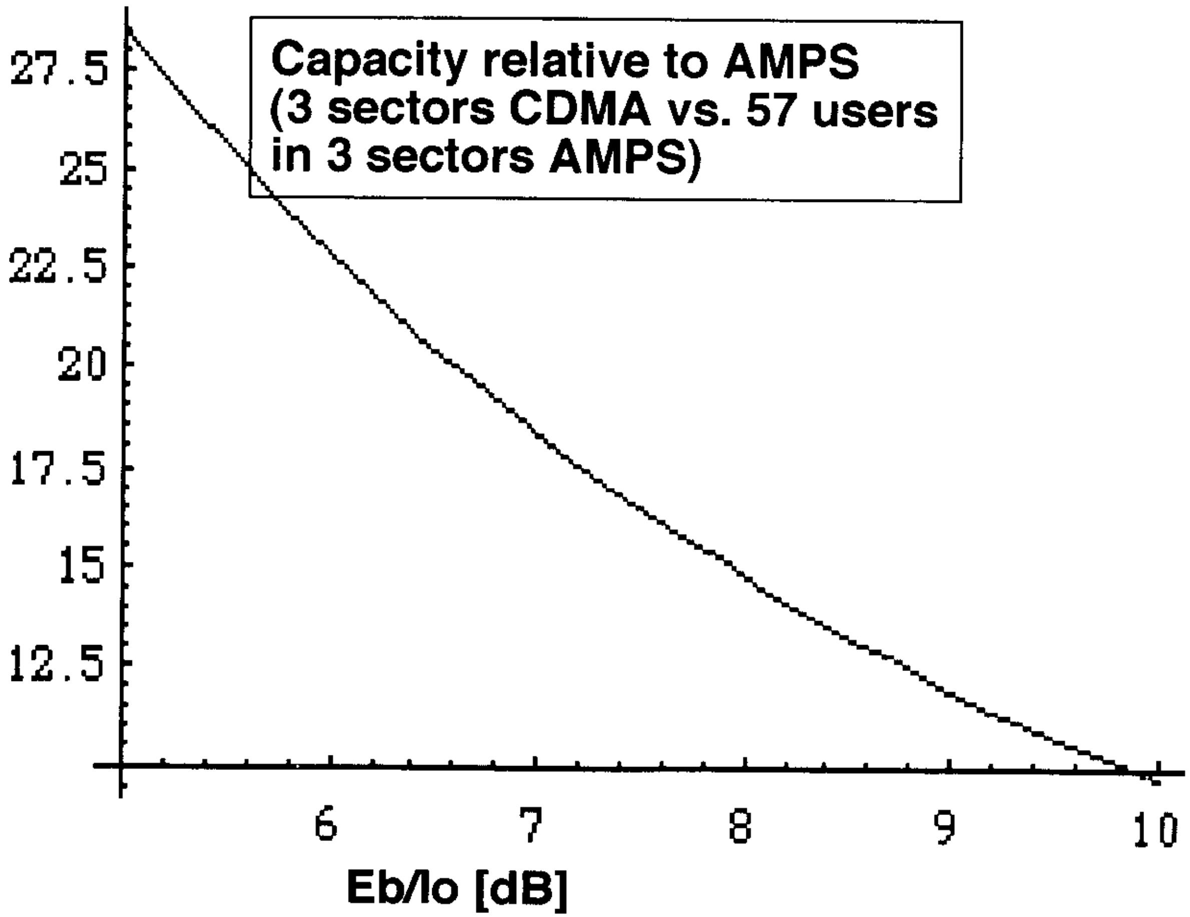
Radius vs. nominal radius



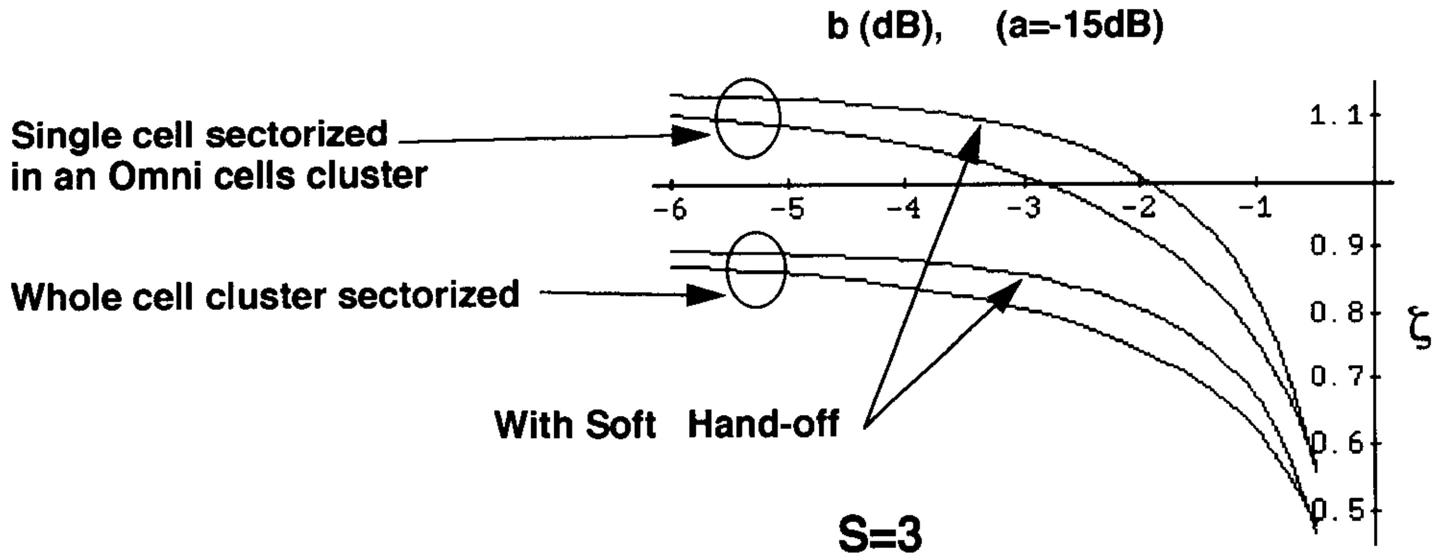
Eb/Io REQUIRED FOR DIFFERENT ENVIRONMENTS

Neighborhood type	Channel characteristics	$\frac{E_b}{N_0}$ [dB]	Notes
Open rural	Line-of-sight, single finger, Rician	5 - 6	If heavily wooded - see "Narrow urban"
Developed suburban	First cluster - 1 - 2 μ s, Nakagami 2. Two or more additional fingers. Delay - to 10 - 20 μs	6 - 7	Additional fingers are less frequent if no tall structures are in sight.
Urban	First cluster - 2 μs. Delay - to 5 μs	7	
Narrow urban	Single finger, Rayleigh	7 - 8	

CDMA CAPACITY VS. AMPS
as a function of Eb/Io



SECTORIZATION EFFICIENCY



Coverage vs. load over a uniform area density of users

- **Assume a user density ρ [users/unit area]**
- **Fixed allocation system (e.g. FDMA)**
  - Lightly loaded (Transmission-loss limited) $R_F = A^{-1/\alpha} T^{1/\alpha}_{max}$
  - Capacity limited $\rho > \frac{N_{max}}{\pi} \cdot \left(\frac{T_{max}}{A}\right)^{-2/\alpha}$ $R_F = \left(\frac{N_{max}}{\pi\rho}\right)^{1/2}$
- **CDMA**
  - Lightly loaded $R_{CDMA} = \left(\frac{T_{max}(\eta_0)}{A} \cdot \frac{1-\eta_0}{1-\eta}\right)^{1/\alpha}$,but $\eta = \pi \frac{V}{F} \cdot \frac{E_b}{I_0} \cdot \frac{R_b}{W} \cdot \rho R^2 = U\rho R^2$

$$R^{-\alpha}(1-U\rho R^2) = \left(\frac{T_{max}(\eta_0)}{A} \cdot (1-\eta_0)\right) = \frac{1}{B}; \text{ For } \alpha=4 \text{ -> } \left(\frac{R}{R_0}\right)^2 = (\rho R_0^2)\left(\frac{U}{2(1-\eta_0)}\right)\left[\sqrt{1+\frac{4(1-\eta_0)}{(\rho R_0^2)U^2}}-1\right]$$

  - Capacity limited $\rho > \frac{\eta_0}{U\left(\frac{T_{max}(\eta_0)}{A}\right)^{2/\alpha}}$ $R_{CDMA} = \left(\frac{\eta_0}{\rho U}\right)^{1/2}$

Coverage vs. load over a uniform area density of users (cont.)

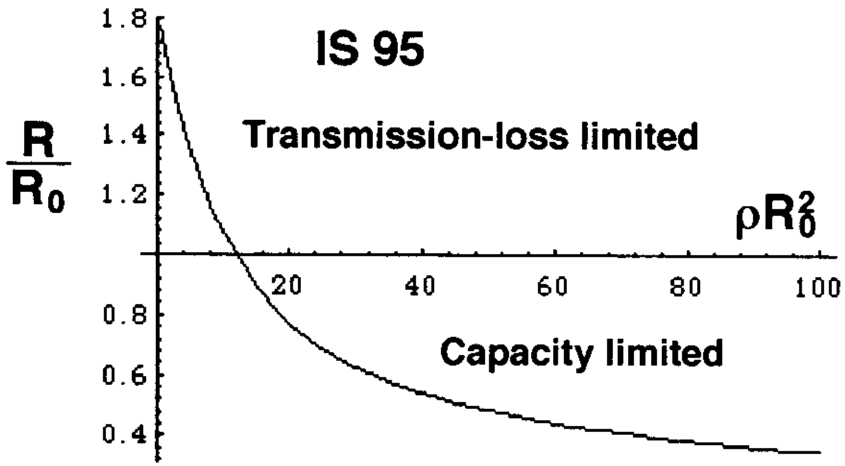
Now, for $\frac{E_b}{I_0} = 5$ (7 dB), $\frac{W}{R_b} = 128$, $V = .4$, $F = 1/1.55$, $\eta_0 = .9$

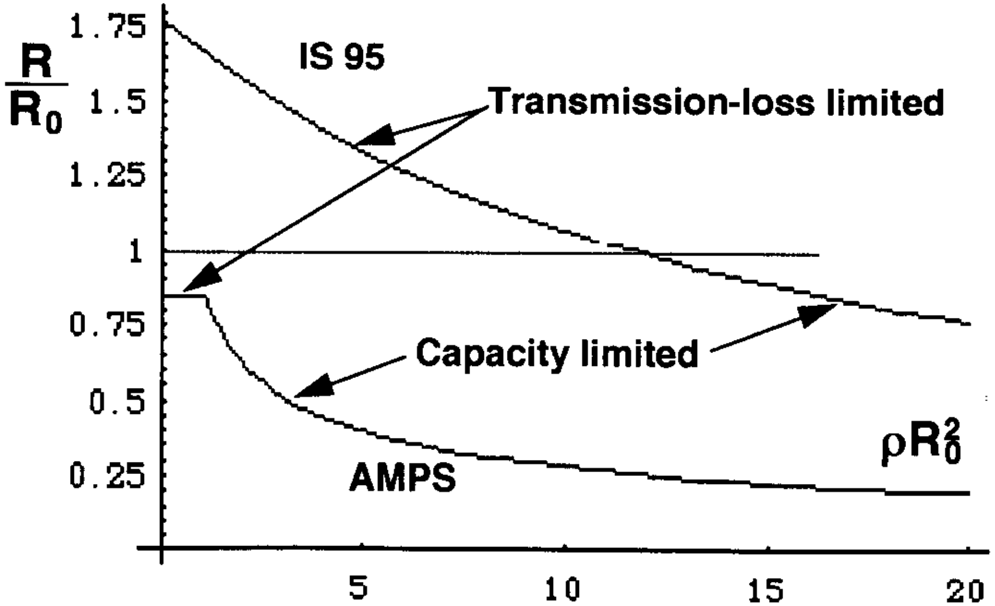
and $\alpha = 4$ $U = .076$, $\rho_0 R_0^2 = 11.84211$, $n_0 = 37.2$

In the capacity limited zone $\left(\frac{R}{R_0}\right)^2 = \sqrt{\frac{11.84211}{\rho R_0^2}}$

IS 95 capacity (3 sectors) in 12. MHz:

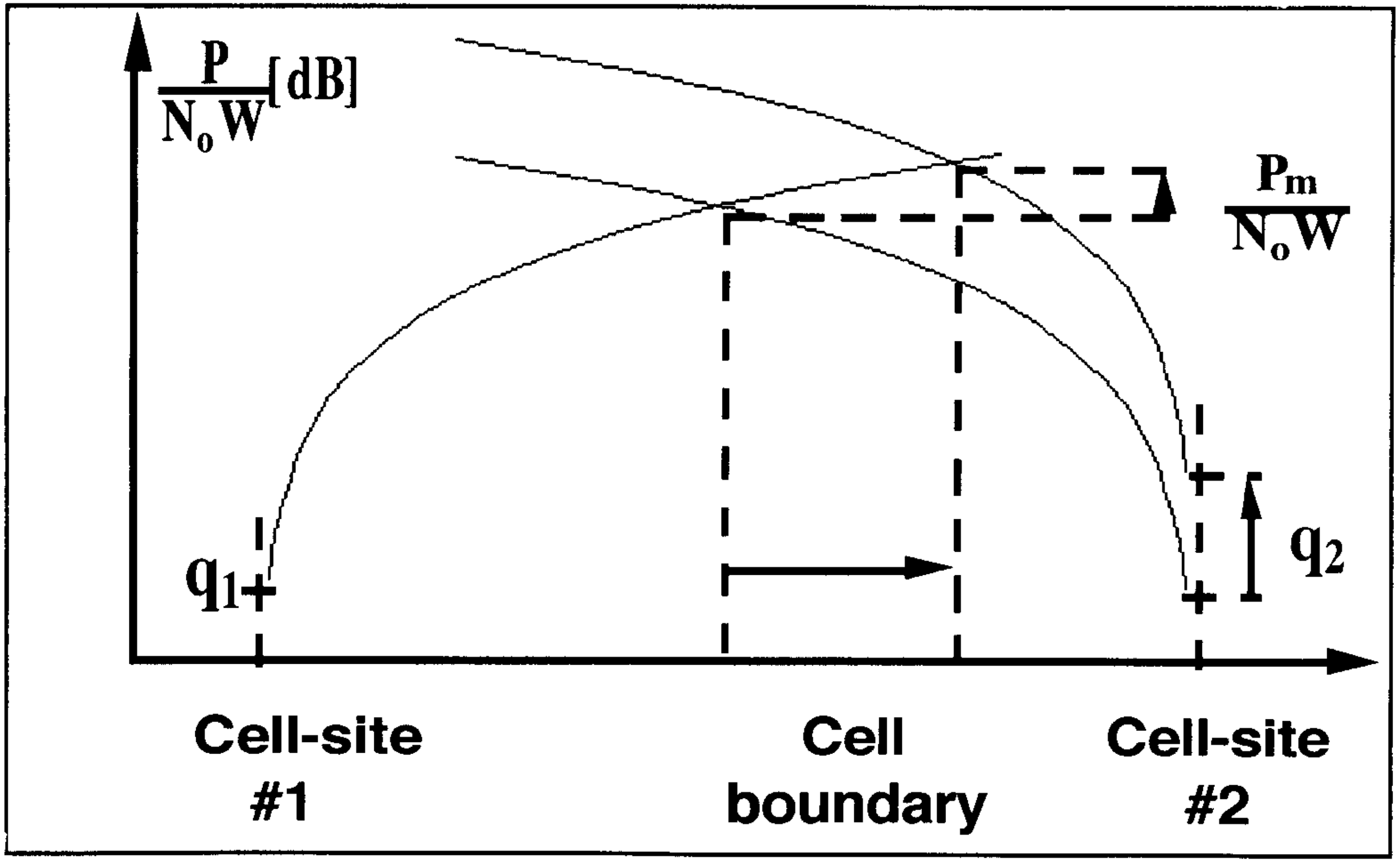
- $N_c = 37.2 * .85 * 3 * 9 = 853.74$, $N_c / 57 = 15$ (Note: this is circuit capacity, not Erlang capacity)





CELL BOUNDARY AND DYNAMICS

$$\frac{q_1}{T_1} = \frac{q_2}{T_2} = \frac{P_m}{N_0 W}$$; Now assume $T_i = A_i R_i^{-\alpha_i}$



FORWARD LINK

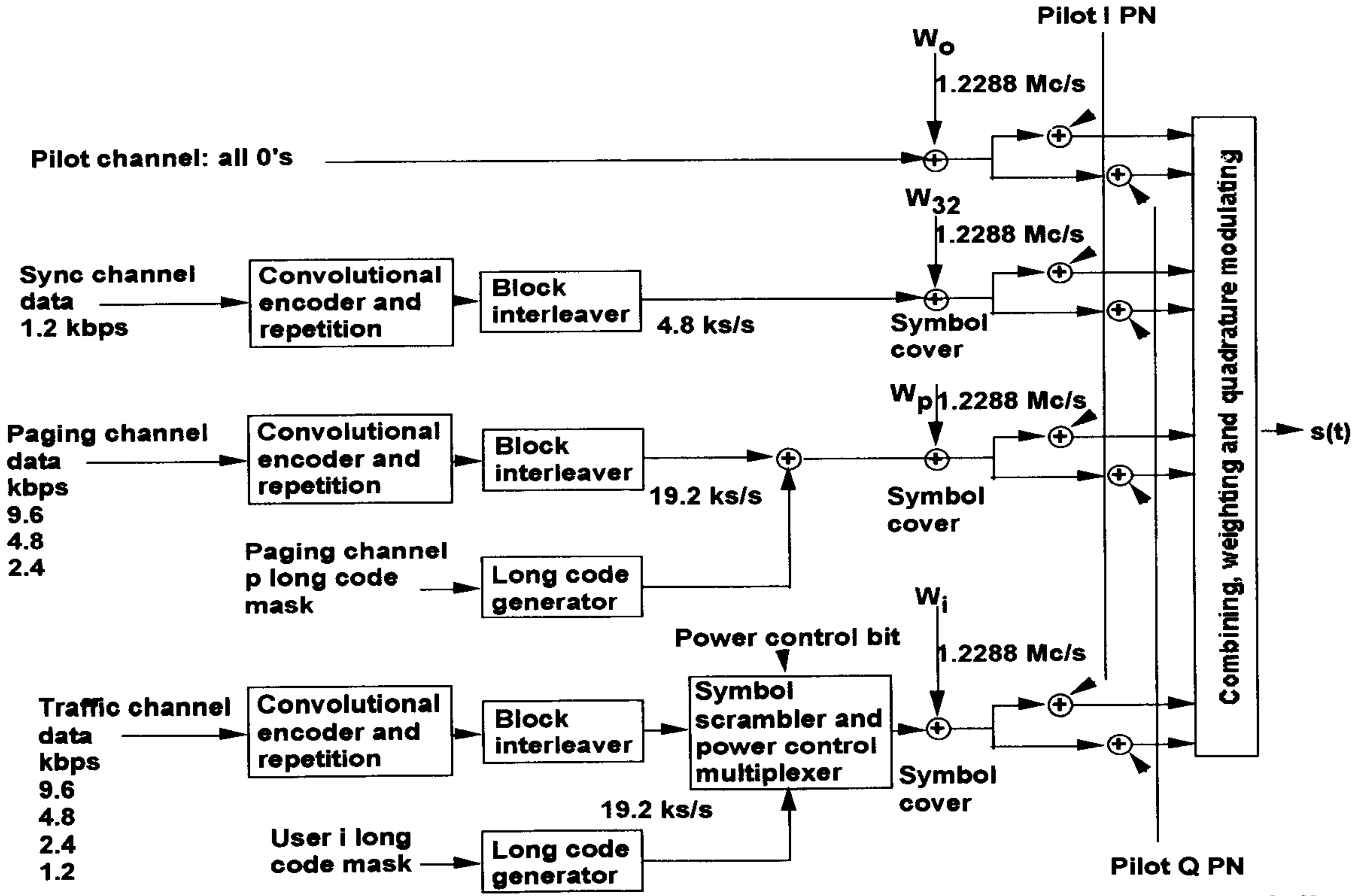
- **FORWARD LINK MAIN ATTRIBUTES**
  - One-to-many
    - » Synchronization and coherent reception are economical with the aid of a pilot
    - » Orthogonal codes may be used. Interference results from long delayed multipath only (over .4μs, or at least 60 m distance to scatterer)
    - » THE FORWARD LINK IS THEREFORE STRONGER: REQUIRES A LOWER MINIMUM E_B/I_O
  - A small number of interfering sources (other base stations)
    - » The interference depends on the location. It is highest at the border of three cells (or more, in certain cases)
  - The total base station power is proportional to the number of users.
    - » Relative power allocation to each user according to its required E_B/I_O or error rate
    - » The average power allocated to each user suffices for reception at the cell border (max $T=T_o$). Strategies for a lower value are possible

FORWARD LINK (CONT.)

- Forward link structure
  - P_p Pilot power. Varies with the cell load, to match the cell boundary in the forward with the reverse link
  - P_{page} Power of paging channel. Fixed (up to m=7 paging channels). $P_{page} = P_s$
  - P_{sync} Sync. channel power. Fixed. $P_{sync} = .25\ P_s$
  - P_s Power in one signal channel. There are n channels.
  - P_{BS} Total power output from the power amplifier of the base Station

$$P_{BS} = P_p + mP_{page} + P_{sync} + nP_s = P_p + lP_s \text{ ; } l = m + n + 1/4$$

FORWARD LINK



CODING AND DECODING

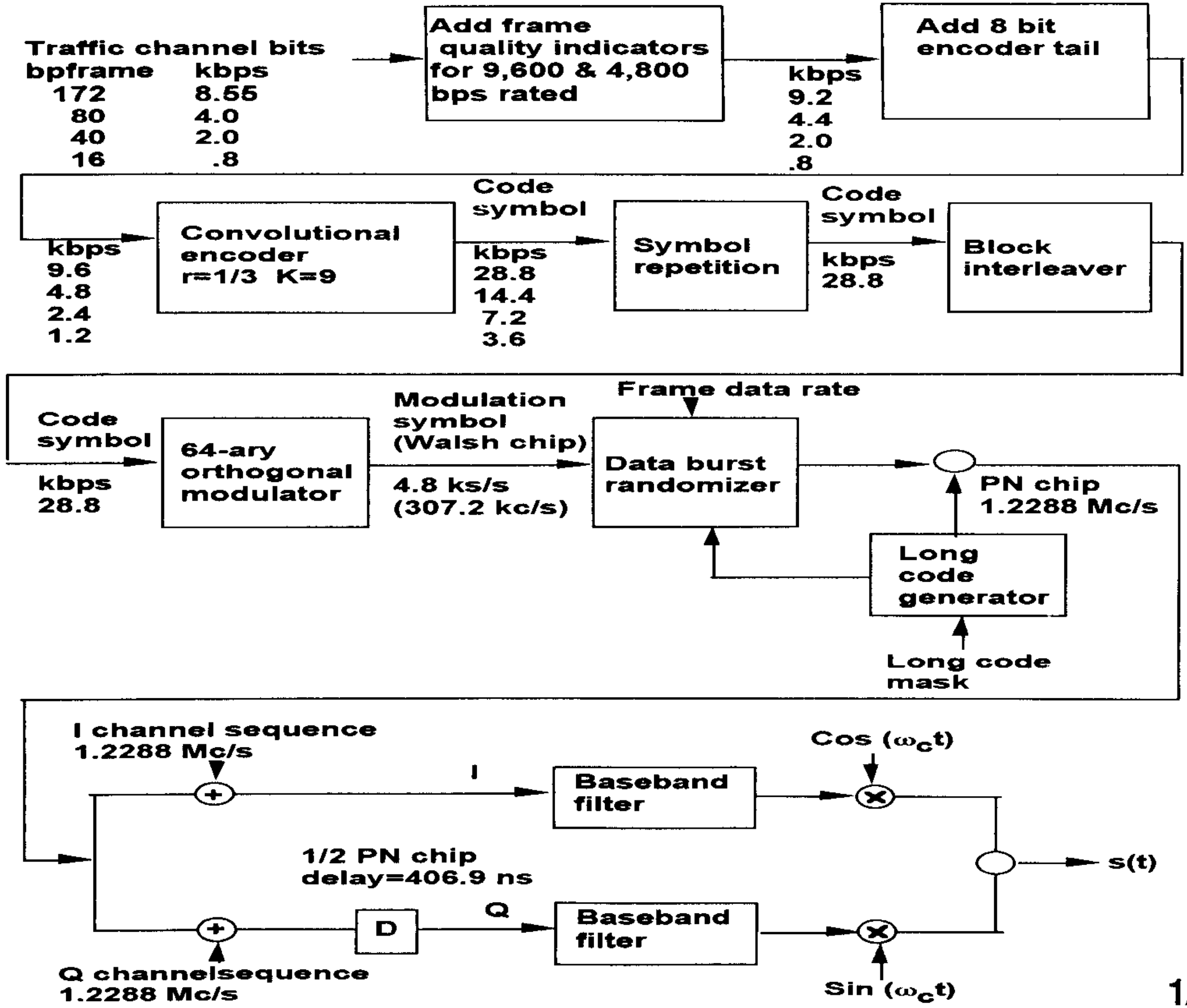
User Input	1	0	0	1	1
Spreading Sequence	1001	1001	1001	1001	1001
Tx Data	0110	1001	1001	0110	0110

Rx Data	0110	1001	1001	0110	0110
Correct Code	1001	1001	1001	1001	1001
	1111	0000	0000	1111	1111
	1	0	0	1	1

Two PN Codes

- Short Code (2^{15})
  - Unique identifier for a Cell or a Sector
  - Repeats every 26.67 msec
  - Consists of *I* and *Q* codes (different polynomials)
- Long Code (2^{42})
  - Unique identifier for:
    - » Subscriber
    - » Access channel (Reverse Link)
    - » Paging channel (Forward Link)
  - Performs spreading on reverse channels only
  - Repeats every 44.5 days

REVERSE LINK



REVERSE LINK

- 64 -ary orthogonal modulation
  - The reverse link does not have a pilot as a phase and amplitude reference
  - Phase estimation of the reverse link requires a high SNR
  - Modulation requiring coherent detection does not have an advantage
  - The Walsh functions provide the large Alphabet (64) modulation
- Spreading sequence. The user population is large. Long code (2^{42}-1 = 32,768 is used, and each user is identified by a given phase offset.
- Modulation is offset QPSK - the Q channel is offset by half a chip. This in order to smooth the envelope and allow amplifier operation closer to the 1 dB compression point. The short code that produces the OQPSK is the same that generates the PN for the pilot on the forward link (a convenience).

LINK BUDGET

	A	B	C	D	E	F
3	FORWARD LINK	Assumed Parameters				
4	Cell Tx Losses			-2.5	dB	Power lost from power amp to antenna
5	Cell Antenna Gain			9.0	dB/dipole	Gain of the TX antenna
6	Active No. Users, Nu	20				Number of active users
7	Voice Activity Factor	0.42				Average fraction of time user speaking
8	Data Rate, Rb	9600	bits/sec	39.8	dBHz	Information data rate
9	Sync Data Rate	1200	bits/sec	30.8	dBHz	Sync Data Rate
10	Paging Data Rate	4800	bits/sec	36.8	dBHz	Paging Data Rate
11	Spreading Bandwidth, W	1E+06	Hz	60.9	dBHz	Chip Rate
12	Mean Path Loss			-135.0	dB	Propagation loss
13	Local Mean Fade Allowance			-8.0	dB	Fading margin for local terrain
14	Mobile Antenna Gain			0.0	dB/dipole	Mobile antenna gain
15	Ref. Thermal Noise Temp.,T	290	K			
16	Mobile Noise Figure			8.0	dB	
17	Frequency Reuse Efficiency, F	65%				Interf. within cell/Total interf.
18		Looped Parameter				
19	Total Traffic Channel Power Amp	25.119	W	44.0	dBm	Power radiated to Total Users in Cell
20		Derived Parameters		1.6		
21	Total Traffic Channels' ERP	112.2	W	50.5	dBm	D19+D4+D5
22	Pilot ERP	42.658	W	46.3	dBm	f(Nu) to balance handoff boundaries
23	Sync ERP	1.5849	W	32.0	dBm	Fixed 6dB below Paging
24	Paging ERP	6.3096	W	38.0	dBm	Fixed
25	Cell ERP	162.75	W	52.1	dBm	B21+B22+B23+B24
26	Cell Power Amp	36.436	W	45.6	dBm	D25-D4-D5
27	Overhead Capacity, x	0.3106				(B22+B23+B24)/B25
28	ERP/Traffic Channel	13.357	W	41.3	dBm	B21/(B6*B7)

LINK BUDGET (cont. 1)

	A	B	C	D	E	F
29	Total Cell Power Rx. by Mobile, Pr	8E-13	W	-90.9	dBm	D25+D12+D13+D14
30	Pilot Rx. Power	2E-13	W	-96.7	dBm	D22+D12+D13+D14
31	Sync Rx. Power	8E-15	W	-111	dBm	D23+D12+D13+D14
32	Paging Rx. Power	3E-14	W	-105	dBm	D24+D12+D13+D14
33	Rx. Power per Traffic Channel, C	7E-14	W	-101.7	dBm	D28+D12+D13+D14
34	Rx. Traffic Channel Bit Energy, Eb	7E-18		-141.6	dBm/Hz	B33/B8
35	Other Users Interference, Io	6E-19	W/Hz	-152.2	dBm/Hz	(B29-B33)/B11
36	Other Cell Interference, Ico	3E-19	W/Hz	-154.8	dBm/Hz	B35/(1/B17-1)
37	Total Other User's Interference,Ict	9E-19	W/Hz	-150.3	dBm/Hz	B35+B36
38	Thermal Noise Density, No	3E-20	W/Hz	-166.0	dBm/Hz	B15*10^(D16/10)*1.38E-23
39	Total Mobile Rx. Power	1E-12	W	-89.0	dBm	B29+(B36+B38)*B11
40	Total RX Pr/No Ratio	3E+07	Hz	75.1	dBHz	B29/B38
41	Total RX Pr/N Ratio	26.289		14.2	dB	B29/(B11*B38)
42	User RX C/No Ratio	3E+06	Hz	64.2	dBHz	B33/B38
43	User RX C/N Ratio	2.1576		3.3	dB	B33/(B11*B38)
44	Pilot Ec/(No+Ict)	0.1807		-7.4	dB	B30/(B11*(B37+B38))
45	Sync Eb/(No+Ict)	6.8759		8.4	dB	B31/(B9*(B37+B38))
46	Paging Eb/(No+Ict)	6.8433		8.4	dB	B32/(B10*(B37+B38))
47	Other Users' Noise, Eb/Ict	7.4388		8.7	dB	B34/B37
48	Combined, Eb/(No+Ict)	7.2437		8.6	dB	B34/(B37+B38)
49	Eb/Nt Minimum			7.0		Min(7.0, .1*(36-Nu)+6.0)
50	Eb/Nt Margin			1.6		D48-D49
51						
52						
53						
54		Forward/Reverse Link Balancing				
55	Balanced Link Parameter (CAI)			-73.0	dB	Constant for the invs. law open loop PC
56	Total Mobile Rx. power at the connector			-89.0	dBm	D39
57	Mobile Tx. Power at the connector			16.0	dBm	D55-D56
58						
59	Closed Loop for Recalculations			44.0	dBm	D19
60	Delta Margin			1.6		D50-D61
61	Margin to Set Point			0.0		Arbitrary (set to zero)

LINK BUDGET (cont. 2)

	H	I	J	K	L	M	N
3	REVERSE LINK	Assumed Parameters					Voice Activi
4	Open Loop Mobile Power Amp			18.031	dBm	Open loop Tx. power - Tx. losses	P1
5	Mobile Tx Losses			-2	dB	Power lost from power amp to connector	P2
6	Mobile Antenna Gain			0	dB/dipol	Gain of the TX antenna (incl. cable losses)	P3
7	Active No. Users, Nu	20				Number of active users	P4
8	Voice Activity Factor	0.4				Average fraction of time user is speaking	**No Punc.**
9	Data Rate, Rb	9600	bits/sec	39.823	dBHz	Information data rate	μ
10	Spreading Bandwidth, W	1228800	Hz	60.895	dBHz	Chip Rate	σ
11	Mean Path Loss			-135.0	dB	Propagation loss	**With Punc.**
12	Local Mean Fade Allowance			-8	dB	Fading margin for local terrain	μ
13	Cell Antenna Gain			9	dB/dipol	Mobile antenna gain	σ
14	Ref. Thermal Noise Temp.,T	290	K				
15	Cell Noise Figure	3.16228		5	dB		
16	Frequency Reuse Efficiency, F	60%				Interf. within cell/Total interf.	
17		Looped Parameter					
18	Closed Loop Power Amp Correction			0.6845	dB	Power control correction factor	
19		Derived Parameters		-8E-10			
20	Closed loop Mobile power Amp	0.0744	W	18.716	dBm	K4+K18	
21	Mobile ERP	0.04694	W	16.716	dBm	K20+K5+K6	
22	User RX Signal Power, C	1.9E-15	W	-117.3	dBm	K21+K11+K12+K13	
23	User RX Spectral Density	1.5E-21	W/Hz	-178.2	dBm/Hz	I22/I10	
24	User RX Bit Energy, Eb	1.9E-19	W/Hz	-157.1	dBm/Hz	I22/I9	
25	Thermal Noise Density, No	1.3E-20	W/Hz	-169	dBm/Hz	1.38E-23*I14*I15	
26	User RX C/No Ratio	147670	WHz	51.693	dBHz	I22/I25	

LINK BUDGET (cont. 3)

	H	I	J	K	L	M
27	Eb/(No+Ict) Set Point	6.09874		7.8524	dB	6.15+0.1(36-N)+0.0004(36-N)^2
28	Minimum User C/No Set Point	147670	Hz	51.693	dBHz	I9/(1/I27-I9*(I7-1)*I8/(I10*I16))
29	Minimum Total Pr/No Set Point	1181357	Hz	60.724	dBHz	I28*I7*I8
30	Other Users Interference, Io	1.2E-20	W/Hz	-169.4	dBm/Hz	I22/I10*(I7-1)*I8
31	Other Cell Interference, Ico	7.7E-21	W/Hz	-171.1	dBm/Hz	I30*(1/I16-1)
32	Total Other User's Interference,Ict	1.9E-20	W/Hz	-167.2	dBm/Hz	I30+I31
33	Total RX Power	4.1E-14	W	-103.9	dBm	I22+(I25+I32)*I10
34	Other Users' Noise, Eb/Ict	10.1053		10.045	dB	I24/I32
35	Combined, Eb/(No+Ict)	6.09874		7.8524	dB	I24/(I25+I32)
36	Eb/(No+Ict) Margin to Set Point			-3E-10		
37						
38						
39	Closed loop for recalculation			0.6845	dB	K18
40	Delta margin			-3E-10	dB	K36-K41
41	Margin to set point			0	dB	Arbitrary (set to 0)
42						
43						
44	Observables at the Cell					
45	Cell Rx. Power (excluding No &Ico)	1.6E-14	W	-107.9	dBm	I22+I30*I10
46	Cell Rx. Power (including No&Ico)	4.1E-14	W	-103.9	dBm	I22+(I25+I32)*I10
47	Total noise power	1.6E-14	W	-108.1	dBm	I25*I10
48	Cell Rx. Power/Noise ratio	2.64238		4.2199	dB	I46/I47

REVERSE LINK POWER CONTROL

WHAT IS IT

- The transmit power of each user is controlled to be received at the base station with the same minimum E_b/I_o as required for the specified link quality. An additional "outer loop" maintains the rate of errors received at the base station at a specified level.

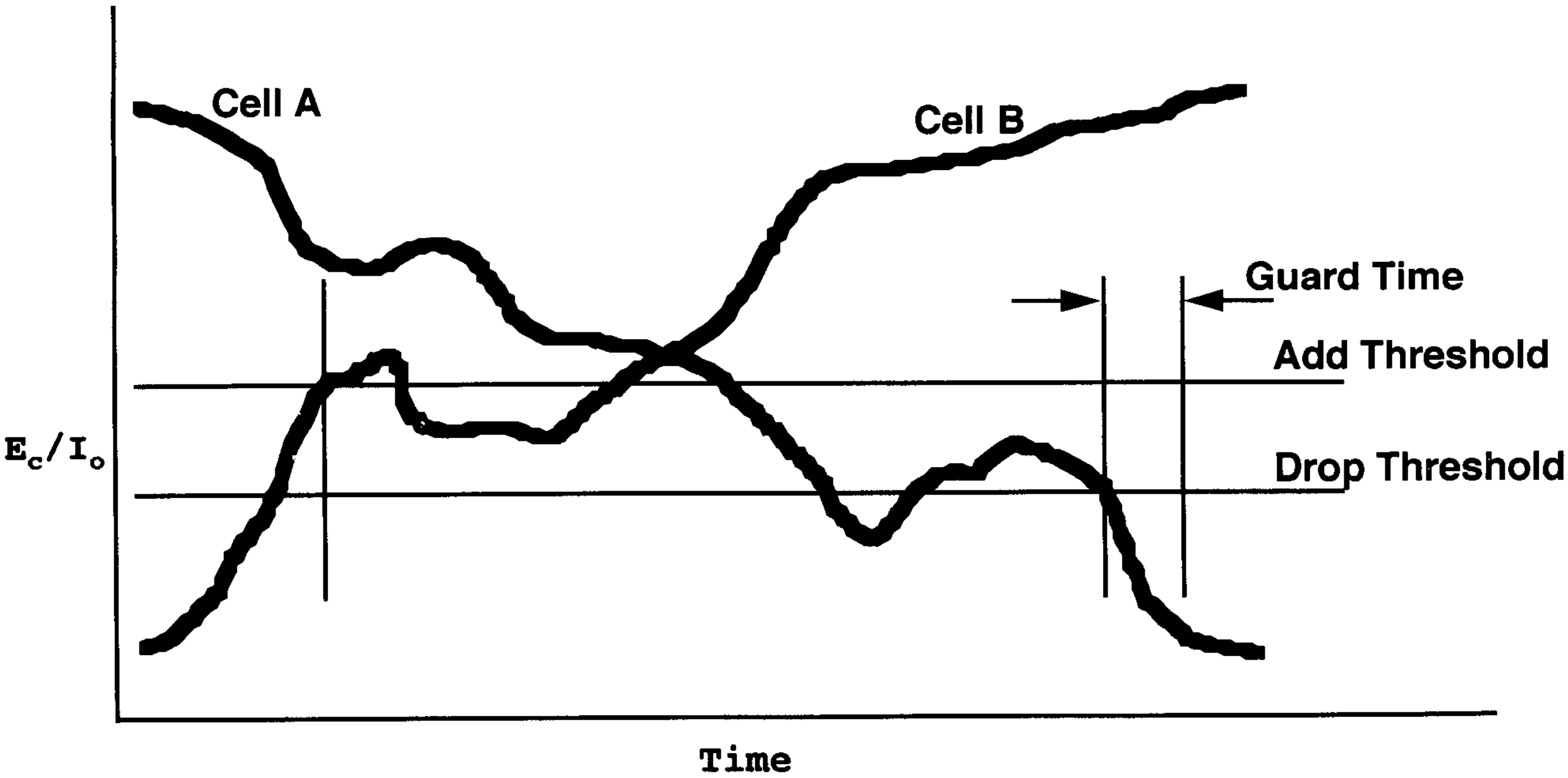
ATTRIBUTES

- Mitigates the "near - far" problem and maximizes cell capacity
  - » In CDMA users closer to the base station may screen distant users.
- Limits the interference to other cells and enhances system capacity
- Controls the quality of the link (error rate)
- Saves power in the mobile unit
- Minimizes the transmission power and reduces Radiation Hazards

THE POWER CONTROL LOOPS

- Open loop (AGC) - over 80 dB. Time constant 20 ms.
- Closed loop - over ± 24 dB, in .5 dB/ 2.5 ms steps
- "Outer loop" - sets the threshold per user according to error rate measurement

HANDOFF PARAMETERS



SOFT HANDOFF COST

- **REVERSE LINK**
  - Mobile transmission power is reduced
    - » The same transmission is received by both base stations
    - » The selection diversity reduces the errors, and the required E_b/I_o. The mobile is required to transmit lower power, and the capacity increases
  - Extra channel cards are needed in the base stations and extra backhaul load (30% or more)
  - The extent of the handoff zone is therefore a design and control parameter.
- **FORWARD LINK**
  - Both base stations transmit
    - » The mobile combines the signals coherently. However, shadows do not match, and each station is required to transmit the full power, to hold the link when the other is in the shadow.
    - » The interference therefore doubles, and capacity reduced
  - A user in soft handoff needs codes from both cells. The number of Walsh codes limits the capacity.

SOFT HAND-OFF ASSETS REQUIREMENTS

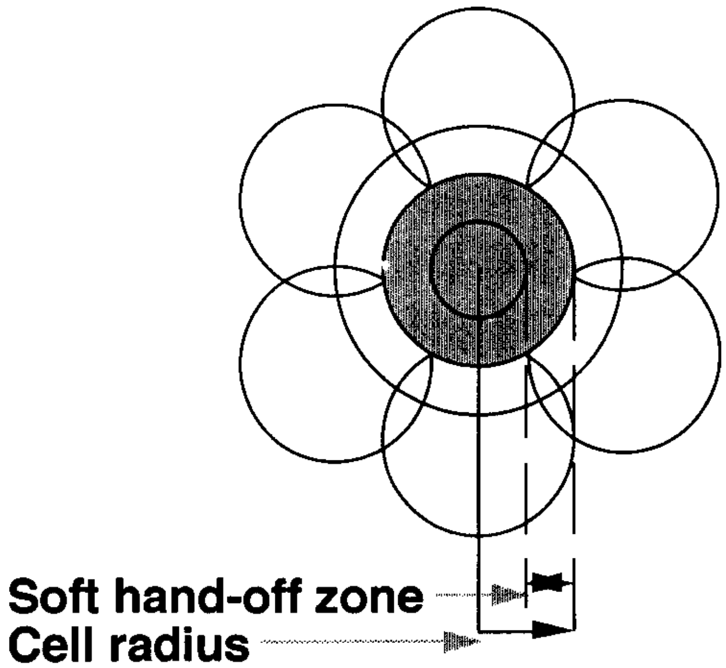
Soft hand-off zone : 3dB from nominal cell boundary
Assume uniform users distribution.

$$\frac{n(r)}{n(R)}=\left[\frac{r}{R}\right]^2$$

For a r^{α} **propagation law**

$$\frac{n(R)-n(r)}{n(R)}=1-2^{-\frac{2}{\alpha}}$$

(n(R)-n(r))/n(R)	a
.3	4
.37	3



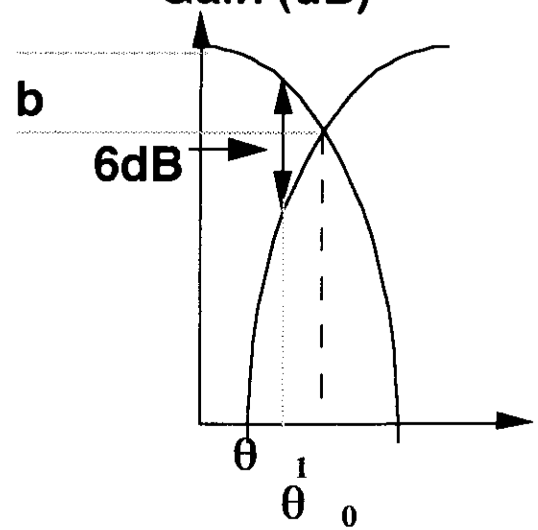
SOFTER HAND-OFF OVERLAP AND INTER-SECTOR DIVERSITY

Antenna gain is approximated by

$$G(\theta)=G_0(1-k\theta^2)$$

$$\frac{\theta_1}{\theta_0}=\frac{8}{3}\left[1-\sqrt{1-\frac{3}{16}\cdot\frac{3-4b+.25}{1-b}}\right]$$

b	$1-\frac{\theta_1}{\theta_0}$
.5 (-3dB)	.277
.4 (-4dB)	.19
.33(-5dB)	.144



FREQUENCY COORDINATION

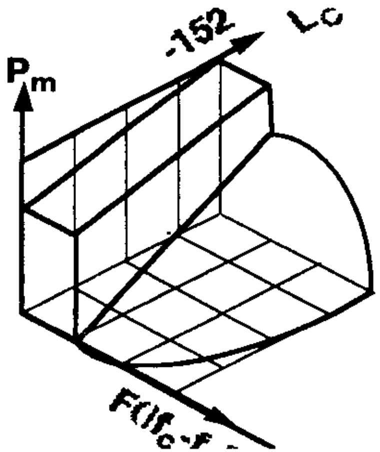
CDMA - CDMA

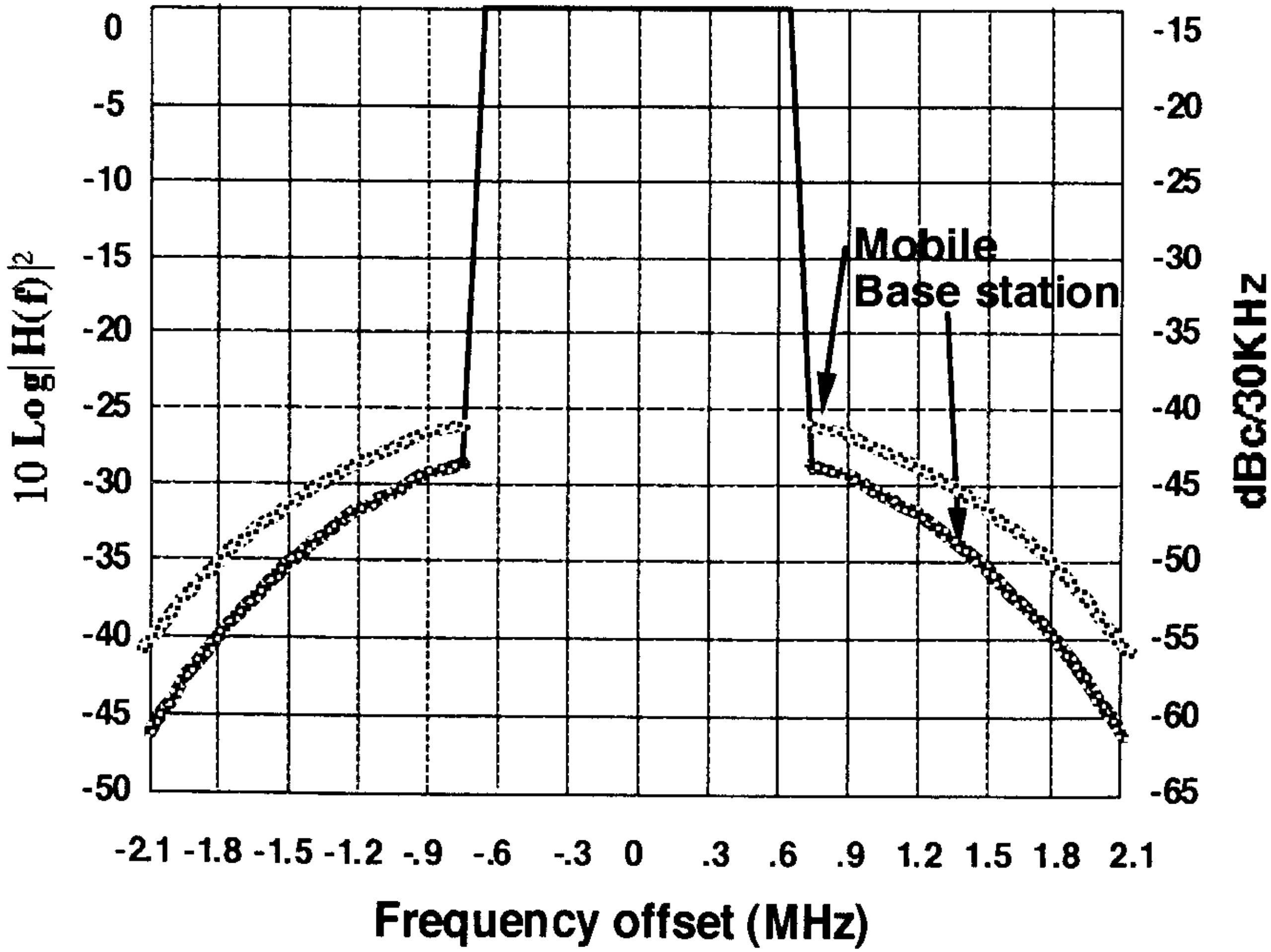
CDMA - FDMA / TDMA

TRANSMITTER EMISSION

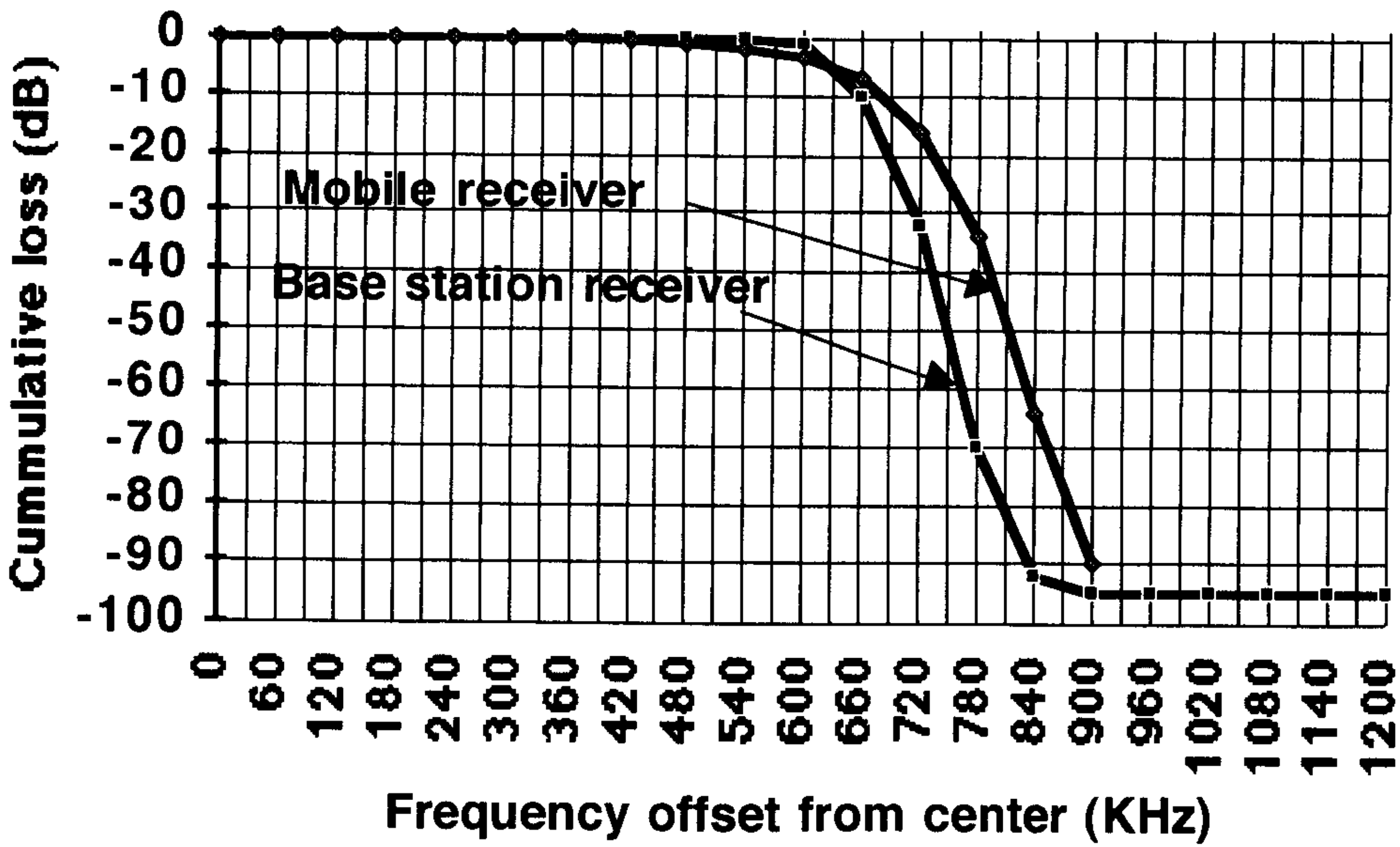
AB AMPLIFIER, 2dB BELLOW 1 dB COMPRESSION POINT

- **The off band emission is due to 3rd order intermod. It decreases 3 dB for 1 dB in transmit power.**





RECEIVER SELECTIVITY



INTERFERENCE PARAMETERS

- F(dB) - Frequency filtering
- L(dB) - Path-loss
- P_m(dB) - Mobile transmission level
  - *Depends on its path-loss L_c from its base station and determines the level of spurious emissions*

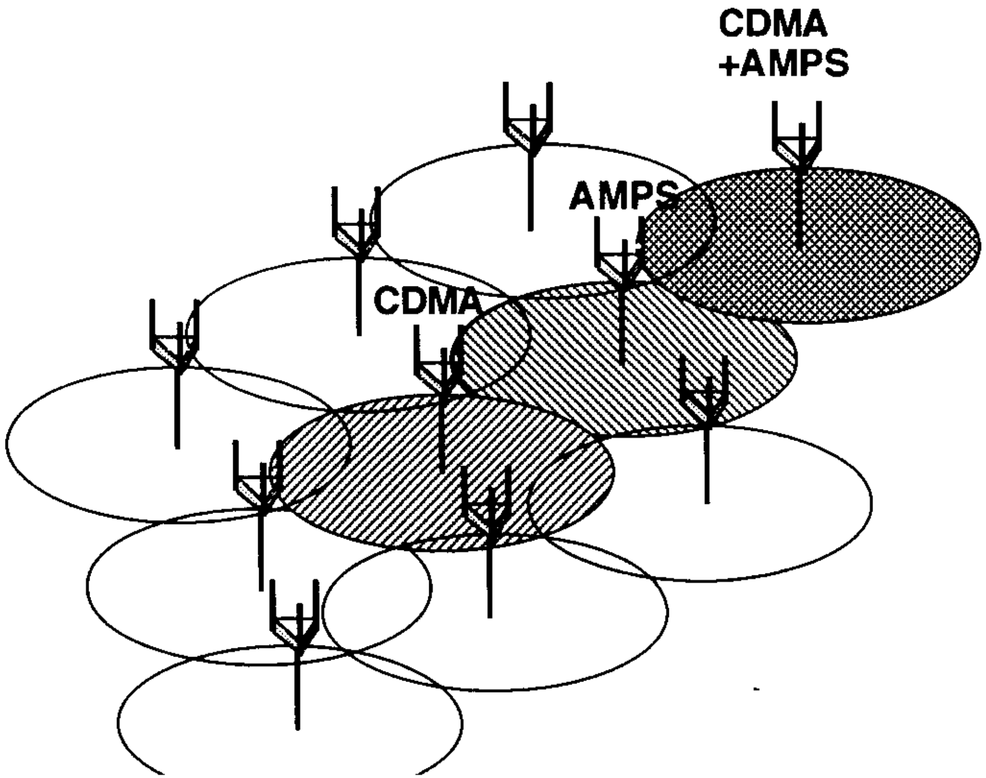
$$J(dB) = P + L + F$$

Victim receiver noise figure:

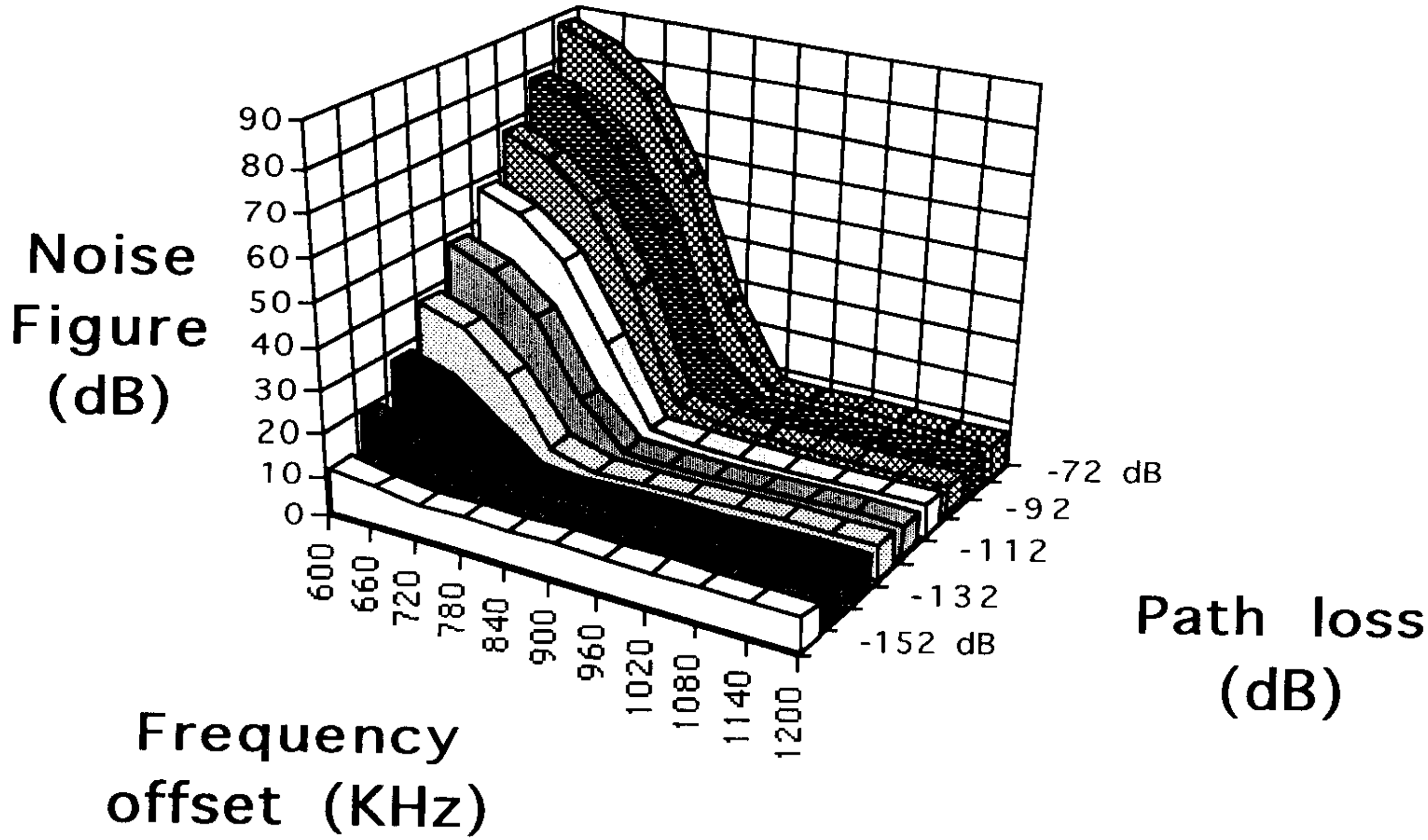
$$NF_J(dB) = 10 \, \text{Log}\left(10^{\frac{NF}{10}} + 10^{\frac{P_m + F + L - (N_0 W)[dB]}{10}}\right)$$

INTERFERENCE BETWEEN CDMA AND AMPS NETWORKS

- CO-LOCATED BASE STATIONS
- DISJOINT BASE STATIONS



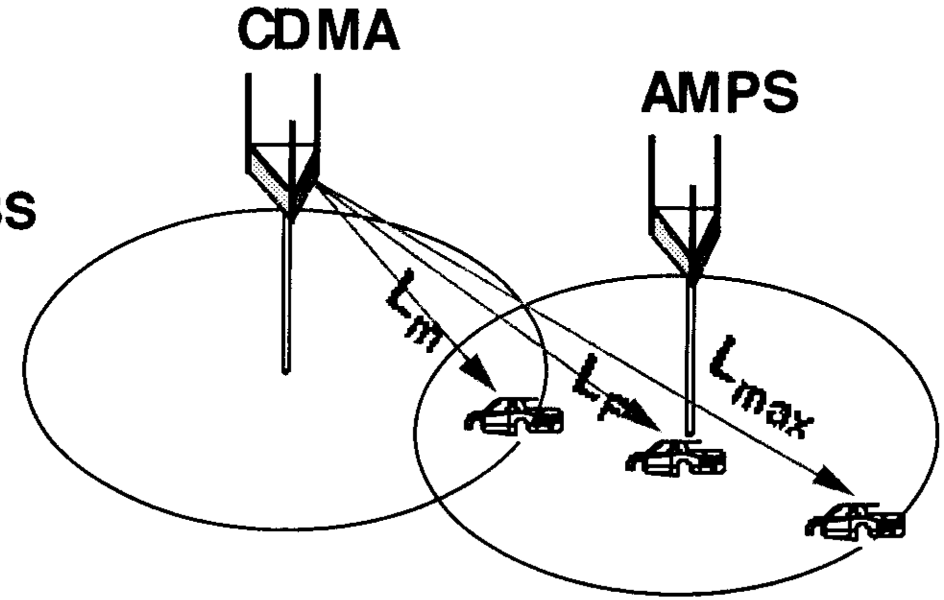
NOISE FIGURE OF CDMA MOBILE
INTERFERED BY AMPS BASE STATION



INTERFERENCE (CONT. 3)
DISJOINT BASE STATIONS

- **ANALYSIS IS PRESENTED FOR A MOBILE ALONG THE CONNECTING LINE.**
  - Jamming by the AMPS BS: mobile NF is raised by 3 dB
  - $J_F = 53+(I-72)+113+F_2 = 8$
  - $F_2(870\ \text{KHz}) = -76$
  - $I_c = -10$ dB

  (path-loss mobile - AMPS BS should exceed 82 dB)



INTERFERENCE (CONT. 4)
DISJOINT BASE STATIONS: JAMMING BY MOBILE

- **Jamming by the CDMA mobile: NF of the AMPS BS is raised by 3 dB.**
  - $I(dB) = L_F - L_m$
  - $J = 31 + I - 72 + (L_{max} - L_F + I) - 15 + 129 + F_1 = 5$
  - $F_1 = -23.8 - 3.9(.87)^2 + 3(L_{max} - L_F + I)$
  - $I_F = 113.35 + .8L_F$
- **GUARD ZONE**
  - $31 + I - 72 - 15 + 129 = 5$
  - $I = -68$

  Minimum path-loss to AMPS BS is

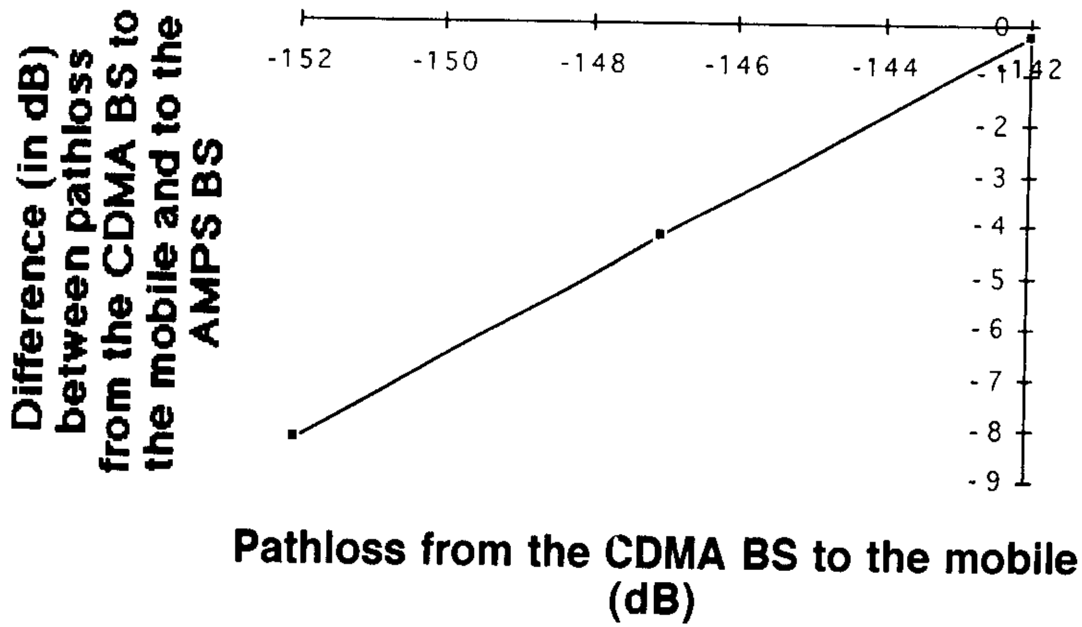
  -68-72=-140 dB

  For jamming by BS:

  53+I-72+113=8

  I = -86, min. path-loss

  -86-72=-158 dB



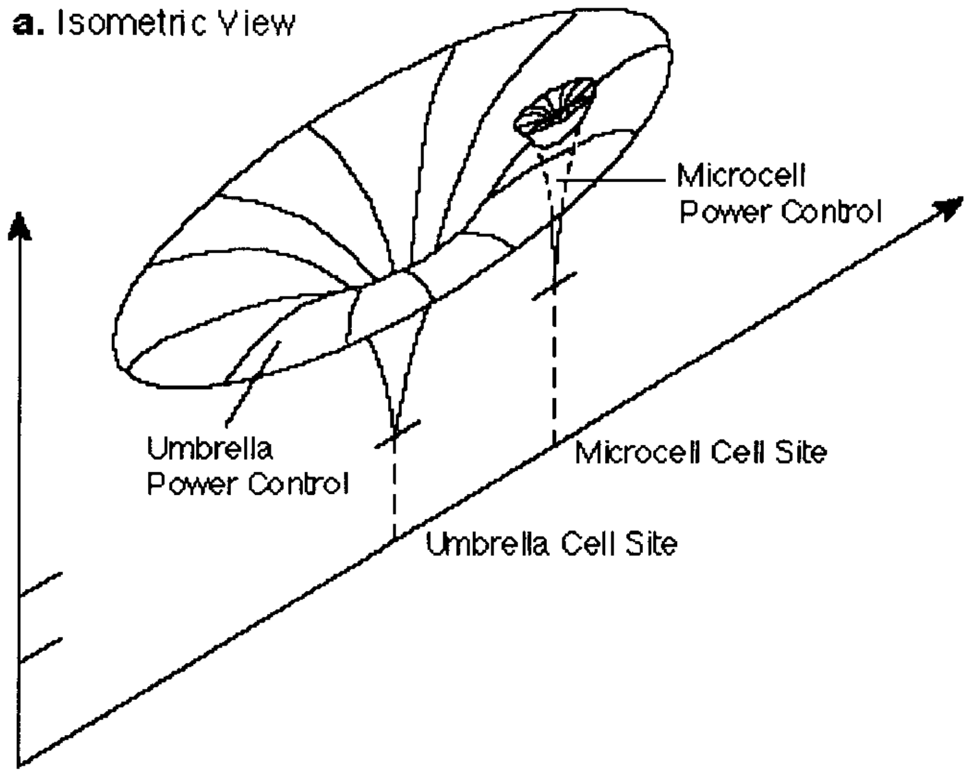
MICROCELLS IN CDMA

MICROCELLS

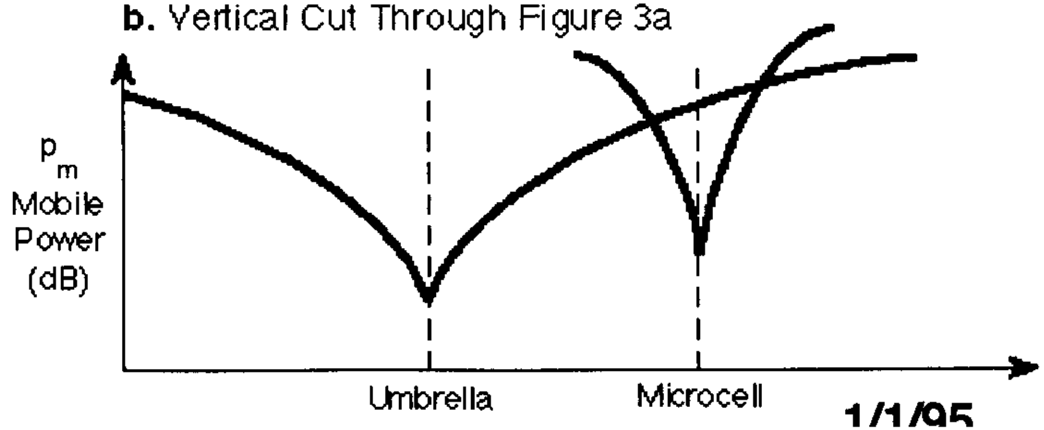
- **Purpose -**
  - Increase capacity density (ERLANG/km^2) by "scaling" the cells
  - Add coverage in a "coverage hole" of a large cell
  - In-buildings (2 or 3D)
- **Challenges**
  - Detailed distribution wireline and switching and control network, mostly in dense urban area. Compactness, operability and cost become a key.
  - Cell coverage is not "scalable" all the way. BS antennas below the rooftops - a different propagation regime. The cell shape is not round, and a major overlap is needed for a contiguous coverage.
  - A mixed population of pedestrians, and mobiles that roam through
- **Microcell technology**
  - Remoting the transceiver unit by an RF link:
    - » Fiber optics
    - » IF cable
    - » Microwave
    - » Cellular band transmission

A MICROCELL WITHIN AN UMBRELLA CELL

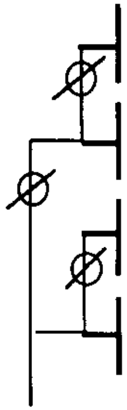
a. Isometric View



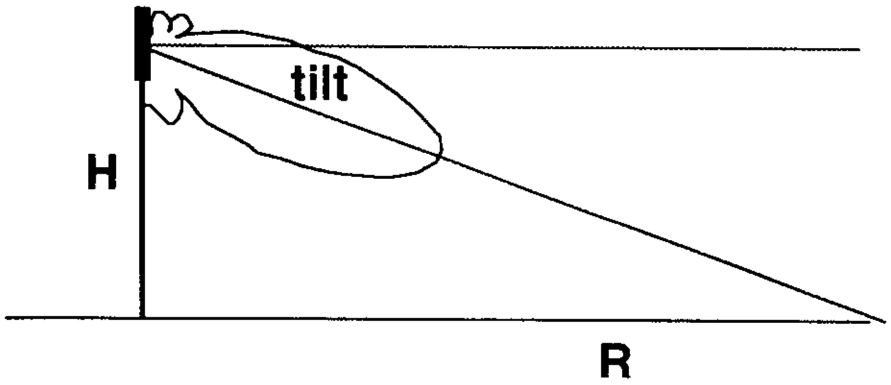
b. Vertical Cut Through Figure 3a



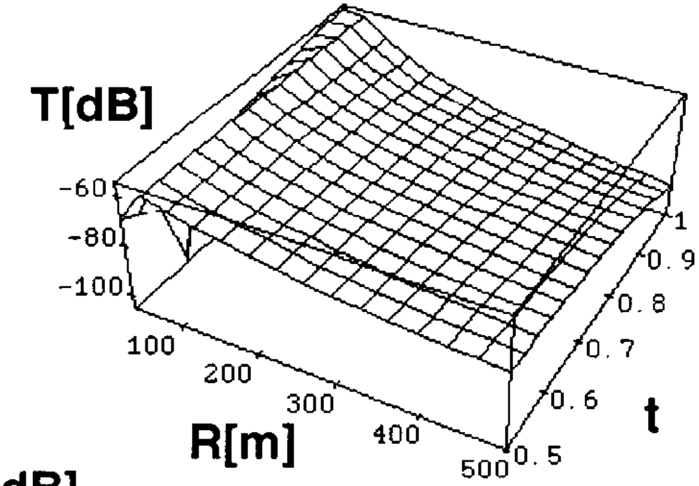
BEAM TILT ISOLATION



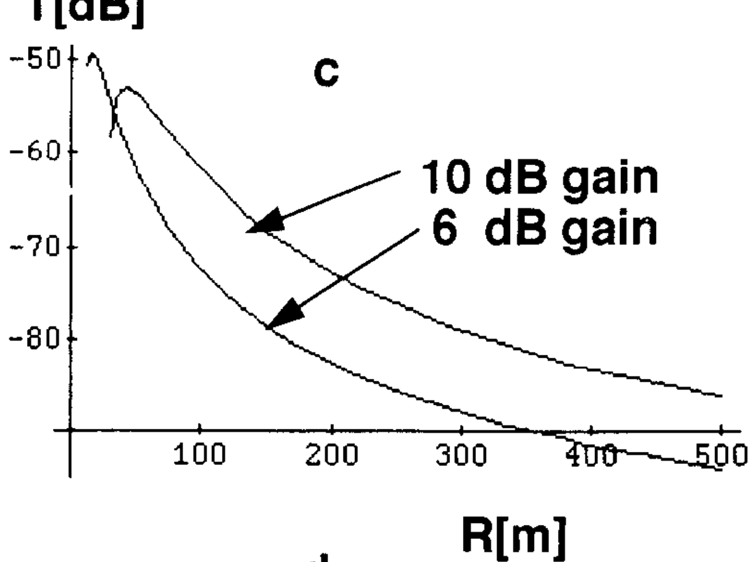
a



b



c

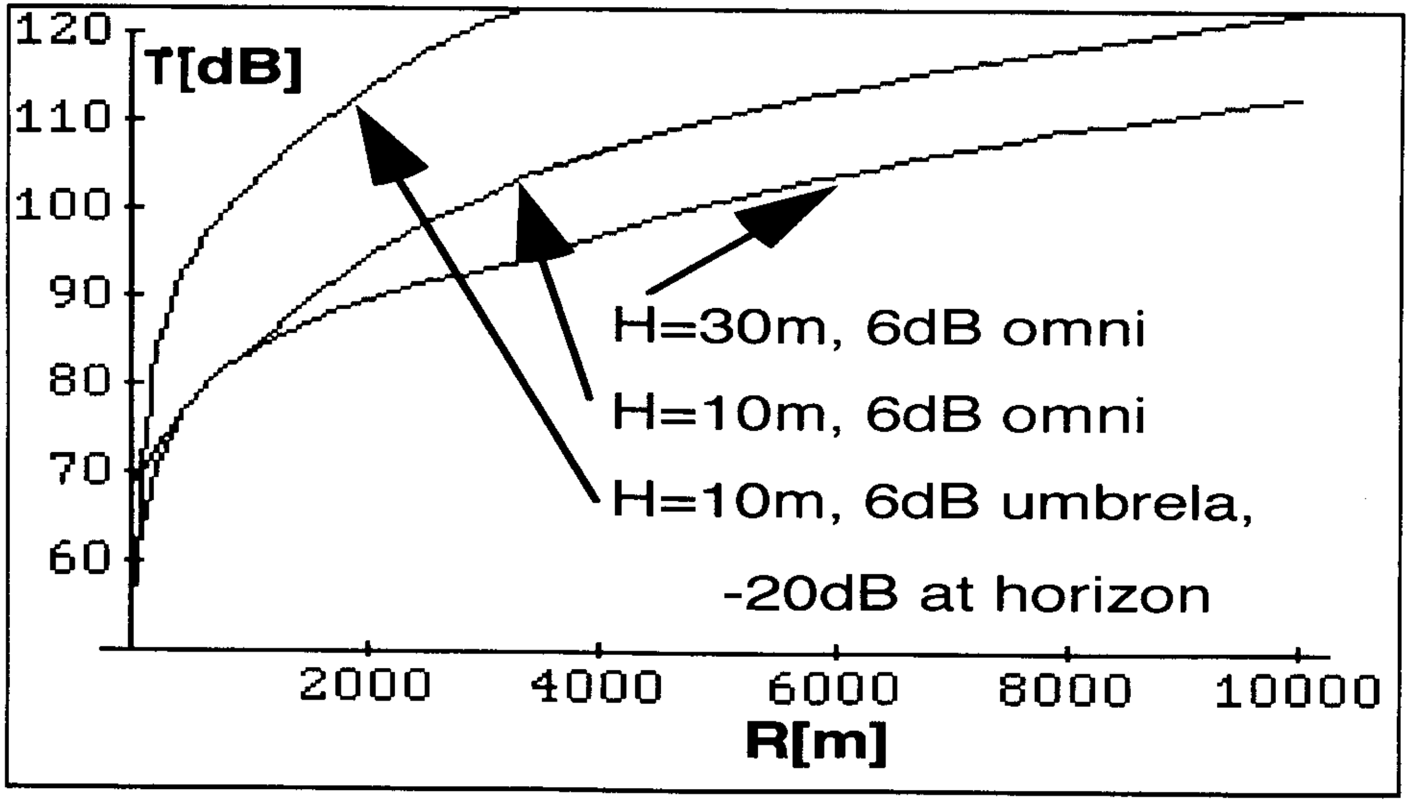


d

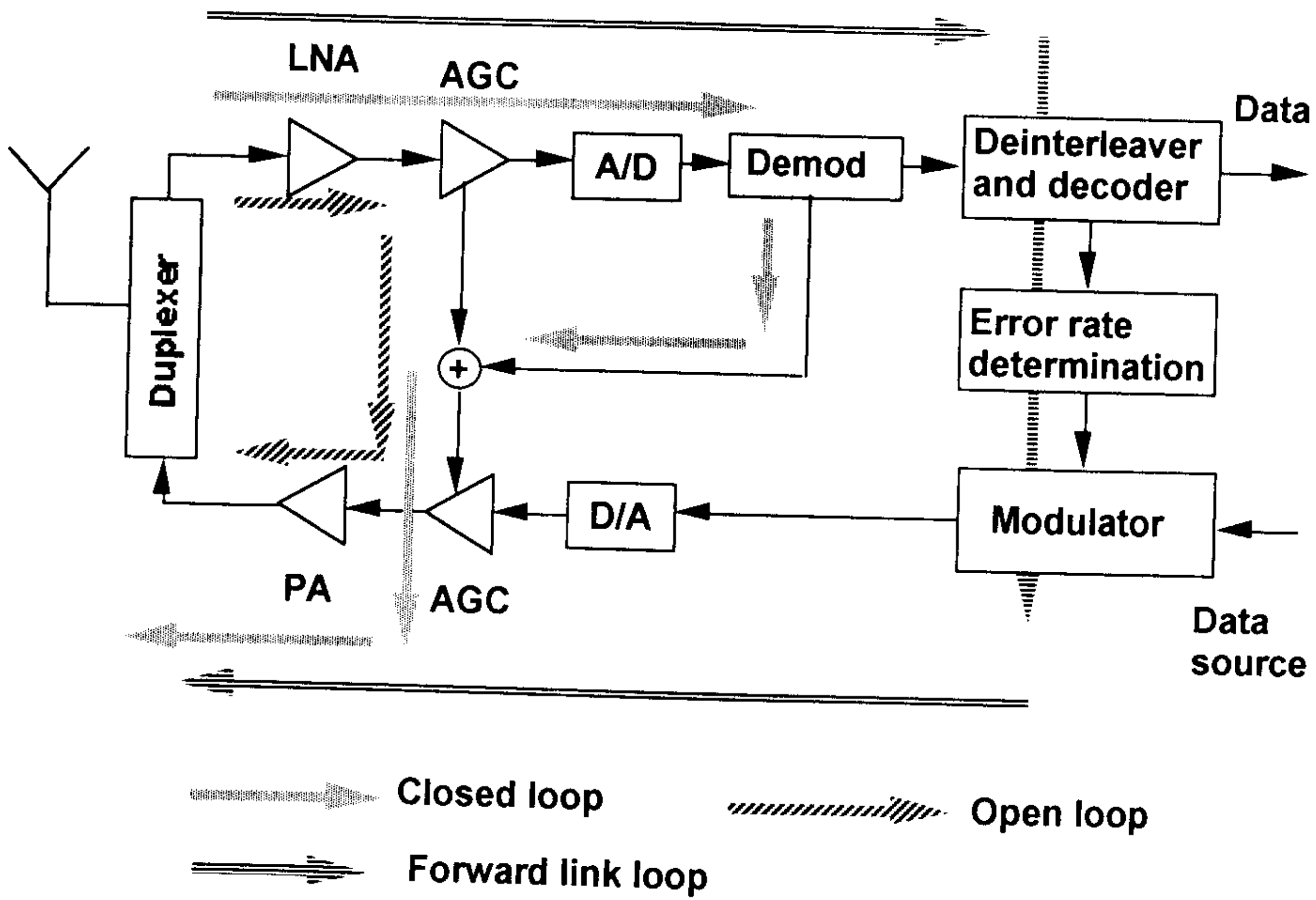
- a Array phasing for beam tilting
- b Omni antenna, down tilted
- c Transmission loss T[dB], as a function of the beam tilt

  t=tilt/(1.13*beamwidth), H=10m
- d Propagation loss, H=10m, t=.909 (-20 DB at the horizon) for a 10 dB and for a 6dB omni antenna

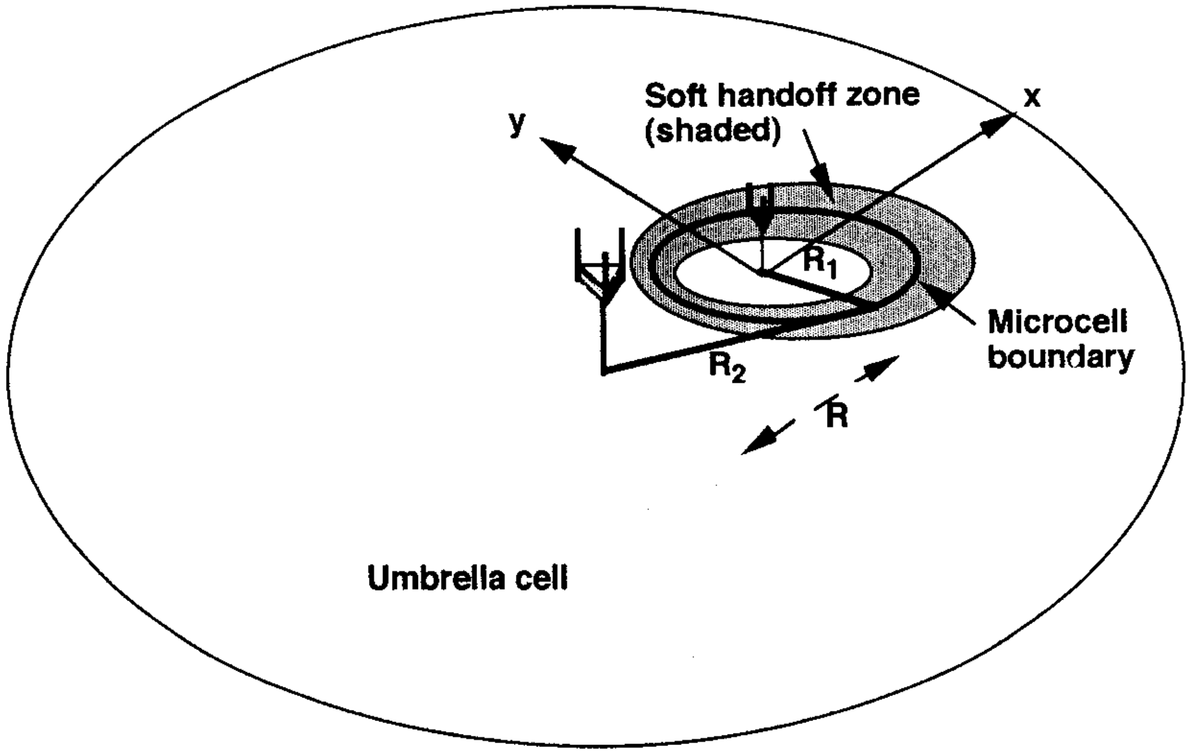
TRANSMISSION-LOSS DESIGN



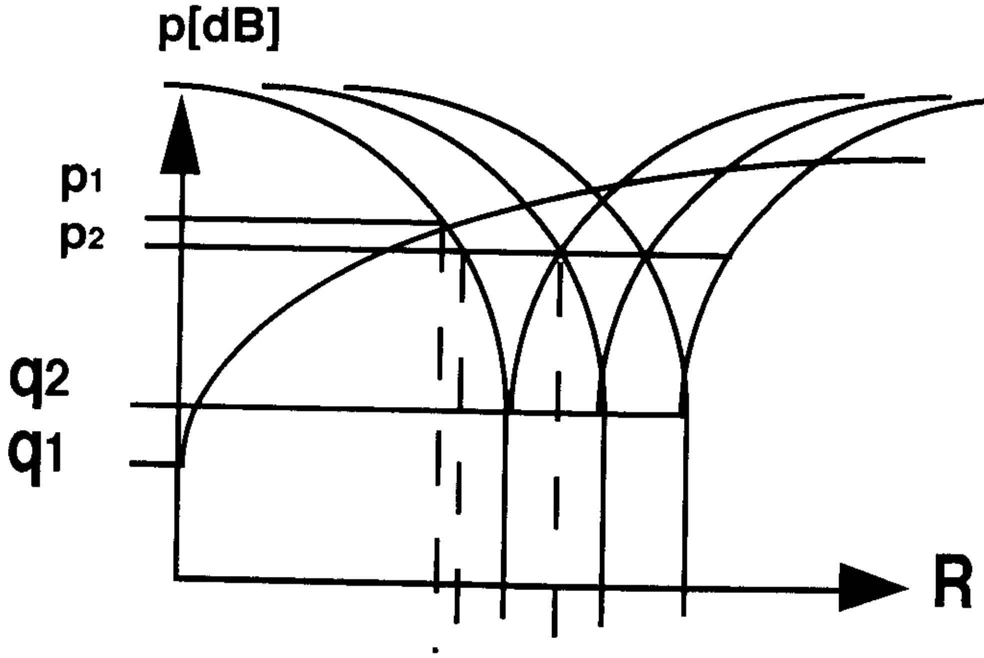
POWER CONTROL LOOPS, MS



THE UMBRELLA - MICROCELL BOUNDARY AND SOFT HANDOFF ZONE

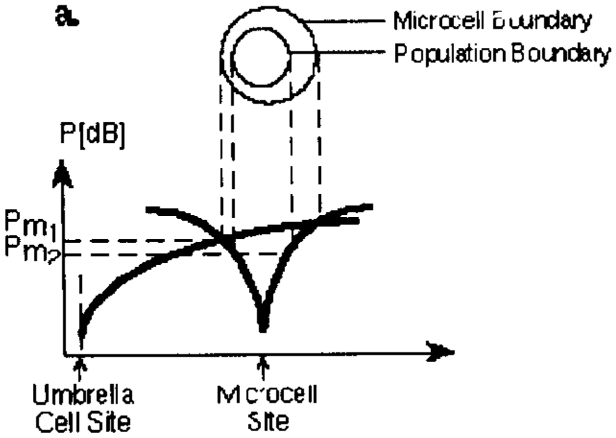


MICROCELL CLUSTER UNDER AN UMBRELLA CELL



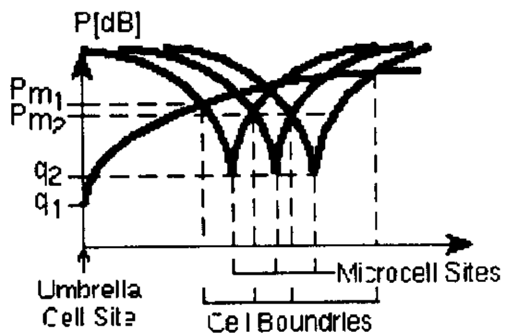
CAPACITY OF MICROCELLS UNDERLAY

a.



Hot spot underlay

b.



Cluster microcells underlay

Capacity / nominal capacity	Hot spot underlay		Cluster underlay (12)	
	D=1	D=10	D=1	D=10
Umbrella	.822	.98	.36	.85
Microcells	1.47	1.46	1.	1.
Umbrella plus Microcells	2.28	2.44	13.2	13.7

THE TRANSMISSION EQUATION - AGAIN

- The transmission equation $P_r = P_t \frac{G_t}{4\pi R^2} \cdot A_r \cdot L_a$
- But $\frac{G_{t1}}{A_{r1}} = \frac{G_{t2}}{A_{r2}}$
- and

$$D = \frac{4\pi K}{\vartheta_x \vartheta_y} = \frac{4\pi \cdot .785}{\left(.886\frac{\lambda}{D_x}\right)\left(.886\frac{\lambda}{D_y}\right)} = \frac{4\pi D_x D_y}{\lambda^2} \Rightarrow \boxed{G = \frac{4\pi A}{\lambda^2}}$$

$$\boxed{P_r = P_t \frac{G_t}{4\pi R^2} \cdot A_r \cdot L_a = P_t \frac{G_t G_r}{(4\pi)^2} \cdot \left(\frac{\lambda}{R}\right)^2 \cdot L_a}$$

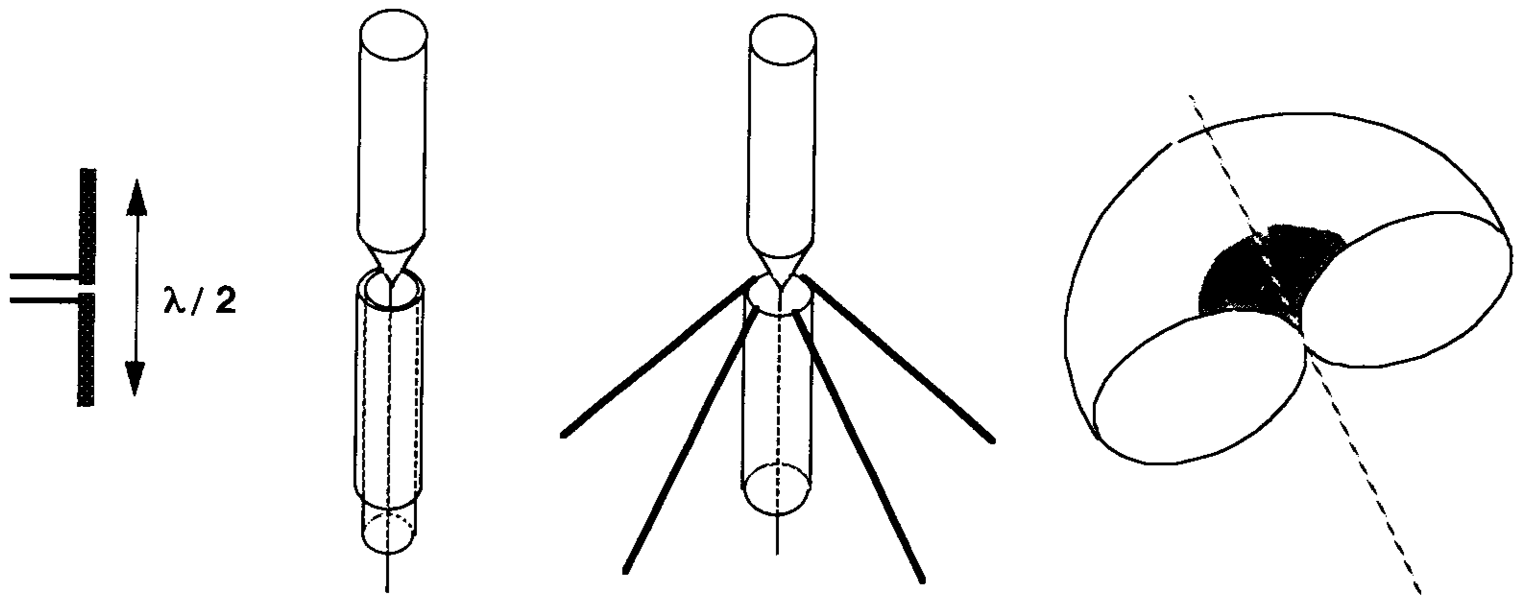
- For general propagation losses $P_r = P_t G_t G_r L = P_t T$

L Path-loss

T Transmission loss. Measured between the output of the power amplifier and the input to the receiver. Incorporates cable losses.

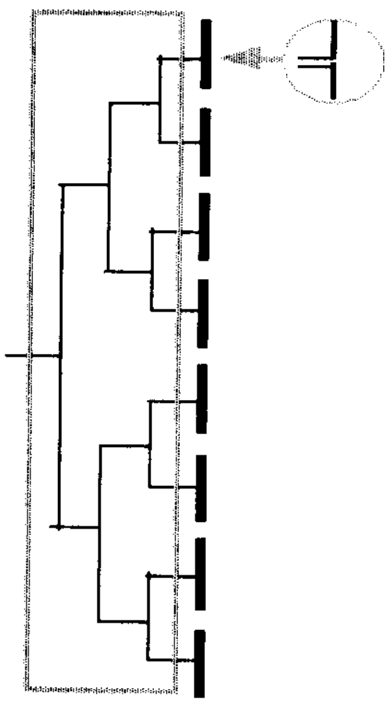
DIPOLES

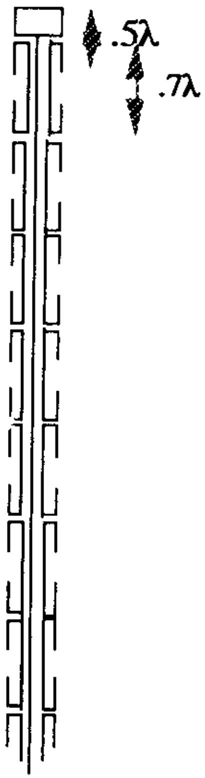
Gain of half a wavelength dipole - 2.16 dB

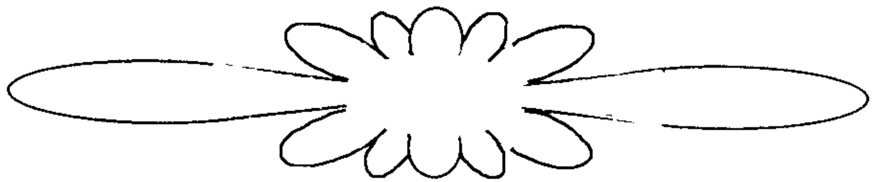


a. Dipole b. Sleeve dipole c. Ground-plane dipole d. Radiation pattern

COLINEAR DIPOLE ARRAY







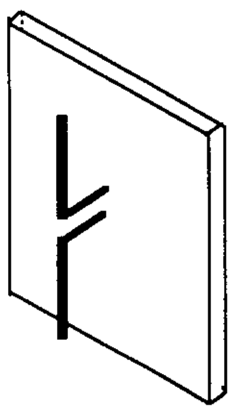
c. Radiation pattern in the vertical plane

a. Corporate feed

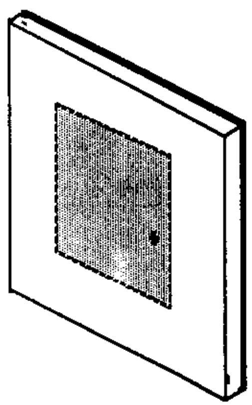
b. Series feed

d. Tilted beam ("umbrella")

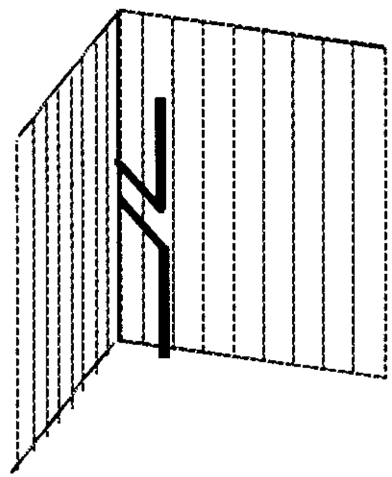
GROUND-PLANE BACKED DIPOLES



a. Ground-plane backed dipole



b. Microstrip (patch) antenna



c. Corner reflector antenna

DIVERSITY ANTENNA DISPLACEMENT

Antenna decorrelation

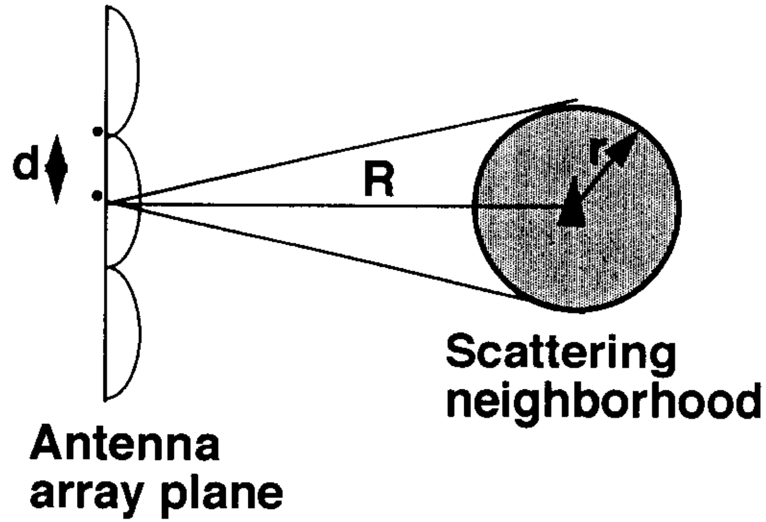
$$\frac{\lambda}{d} \cong \frac{R}{r} \Rightarrow d \cong \frac{\lambda R}{r}$$

where

d antenna displacement

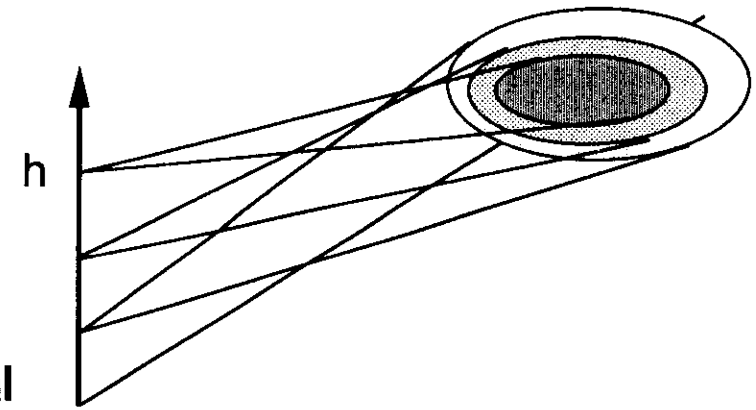
r radius of the neighborhood

R distance from the mobile to the base-station



THE HEIGHT - DIVERSITY BASELINE FUNCTION

- A desired ratio $\eta = h / d$ is defined by W.C. Lee
  - The basis for the dependance is a set of measurements in a quasi rural environment, with antenna heights not much above the height of the scattered houses.
- The rationale offered here is that the scattering neighborhood shrinks with height.
  - With a BS antenna slightly above the average roof tops, the communication is NLOS and the scattering neighborhood is large
  - The higher the antenna, the smaller this neighborhood is.
  - The function may be linear only over a limited range of h above the roof top.
  - Under the roof level the angle of arrival of the multipath component widens and there is no universal dependence.



ANTENNA COUPLING, PATTERN AND WEIGHTS

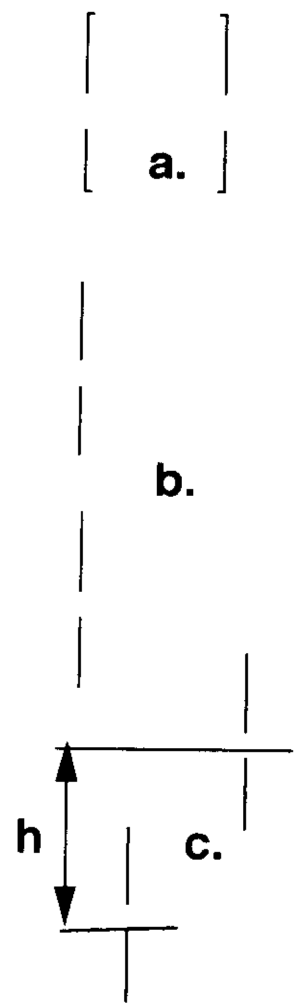
- **Mutual coupling between dipoles:**
  - **Side-by-side (a.) - decays to -6 dB @.8 λ**
  - **Colinear (b.) - decays to - 9 dB @ .2 λ**
  - **Staggered (c.) - decays to - 9 dB @ .25 λ(h=.5 λ)**
- **Mutual coupling between colinear arrays:**
  - **The boundary of the near (inductive) field**

$$\frac{r}{\lambda} = .62\left(\frac{l}{\lambda}\right)^{3/2}$$

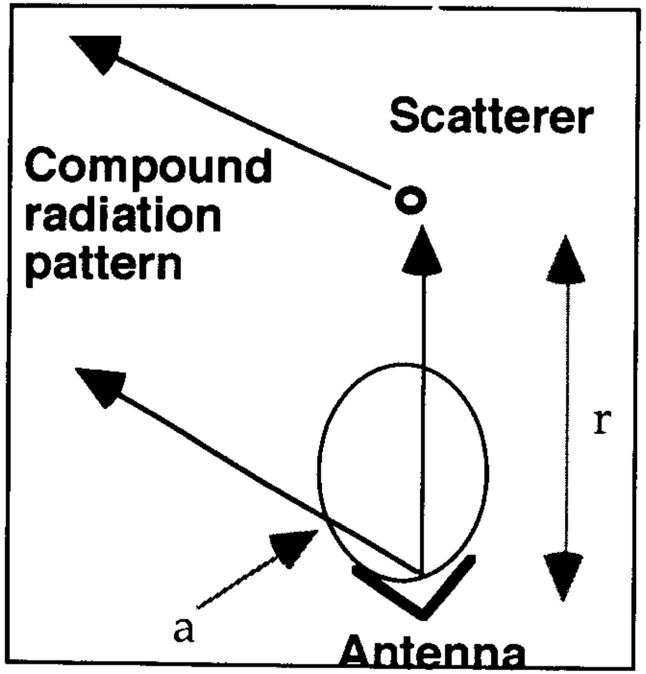
  - **The mutual coupling has a proportional decay:**
    For a side-by side arrays -6 dB @
    (a 10 dB gain array r≅ 4 λ)

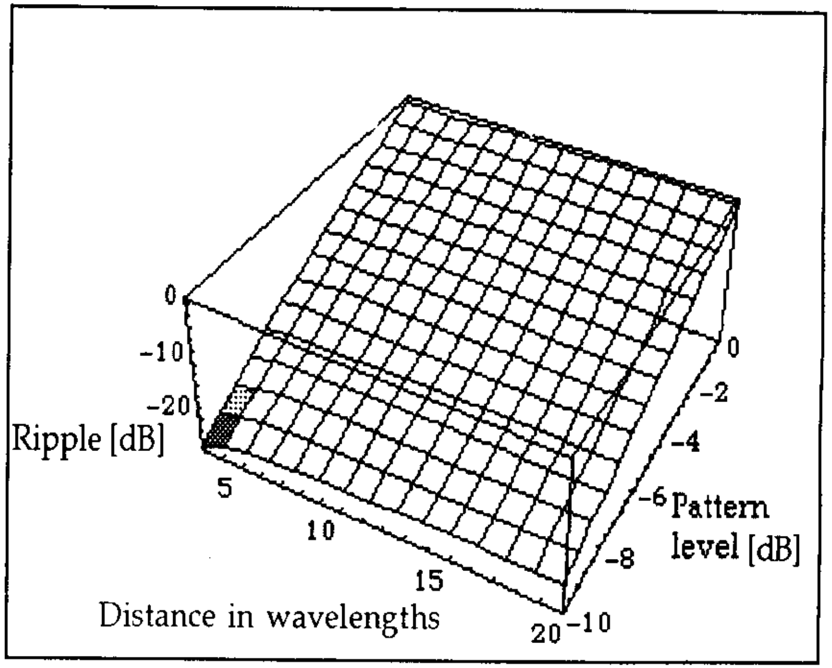
$$\frac{r}{\lambda} = .3\left(\frac{l}{\lambda/2}\right)^{3/2}$$

- **Pattern ripple:**
  - **The diversity branches have to be within 3 dB to be effective.**
  - **A pattern ripple does not allow for gain adjustment.**
  - **The pattern ripple is bounded to < 2 dB for r=10 λ for 10 dB arrays.**
  - **Smaller ripple is obtained when staggering the arrays.**



PATTERN RIPPLE



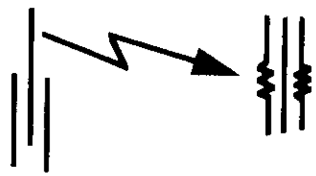


Ripple[dB] < 20 Log$\left[a - \sqrt{\frac{\sigma}{4\pi r^2}}\right]$

σ **Radar cross section of the scatterer**
For a dipole $\sigma = 0.215\,\lambda^2$

ANTENNA FARMS - COSITE ENGINEERING

- **Interaction in an antenna farm:**
  - Antenna coupling
    - » Far field (dipoles): $T(dB) = -25.5 - 20 \, Log(R/\lambda) + 30 \, Log(Cos \, \alpha)$
    - » Near field $\frac{R}{\lambda} < .62 \left(\frac{D}{\lambda} \right)^{\frac{3}{2}}$
  - Distortion of the radiation pattern
  - Antenna to cable
    - » The cable shield is an antenna.
      Signal leaks through shield
      or connector impedance



  - Cable to cable
  - Common ground plane impedance
  - Non linear coupling (harmonics, intermod.)

ANTENNA FARMS - COSITE ENGINEERING (cont.)

- **MITIGATION**
  - Avoid near field
  - Maximum isolation - in colinear antennas
  - Consider reflections and scatterers
  - Do not run low signal cables parallel to antennas
  - Bunch the cables according to signal levels
  - Minimize the cable shield impedance: connector, damaged shield
  - Minimize the ground plane common RF impedance.
  - Corrosion creates a non linear impedance.

CELLULAR NETWORK PLANNING AND DESIGN

RADIO NETWORK ENGINEERING

PHASES

- Preliminary cost and business evaluation
- Radio network design
- Network tuning
- Network upgrading

CDMA NETWORK DESIGN PROCEDURE
Designing a new network

1. DATA GATHERING

1. PRELIMINARY ARCHITECTURAL DESIGN

3. MEASUREMENTS AND ANALYSIS

4. NETWORK DESIGN

5. NETWORK TESTING

Radio Network Design (cont. 1)

DATA GATHERING

- Demographics
  - » subscriber distribution and traffic
  - » market growth rate
- Service objectives
  - » Grade of service by subscriber group
  - » Deployment timetable
- Propagation related data
  - » Topography (DTM)
  - » Land use: type, density, height distribution
- Interference environment: other systems
- Zoning and boundaries: Design constraints, Coordination
- Fixed network
  - » Candidate BSS locations
  - » Trunk lines, PSTN hooks

Radio Network Design (cont. 2)

PRELIMINARY ARCHITECTURAL DESIGN

- Cells' coverage and network layout: service oriented design
  - » Portray cells' coverage by load and density
  - » Allow for growth
- Fixed network architecture design
  - » Use PSTN hooks, trunks and PSTN costs to structure the network
- Cell radiation design
  - » Use candidate locations to assess coverage shaping and handoff zones
  - » Reiterate cells' location and load
  - » Estimate basic cell parameters: sectors, channels
- Assess network cost
  - » Perform cost trade-offs

Radio Network Design (cont. 3)

MEASUREMENTS AND ANALYSIS

- Coverage measurements for candidate cells' locations. CW or sounder measurement
  - » Coverage
  - » Best server
  - » handoff zones
- Channel measurement and analysis (optional). This can be made with a sounder
  - » Typify areas by the multipath characteristics
- Interference measurement and analysis
  - » Stationary measurement at the base stations
  - » Survey of the service area for the mobiles interference
- Use the measurement data to calibrate the design tool.

Radio Network Design (cont. 4)

NETWORK DESIGN

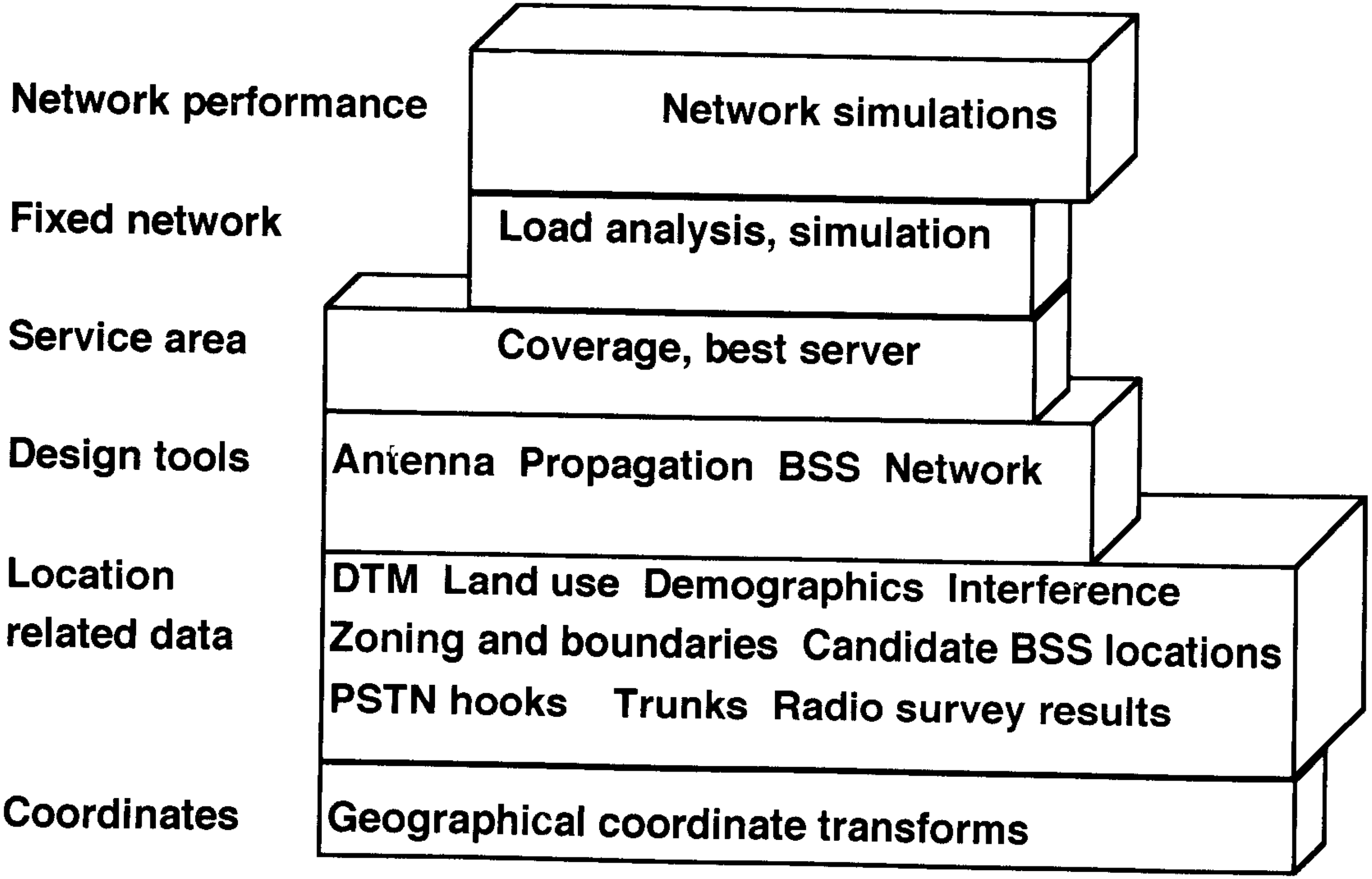
- Final base stations specifications and coverage design
  - » Location, sectors, antenna height, antenna parameters, channels, power
  - » base station specification document
- Final fixed network design
  - » PSTN hooks
  - » network topology, and specs for each constituent
  - » trunks
  - » Specification documents
- Frequency coordination
- Network parameter setting

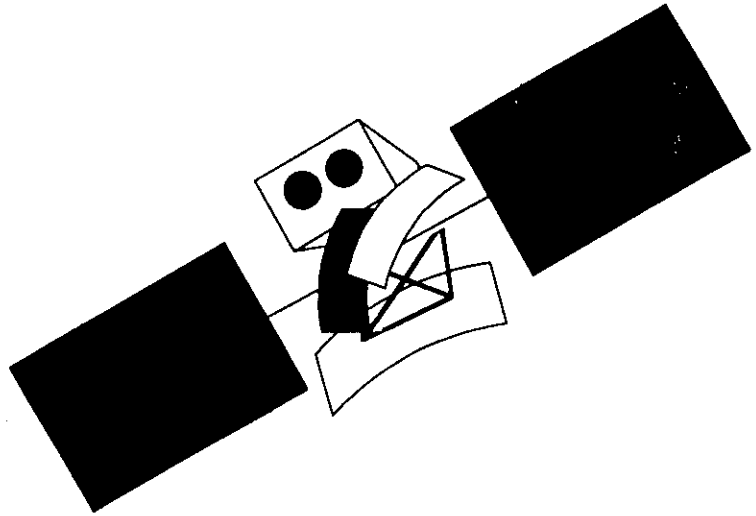
Radio Network Design (cont. 5)

NETWORK TESTING

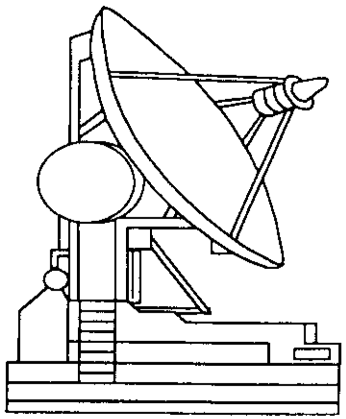
- Sounder test (optional). A CDMA sounder and diagnostics monitor may be used to assess network performance with the antennas in place, but prior to the full deployment of the base stations. Measured parameters:
  - » Coverage: pilot and reverse links
  - » Multipath and E_b/I_o requirements
  - » Soft and softer handoff zones
- Service test for the operational network (optional if the sounder test was performed)
  - » Parameter tuning should be done through this test.

RADIO NETWORK DESIGN TOOLS





PERsonal SATellite COMmunications



CONTENTS

THE BUSINESS CASE

- Wireless communications is mushrooming
  - Cellular subscribers expected by year 2000 - 40 M
  - Personal (PCS) subscribers expected - 40 M
    - (Source: TELOCATOR)
  - Teletraffic densities - 65 ERLANG/km^2 in today's cellular, expected hundreds ERLANG/km^2
- Services become integrated and focused on the (roaming) subscriber
- The infrastructure cost is not justified in sparsely populated areas
- The capacity of PerSatCom will be 1 ERLANG/km^2
- THE PERSATCOMM PROGRAMS ARE AIMING AT
  - The rural (sparsely populated) developed areas, and roaming between rural and cellular-covered areas
  - Disaster communications, backup to cellular
  - 3rd world basic communications (fixed service)

THE BUSINESS CASE (Cont.)

- Requisites from the service
  - Near toll-quality voice
  - At least 2400bps data, and all cellular data services
  - Ubiquitous service, by global coverage and services and/or by integrability with other networks (service transparent to the user)
  - Cost competitive
    - » The cost of communication services HAS TO GO DOWN.
    - » The volume of the services is predicted to grow exponentially.
    - » This means a growth in teletraffic per citizen
    - » The communications cannot overwhelm the citizens' budget. The cost of the service will therefore go down side-by-side with the growth of the volume.
    - » THE PERSATCOM M WILL HAVE TO COMPETE IN THIS MARKET
  - Compactness and simplicity(in operation) of the user equipment
    - » Dual mode units may become a necessity for roaming in and out of the crowded (business) areas.

SATCOM BASICS

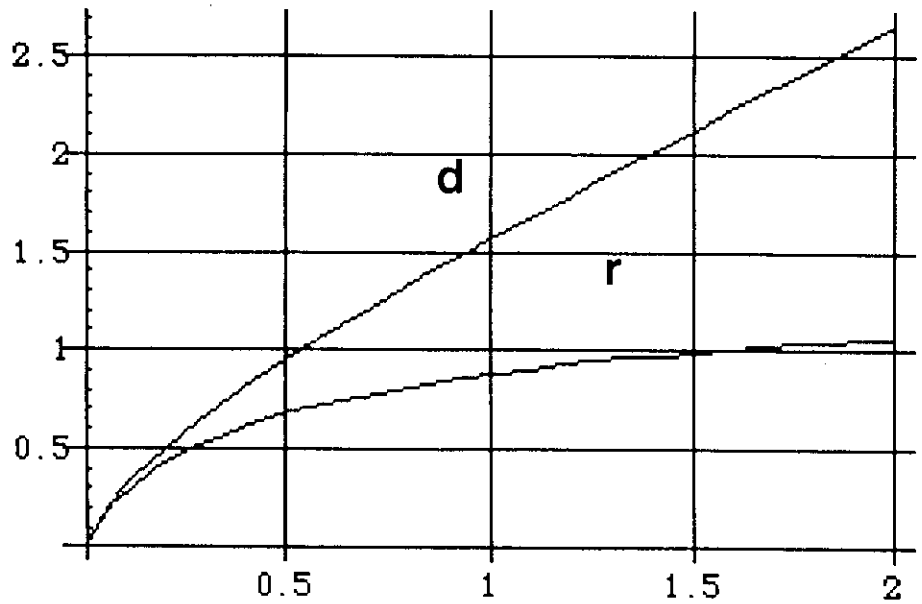
- Architecture
  - Satellites are power limited and interference limited.
  - PERSATCOM are also band limited (due to limited frequency allocation)
  - Comsat architecture is STAR: multiple access to the satellite, and trunk (feederlink) to the gateway
  - All current commercial satcoms operate as "bent pipes": the satellite is an amplifier (and frequency translator). No down conversion and signal processing on board.
  - Exception is Iridium. The experimental NASA satellite ACTS (a GEO satellite) will also provide on-board processing.
- Connectivity
  - Each call is processed at the gateway (except for Iridium)
  - Connection to the PSTN is through the gateway. Connection to terrestrial wireless networks is via PSTN.

SATCOM BASICS - ORBITS

- Satellites rotate around the center of Earth
- The satellite orbits obey the Keplerian lows of motion
- The period of a circular orbit is proportional to $(R_{orbit})^{3/2}$
- Satellites at R=42,000 km in the equator plane rotate at the rate of the Earth and are Geo Stationary.
  - The main objection to GEO PerSatCom is the propagation delay - 220 ms from mobile to gateway, twice that much for mobile-to-mobile.
- Altitude of 13,820 km maintains an 8 hours period. The satellite footprint retracts itself every day, over 3 coverage regions.
- Altitude of 10,290 maintains a 6 hours period. Same for 4 coverage regions.
- The radiation (Van Allen) belts extend from 1.4 to 1.7 R_E and from 3.1 to 4.1. These belts are considered hostile to satellites.
- Low Earth Orbits are affected by the Earth oblateness. The corrections to the Keplerian rules depend on the inclination and altitude.

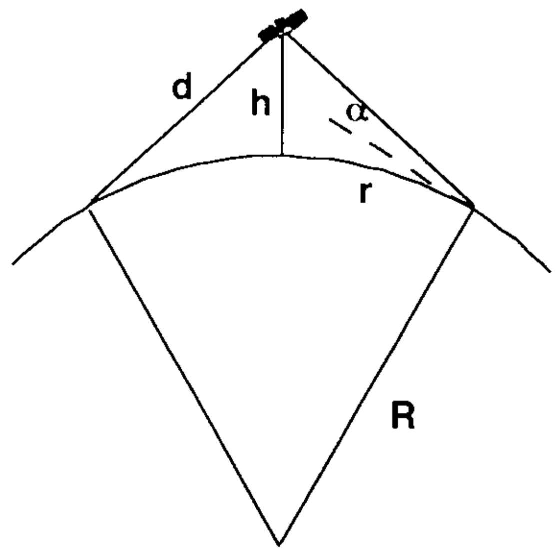
SATCOM BASICS - COVERAGE AND LINK BUDGET

- L (path-loss) proportional to $d^2 L_{atm.} L_{shadow} L_{fading}$
  - L_{atm} is atmospheric loss, mainly rain. Depends on the region and increases at low elevation angles
- L_{shadow}, L_{fading} depend on the obstructions. Increases substantially at low angles.



h/ R orbit altitude vs. Earth radius

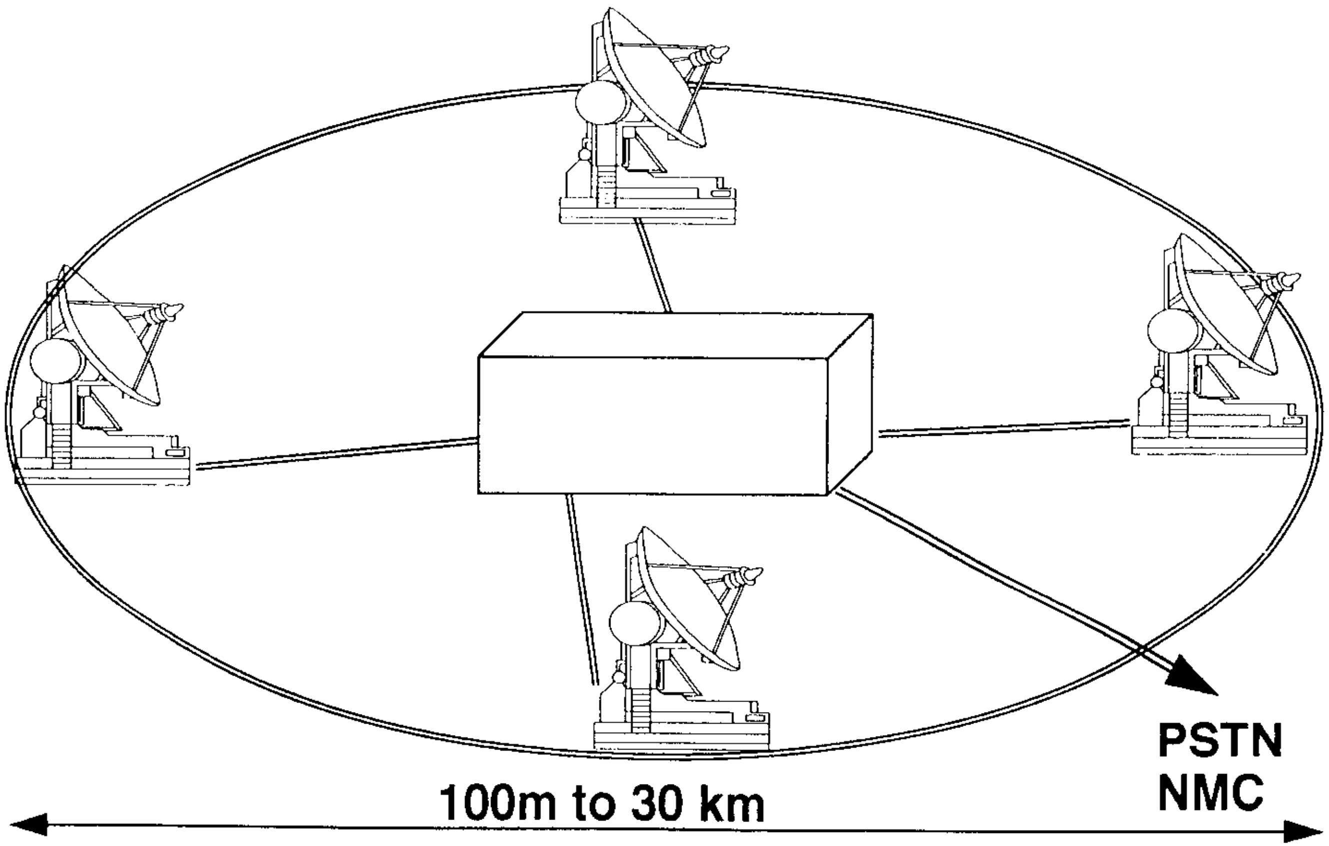
d - slant distance at 10° elevation
r - radius of footprint at 10°



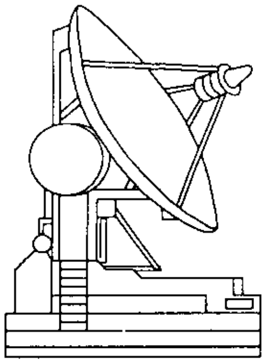
THE GATEWAY

- A LEO gateway consists of 4 tracking antennas
- Minimum spacing between the tracking antennas is defined by the blockage at low angles, and the max. - by the rain diversity.
- Each antenna may be 3 to 6 m diameter
- Each antenna tracks from horizon to horizon
- The feederlink frequencies differ between the programs: C band or Ka Band

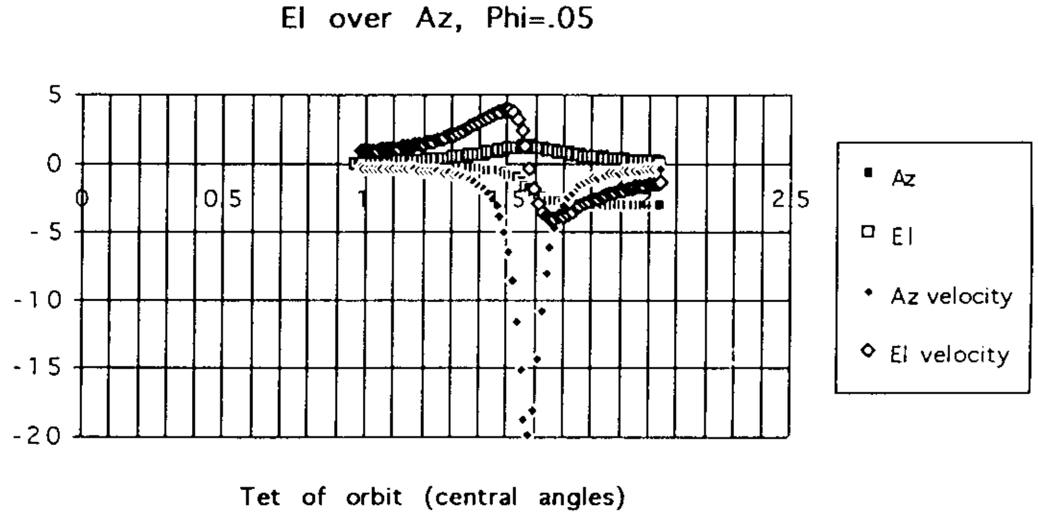
THE GATEWAY IS THE CONNECTION TO THE PSTN AND TO THE NETWORK MANAGEMENT CENTER. ALL THE TRAFFIC OF THE SATELLITE IS ROUTED THROUGH THE GATEWAY

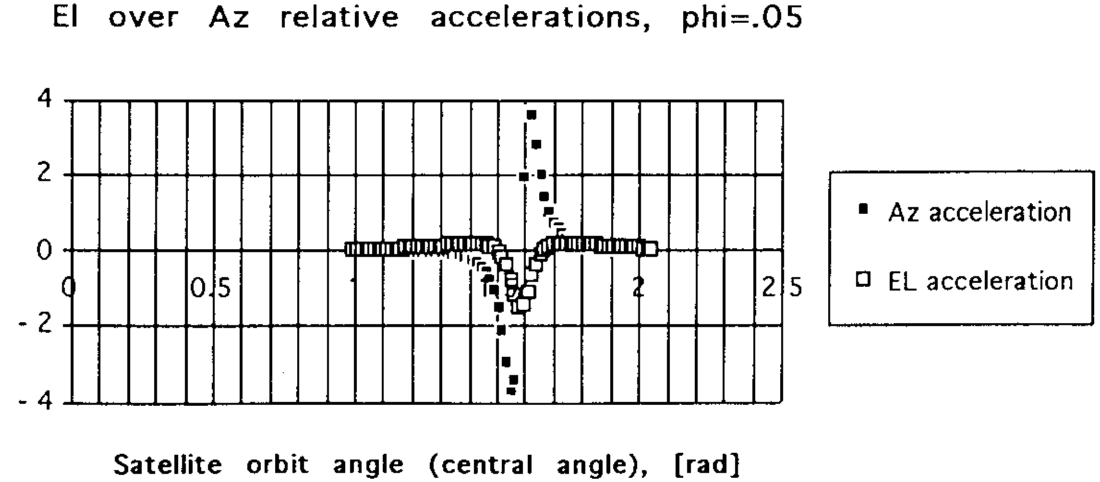


LEO TRACKER DYNAMICS



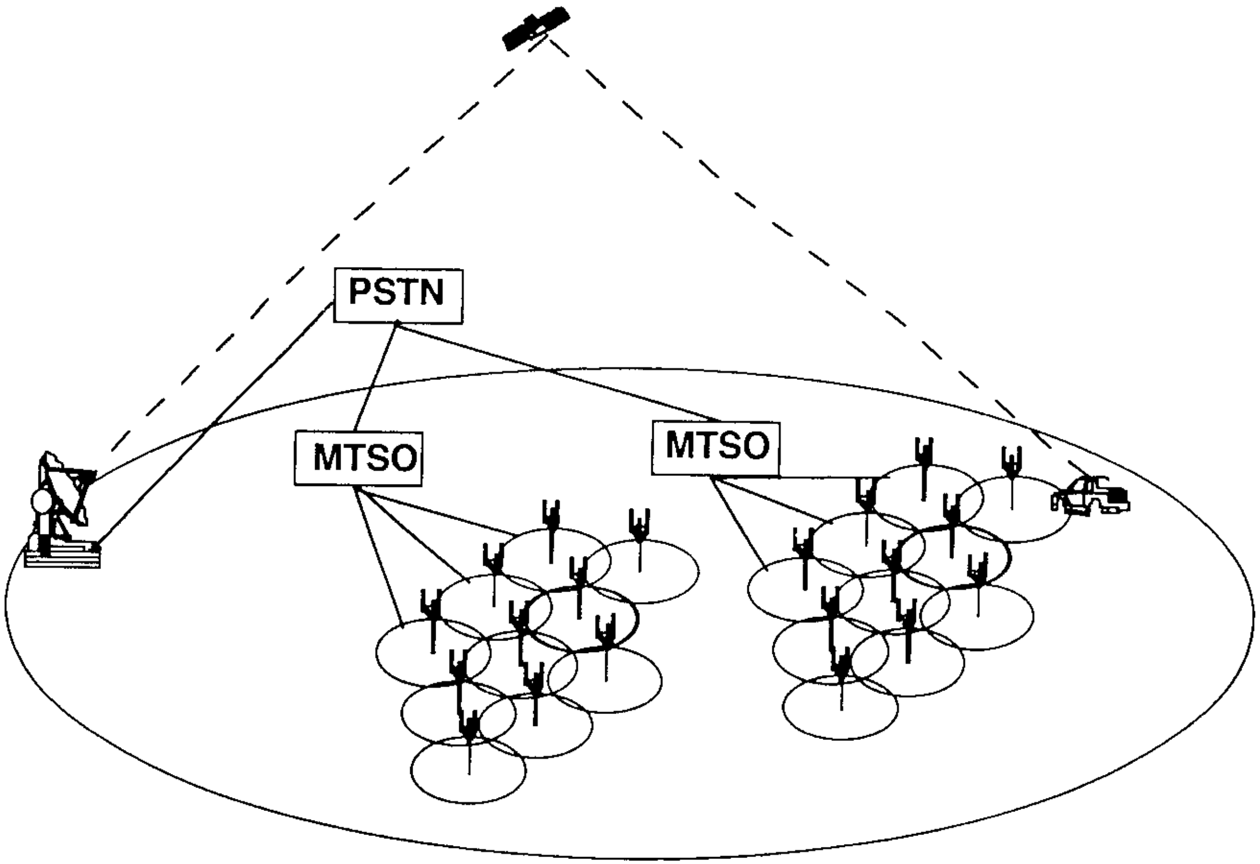
- The satellite crosses from horizon to horizon.
- The typical tracker has Elevation over Azimuth axes.
- Satellites passes near the zenith are most stressing to the tracker
- Note that the tracking antenna is 3 to 6 m Φ and tracking accuracy required is high (1 to 5 mr)





HANDOFF SATCOM - TERRESTRIAL CELLS

- Sat to ter HO poses a problem of cell identification
- Use has to be made of the separate sat and ter channels
- The propagation regimes are different and frequent back-and-forth ("ping-pong") may occur. New protocols are required.
- Handoff commands are routed via a complex PSTN route and may have delays and reliability issues. Hence the advantage to distributed gateways.



GATEWAYS - HOW MANY AND WHERE?

THE PARAMETERS THAT INFLUENCE GATEWAY LOCATION:

- Bent-pipe systems need a gateway for every satellite footprint
- On-board processing systems (iridium) are relieved from this requirement
- The length of the PSTN line to the fixed subscriber (PSTN tariff)
- Handoff to terrestrial cellular systems may require regional gateways to avoid excessive lengths network control signals.
- Cross border issues: nations may require sovereignty over the teletraffic in their territory, and thus - a gateway

"BIG LEO" PROGRAMS

	Ellipso	Globalstar	Inmarsat	Iridium	Odyssey
No. of satellites	15, 9	48		66	12
# of orbit planes	3, 1	8		6	3
Inclination(^{0})	63.4,0	52		86.4	55
Altitude (km)	7800*540 7800	1400		780	10400
Sat. mass (kg)	300-450			700	1917
Cost to build($B)	.7	1.6 (2.6)	1-2	3.4	1.3
Implementation	1996	1997	2000	1998	1997-8
Rate (air-time)/min.	<50¢	30¢	$1-2	3	65¢

TERSATCOM COST DRIVERS

- Satellite
  - Antenna size (proportional to d)
  - Power requirement (proportional to d)
  - Stabilization (proportional to d)
  - Lifetime required
  - Special environment (Radiation - Van-Alen belt)
  - Number of satellites (inversely proportional to r)
- Satellite launch
  - Depends on satellite size, altitude and orbits
- Terrestrial system
  - Gateways
  - Network management centers
- Operation costs
  - PSTN and trunking
  - Network coordination and management
  - Network maintenance
  - Billing and customer services

ODYSSEY

- Company: TRW, Redondo Beach, CA
- Market - main land masses and coastal areas.
- Cost $1.3 B
- Implementation 1997-8
- No. of satellites 12
- Orbit - 6 hours, 10370 km altitude, 3 planes, 55^o inclination
- Spacecraft - 1134 kg, power load 1800 Watts
- Minimum elevation angle - 30^o, 95% of the time
- Visibility of each satellite 2 hours, overlap 10 minutes
- 19 beams, 5^o each
- Steerable antennas to reduce handoffs
- 10 or 11 gateways. Each 4 antennas, spaced 30km.
- Capacity 23,000 voice circuits worldwide (4600 circuits over CONUS). Assumes 100 subs/ circuit -> 2.3 M subs.

ODYSSEY (Cont.)

- Frequency plan
  - User uplink - 1610-1626.5 MHz
    - » 3 sub bands, each 4.83 MHz, centered at 1612.32, 1618.25, 1623.58 MHz
  - User uplink - 2483.5-2500 MHz
    - » 3 sub bands, each 4.83 MHz, centered at 2486.42, 2491.75, 2497.08 MHz
  - Feeder links
    - » Uplink 20 GHz
    - » Downlink 30 GHz (104 MHz)
- COMMUNICATION SYSTEM
  - CDMA . 4.83 MHz (no details)

GLOBALSTAR

- Company : GLOBALSTAR, San Jose, CA (LORAL-QUALCOMM)
- Market - Land masses, except for polar regions (>70°)
- Implementation - 1997
- No. of satellites 48
- Orbit - , 113 minutes, 1400km altitude, 48/8/1 Walker constellation(8 planes), 52° inclination. Average connection time 10-12 minutes
- Spacecraft
- Minimum elevation angle - 10° (at 70° and 12° latitude. Over 20° over most CONUS, central Europe). Average >40° @ latitudes <58°
- At least 2 satellites visible 85% of time over main target markets
- 6 beams per satellite (oval)
- >200 gateways (for domestic control and multi-satellite diversity)
- Capacity 32,000 voice circuits worldwide (6500 circuits over CONUS). Assumes 100 subs/ circuit -> 3.2M subs (year 2002)

GLOBALSTAR (cont.)

- Communications system
  - CDMA (similarity to IS 95). 1.23 MHz / channel
  - Frequency reuse throughout the system
  - Soft handoff and power control applied
- Frequency plan
  - User uplink - 1610-1626.5 MHz
    - » 13 channels of 1.25 MHz, in each beam
  - User downlink - 2483.5-2500 MHz
    - » 13 channel of 1.25 MHz in each beam
  - Feeder links (tentative until WRC 95)
    - » Gateway uplink 6484-6541.5 MHz (polarization reuse LHCP, RHCP)
    - » Downlink 5158.5-5216 MHz (polarization reuse LHCP, RHCP)

INMARSAT - P

- Company - INMARSAT, London
- Market - Global
- Cost $2.6 B
- Implementation 2000
- No. of satellites 10 (plus 2 spares)
- Orbit - ICO 10,355 km(6 hours), 2 planes* 5 satellites or 3 planes * 4
- Spacecraft - power load 500W
- Satellite life 10 years
- Minimum elevation angle ? (assume 30 deg.)
- Total 85 beams
- Minimum 10 gateways
- Capacity 4000 circuits per satellite (*note: does not conform with the similar system Odyssey unless a much wider band is allocated*)

INMARSAT - P (cont.)

- Frequency plan
  - Mobile links 1.9 / 2.2 GHz
    - » Allocation of these bands is scheduled for 2005 by the ITU
    - » Inmarsat will try to influence an earlier decision (1999-2000)
    - » This band, if allocated, seems to be less congested (at the moment)
  - Feeder links 20 30 GHz
    - » Feeder links allocation will be negotiated in WRC 95
    - » Inmarsat will also try to influence an allocation below 16 GHz.
- Communication system
  - No definition is available
- Note
  - The design of the Inmarsat system is not complete, or not revealed.
  - It seems that Inmarsat is relying on its signatory base to guarantee the licensing and the market worldwide

IRIDIUM

- Company: Iridium Inc. Washington D.C. (Motorola leading the consortium)
- Market: Global. Addresses mainly the travelling business man
- Cost: $3.4 B
- Implementation - 1998
- No. of satellites 66
- Orbit - polar, altitude 780 km, 6 planes, 5 active and one spare in each plane, inclination 86.4°
- Spacecraft - 700 kg
- Minimum elevation angle - 10°
- Visibility of each satellite is about 6 minutes
- 48 beams, 3168 cells total, 2150 of which need to be active for earth coverage.
- Processing satellites. The channels are trunked between the satellites. A few tens of gate ways.
- Capacity 4400 circuits in CONUS (10.6MHz)

IRIDIUM (cont.)

- Frequency plan
  - User up and down link - 1616 1626.5 MHz (to be extended if only one CDMA competing system will be in use)
  - Feederlinks
    - » Uplink 29,100 - 29,300 MHz
    - » Downlink 19,400 - 19,600 MHz
  - Intersatellite 23,180 - 23,380 MHz
- Communications system
  - FDMA / TDMA

REGULATORY ISSUES

- User bands allocation - WARC 92
  - 1610 - 1626.5 MHz
    - » Used for uplink by all except Iridium
    - » Used for both up and down links by Iridium
- Feeder links - to be determined in WRC 95
  - C band
    - » Up link
    - » Down link
  - Ka band
    - » Up link
    - » Down link
- Interference issues
  - To other services
  - To Radio Astronomy
- Domestic issues
  - Example - the FCC process (filing to 1/3/95. Decision 1/31/95)

Approved bands and limitations

		1610 MHz	1613.8 — 1626.5
Primary	Worldwide	aero radionav Mobile sat (up link)	aero radionav Mobile sat (up link)
	Region	RDSS up (region 2) Fixed (fn 730) RDSS up (fn 733b)	RDSS up (region 2) RDSS up (fn 733b)
Secondary	Worldwide	Electronic Air nav aids(fn 732)	Electronic Air nav aids(fn 732) Mobile satellite downlink
	Region	Fixed (fn 727 countries) RDSS uplink (RGN 3) RDSS uplink (fn 733f RGN 1)	Fixed (fn 727 countries) RDSS uplink (RGN 3) RDSS uplink (fn 733f RGN 1)
Coordination	GLONASS	GLONASS (coordinated)-------------1617 MHz GLONASS (M)---------------------------------------1620.6 MHz	
	worldwide	<-----------------------------fn 731x applies----------------------------->	

Approved bands and limitations (cont.)

		2483.5 – 2500
Primary	Worldwide	Fixed, mobile, mobile satellite downlink ISM band interference must be accepted
	Region	RDSS downlink (fn 753c) RDSS up (fn 733b) Radio Location (RGN 2 & 3)
Secondary	Worldwide	
	Region	Radiolocation (RGN 1) RDSS Downlinks (fn 733f - region 1) RDSS Downlinks (RGN 3)
Coordination	Worldwide	<--------------------------fn 753x applies-------------------------->

PROGRAMS' RISKS

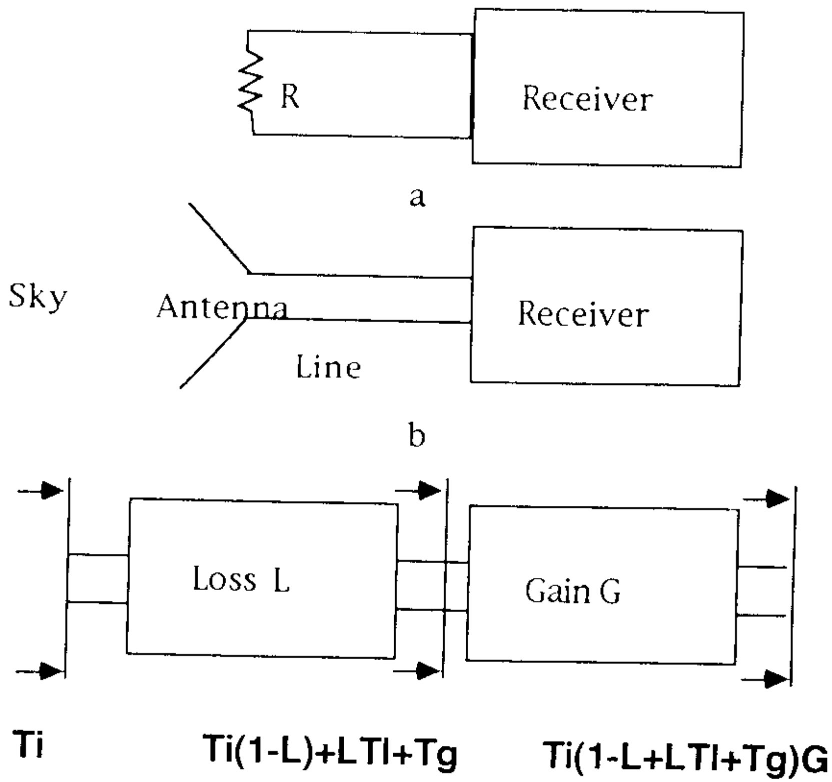
- System concept and grade of service
  - Particularly interoperation with other systems and the "system transparency"
- Serviceable areas
  - Link budget and system features to support
    - » A contiguous coverage
    - » A smooth handoff to and from terrestrial systems
    - » In-buildings, heavy urban, woods
  - Implications of possible required changes in the bird and in the users' equipment
  - Scheduled field tests and their validation potential
  - Capacity predictions and validation
  - Interference to and from the system
- Development plan
  - Potential of delays and/or performance fallback
- Regulatory and licensing issues
  - Internationally (ITU) and domestically in each serviceable country
- Business: financial backup, market development

ANTENNA TEMPERATURE -ES

- Noise power N = KTB
  - K is Boltzman constant
    =1.38*10-23 [J/K]
  - T is the absolute (Kelvin) temperature of the noise source, and
  - B is the receiver bandwidth (Hz)
- Noise temperature T = N/KT
- Noise temperature of a cascaded chain

  Ti(1-L)+LTI+(1+r2)Tg

  - r reflection coefficient



CONTRIBUTORS TO THE SYSTEM TEMPERATURE

1. Aperture temperature
1.1. Sky temperature
1.2. Sun temperature
1.3. Atmosphere temperature
1.4. Rain temperature
1.5. Ground temperature
1.6. Radome temperature

2. Passive front end temperature
2.1. Antenna feed and line temperature
2.2. Passive front-end network temperature

3. Receiver temperature

APERTURE TEMPERATURE

The aperture temperature is defined as

$$T_A = \frac{\int_0^{4\pi} T(\Omega)G(\Omega)d\Omega}{\int_0^{4\pi} G(\Omega)d\Omega}$$

where G is the (normalized) gain
T is the temperature of the sources in that direction
Ω is the spherical angle (steradian).

SKY TEMPERATURE

- The sky temperature
  - The cosmic background noise is 3K°
  - Galaxies and other local sources are wormer. Consult the sky map wherever the sky temperature is a dominant constituent
- The Sun temperature 2000K
  - In order for it not to increase the system temperature by more than 100° it has to be attenuated 23 dB, which represents the second sidelobe of the antenna.
- Atmosphere temperature (physical temperature 270 K)
  - The atmosphere attenuates the radiation and thereby generates noise
  - It depends on the elevation Aangle

$$T_{At} = 280^* \left(1-10^{-\left(\frac{att.}{10}\right)}\right)$$

att - atmosphere attenuation

Elevation angle (degrees)	Attenuation (dB)	Temp. (computed, K)	Temp. (incl. sky) (reported)
0^0	3	135	
5	.8	45	35
10	.42	27.5	18
20	.21	12.7	
90	.0075	.5	5

GROUND TEMPERATURE

- **Ground noise enters the antenna through the sidelobes**
- **The reference pattern**

$$G(\theta)=G_0\left(\frac{\theta}{\theta_0}\right)^{-2.5}\ ;\ g(dB)=g_0+25\,Log\,(\theta_0)-25\,Log(\theta)$$

- **The horizon, interms of the antenna coordinates**

$$Sin(\theta_{horizon})=\frac{Sin(elevation)}{\sqrt{1-Cos^2(elevation)Sin^2(Azimuth)}}$$

- **The table refers to:**

  skirt exponent

  γ = 2.5, 3

  G= 50 dB, 46.5 dB

Antenna gain (dB)	Elevation angle (degrees)	Ground temperature (K), γ = 2.5	Ground temperature (K), γ = 3
50	2.5	33.7	13.5
	5	21	6.4
	10	12.3	2.9
46.5	10	15.3	

SYSTEM TEMPERATURE

$$T_{System} = (T_{sky} + T_{ground})L + 280(1-L) + T_{amplifier}$$

$$\text{where } L = 10^{-(\text{Atmospheric+radome+line+passive comp.})}$$

G/T, gateway	
Sky temp.	3 K
Ground temp., gam= 2.5, 10 degrees	12.3 K
Atmospheric attenuation, 10 degrees	0.42 dB
Radome attenuation	0.2 dB
Line attenuation	0.2 dB
Passive circuits attenuation	0.5 dB
Total passive losses	1.32 dB
LNA temperature	70 K
System temperature (K)	154.67675 K
Antenna gain	50 dB
G/T (dB/K)	28.1057496 dB/K