ECSE413B: COMMUNICATIONS SYSTEMS II

Tho Le-Ngoc, Winter 2008

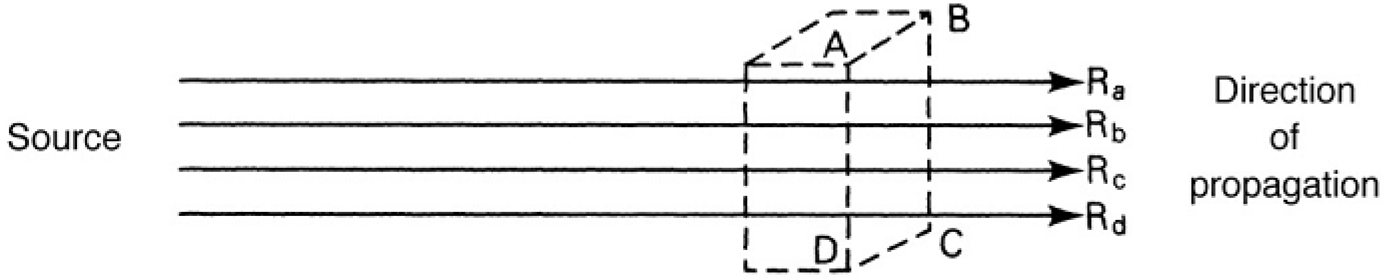
BASIC RADIO PROPAGATION & PATH ENGINEERING

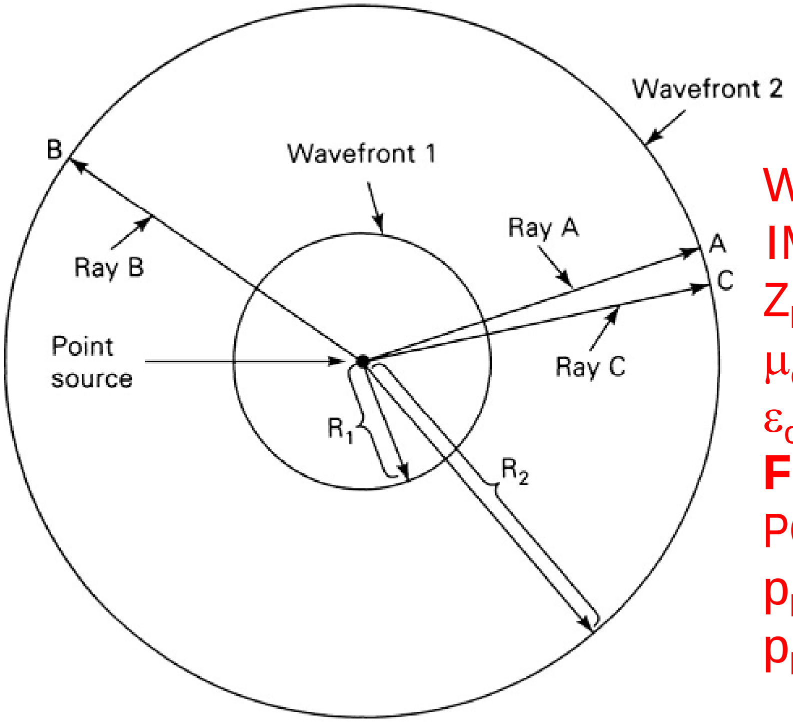
Basic radio propagation

Line-of-sight (LOS) link design

LOS point-to-point communications design considerations.

PLANE WAVE AND WAVE FRONT





WAVE FRONT FROM AN ISOTROPIC SOURCE

IMPEDANCE OF FREE SPACE:

$Z_{FS}=(\mu_o/\varepsilon_o)^{1/2} =(1.26E\text{-}6/8.85E\text{-}12)^{1/2} =377\Omega$

μ_o: MAGNETIC PERMEABILITY (in H/m)

ε_o: ELECTRIC PERMITIVITY (in F/m)

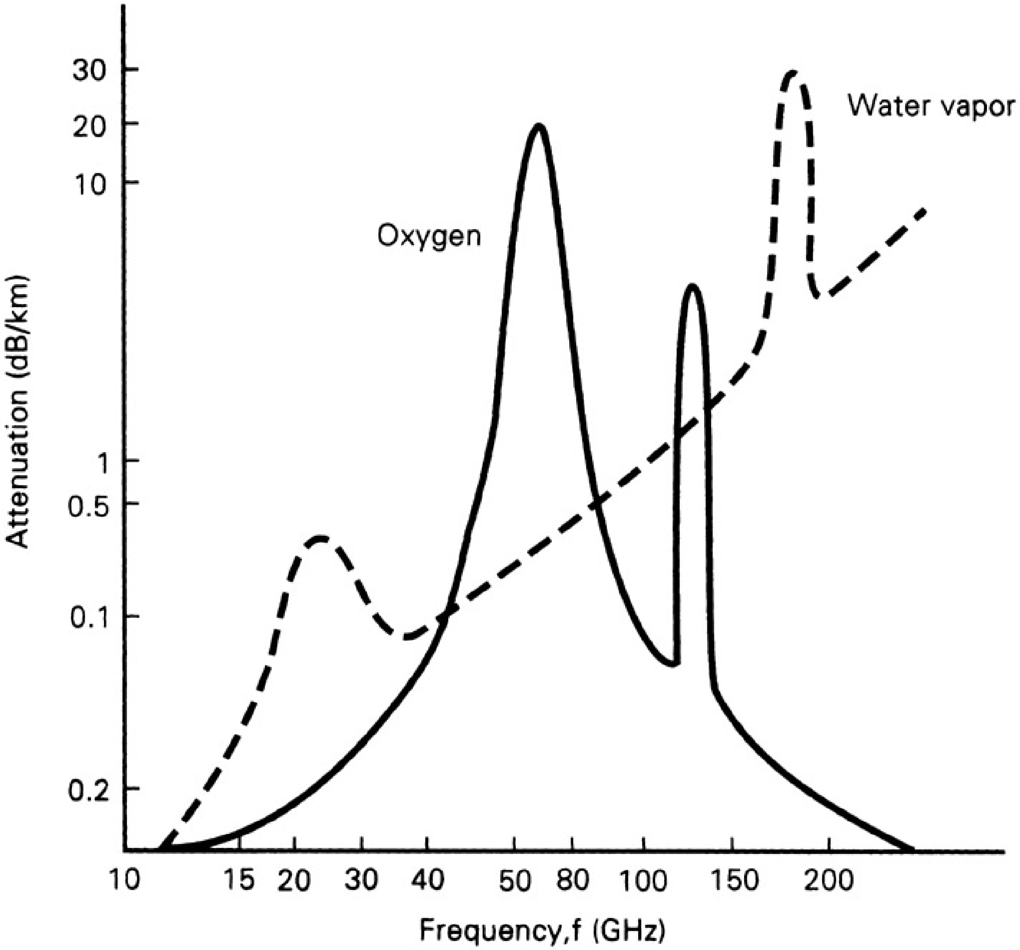
FREE-SPACE LOSS: $L_{FREE\text{-}SPACE}=(4\pi Rf/c)^2$

POWER DENSITY PER UNIT AREA AT R

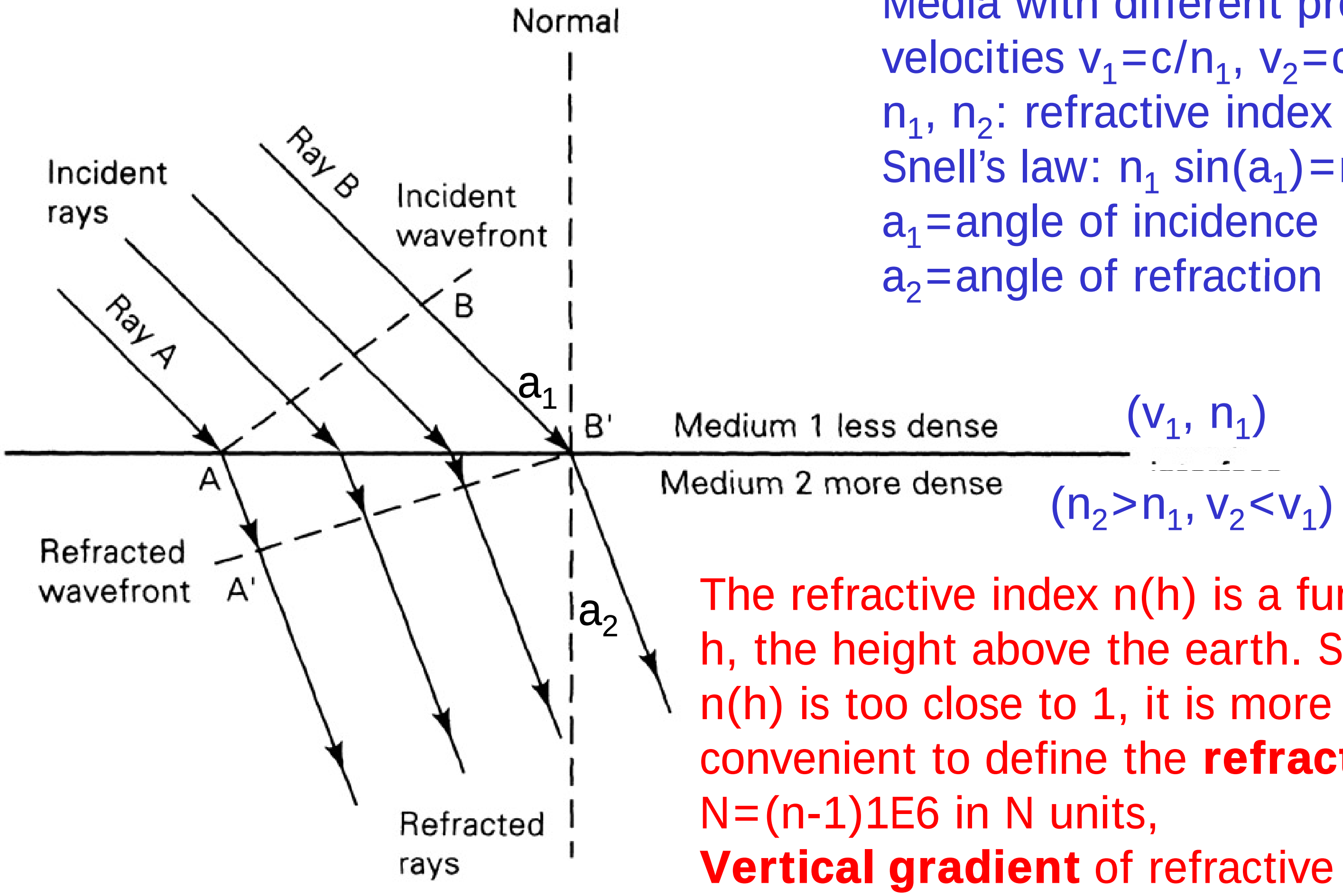
$p_R=P/\ 4\pi R^2$

$p_{R2}=p_{R1}(R1/R2)^2$: square-law

Atmospheric absorption of electromagnetic waves



Refraction at a plane boundary between two media



Media with different propagation velocities $v_1=c/n_1$, $v_2=c/n_2$

n_1, n_2: refractive index

Snell's law: $n_1 \sin(a_1)=n_2 \sin(a_2)$

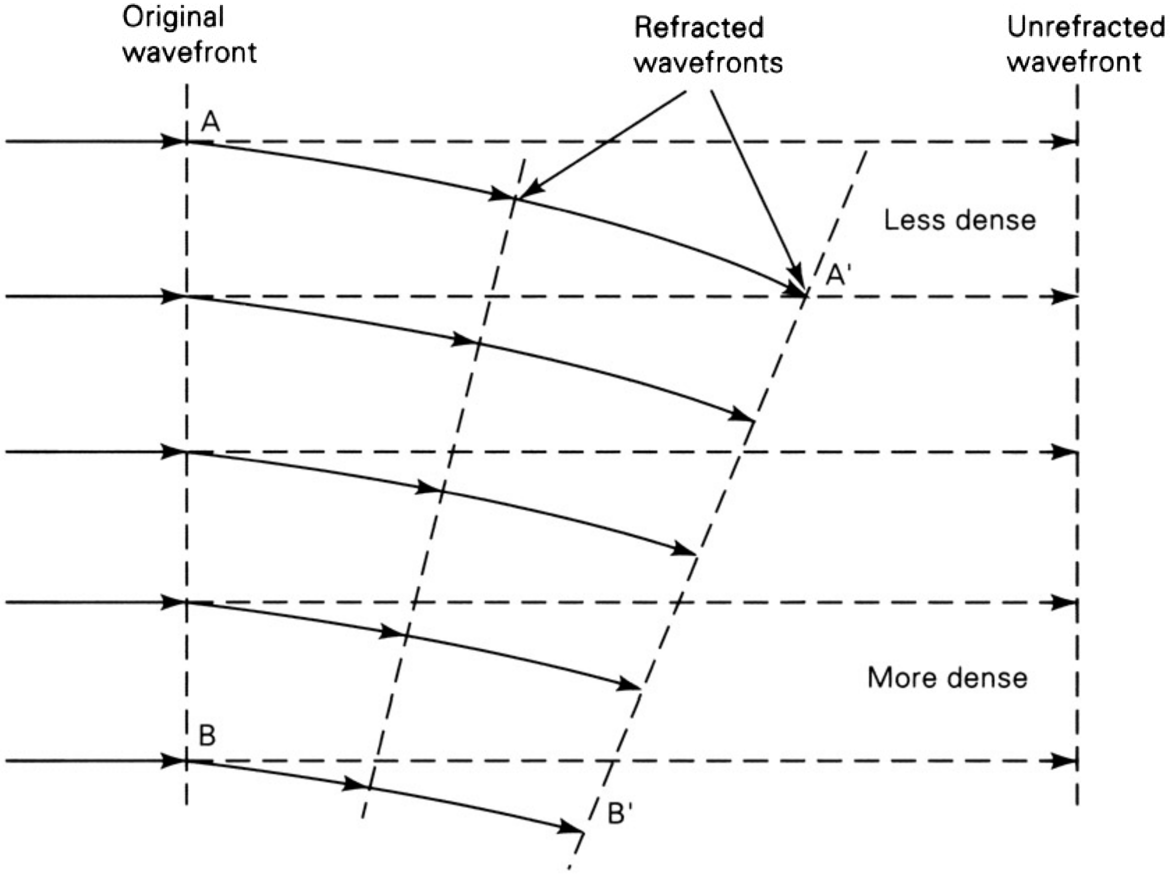
a_1=angle of incidence

a_2=angle of refraction

The refractive index n(h) is a function of h, the height above the earth. Since n(h) is too close to 1, it is more convenient to define the **refractivity** N=(n-1)1E6 in N units,

Vertical gradient of refractive index: dn/dh

Wavefront refraction in a gradient medium



The rays are bent toward the region of higher refractive index

N proportional to $(\varepsilon_r)^{1/2}$. Hence, $dn/dh=0.5(d\varepsilon_r/dh)$

The rate of change of the dielectric constant $(d\varepsilon_r/dh)$ **is nearly constant** for the first few hundred meters above the earth's surface

K: EFFECTIVE EARTH RADIUS FACTOR

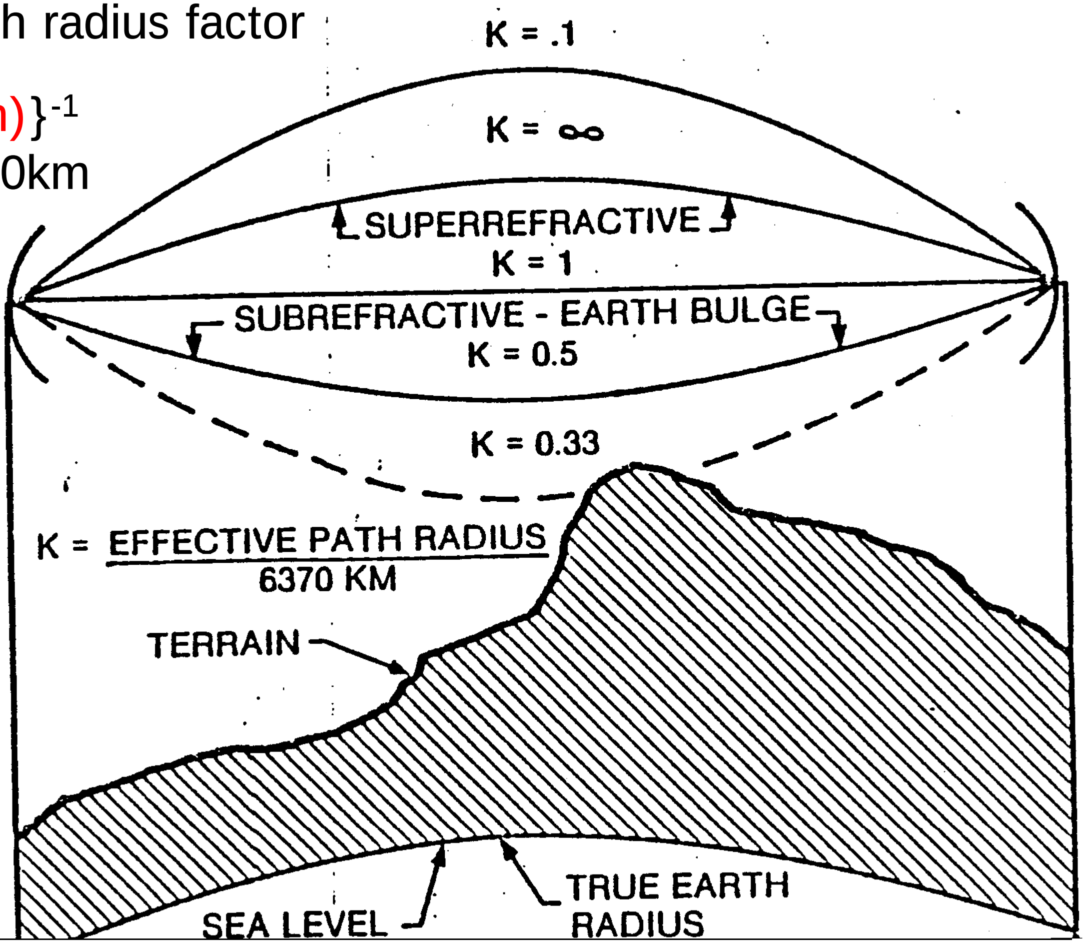
If dn/dh is constant, the net effect of refraction is the same as if the radio waves continued in a straight line but over an earth whose EFFECTIVE radius is $\mathbf{r_e = K.r}$ where K is called the effective earth radius factor

$K=\{1+r(dn/dh)\}^{-1}=\{1+0.5r\,(d\varepsilon_r/dh)\}^{-1}$

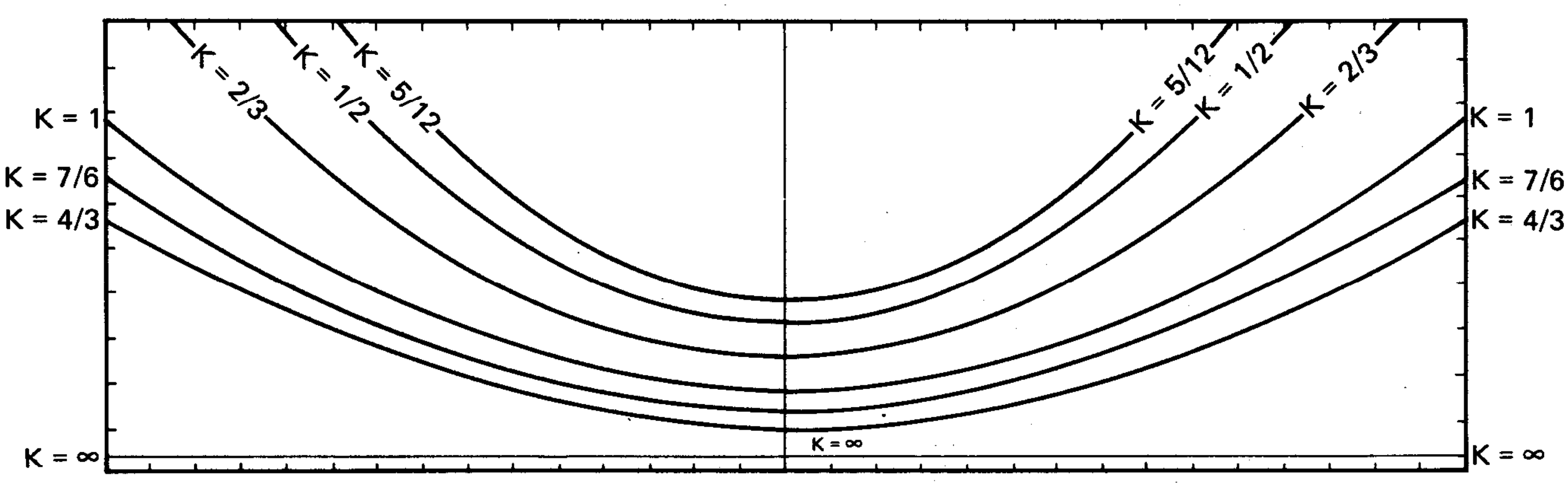
r is true radius of the earth, r= 6370km

$K=\{1+(dN/dh)/157\}^{-1}$ where (dN/dh) in N units per km.

(dN/dh)	**K**
314	0.33
157	0.5
0	1
-157	∞
-314	-1



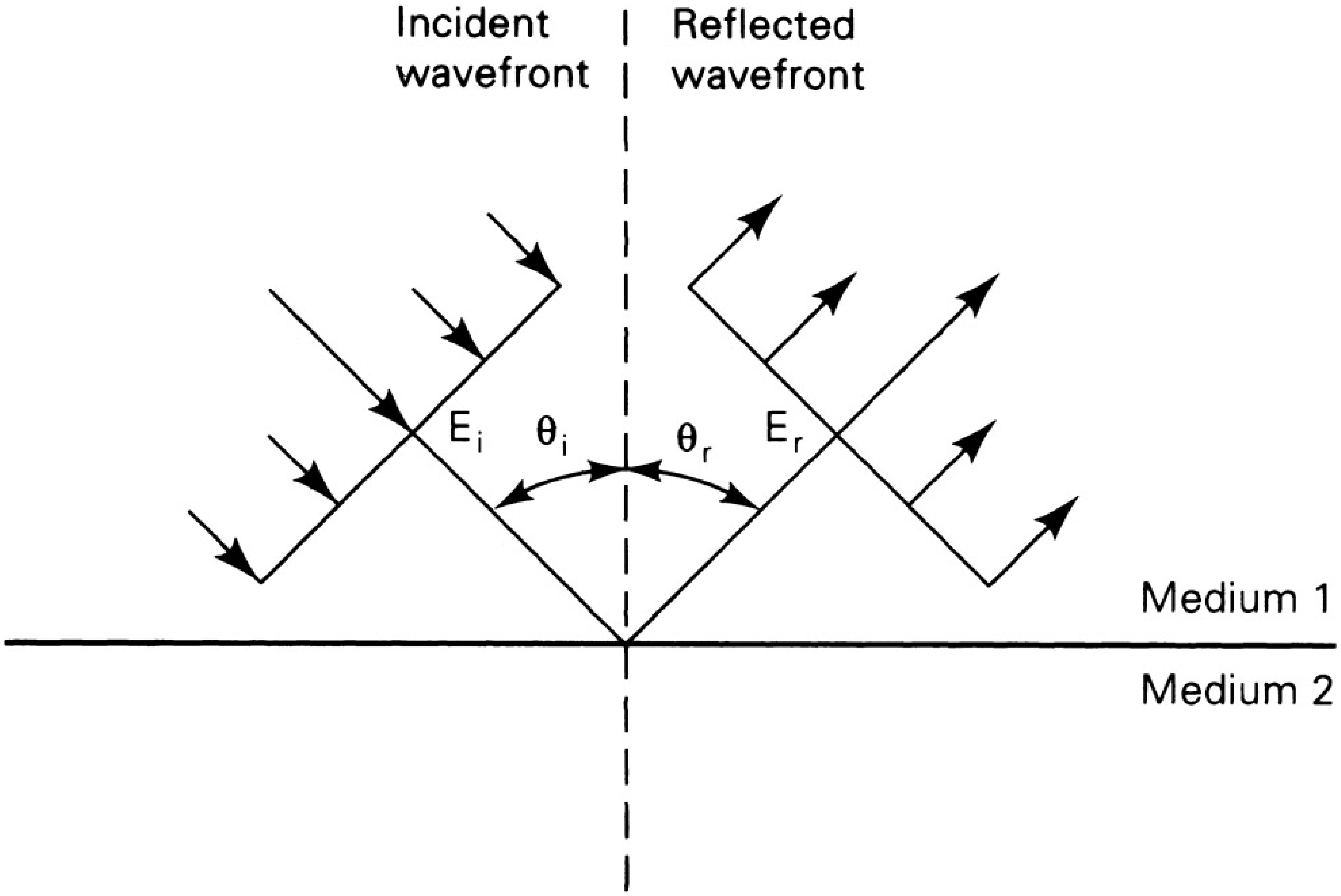
EQUIVALENT EARTH PROFILE CURVES



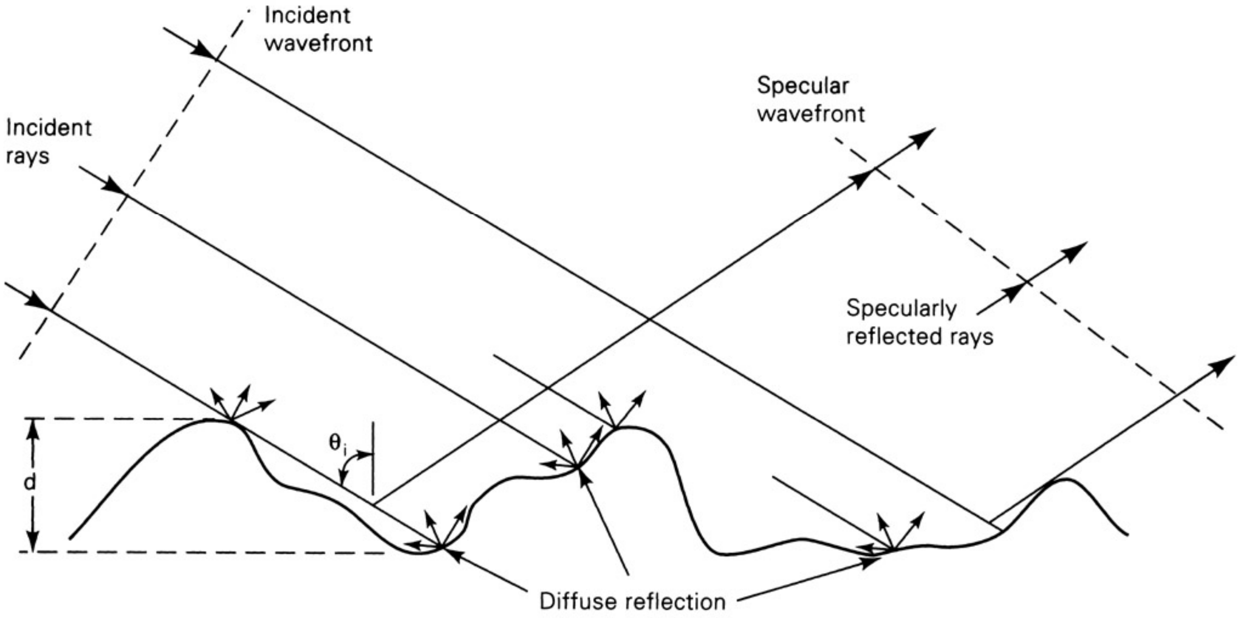
K-FACTOR GUIDE:

K	Propagation	weather	terrain
4/3	perfect	standard atmosphere	temperate zone, no fog
1-4/3	ideal	no surface layers, fog	dry, mountainous, no fog
2/3-1	average	substandard, light fog	flat, temperate, some fog
0.5-2/3	difficult	surface layers, ground fog	coastal
0.4-0.5	bad	fog moisture, over water	coastal, water, tropical

reflection at a plane boundary of two media



Reflection from a semi-rough surface

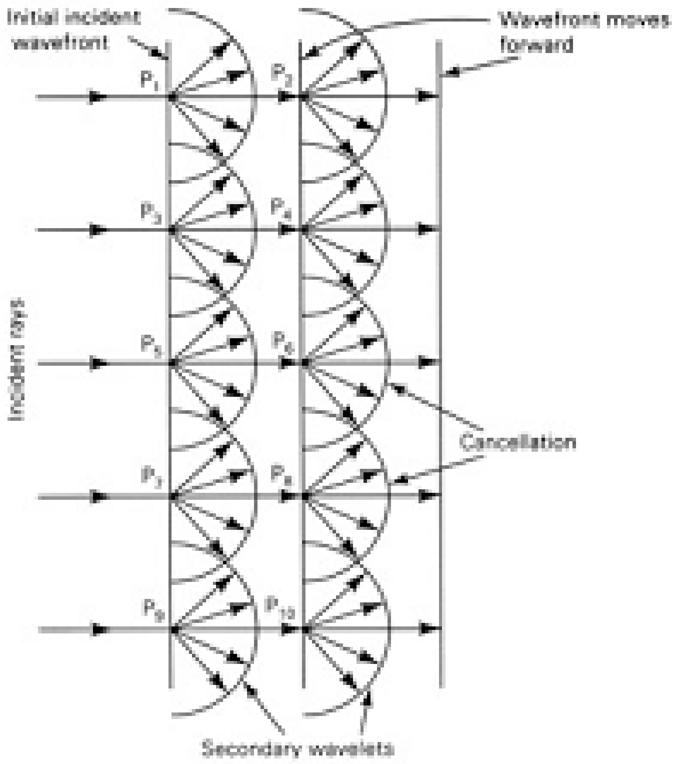


RAYLEIGH CRITERION: SEMIROUGH SURFACE WILL REFLECT AS A SMOOTH SURFACE WHENEVER $\cos(\theta_i) > \lambda/8d$

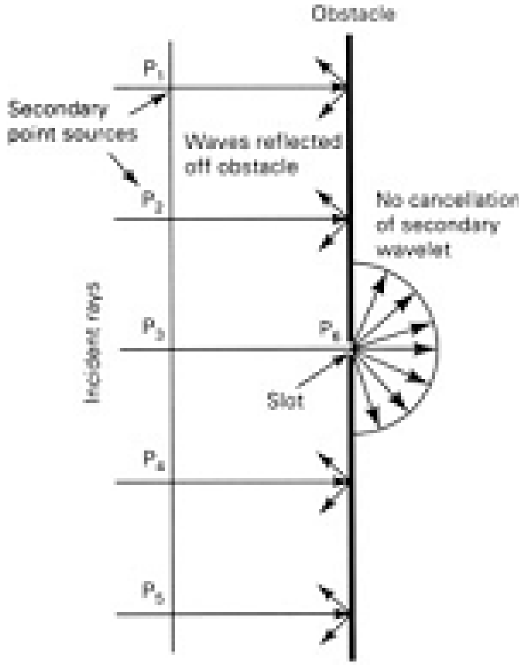
WHERE d: DEPTH OF THE SURFACE IRREGULARITY.

WAVE DIFFRACTION

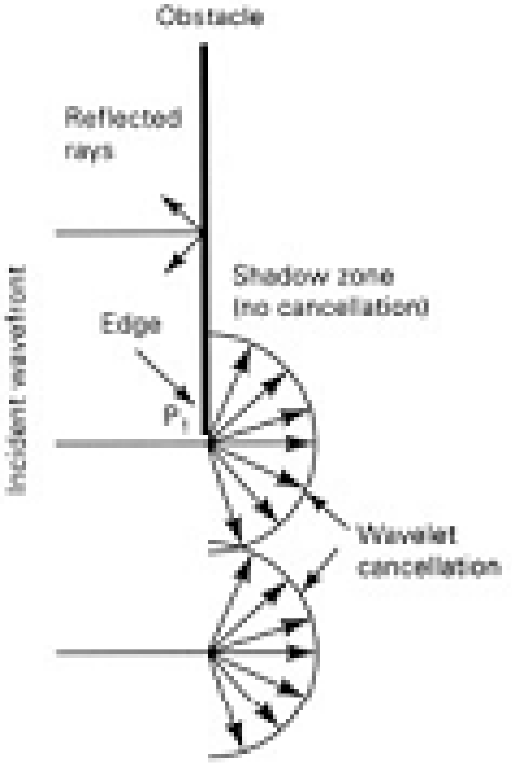
(a) Huygens’s principle for a plane wavefront



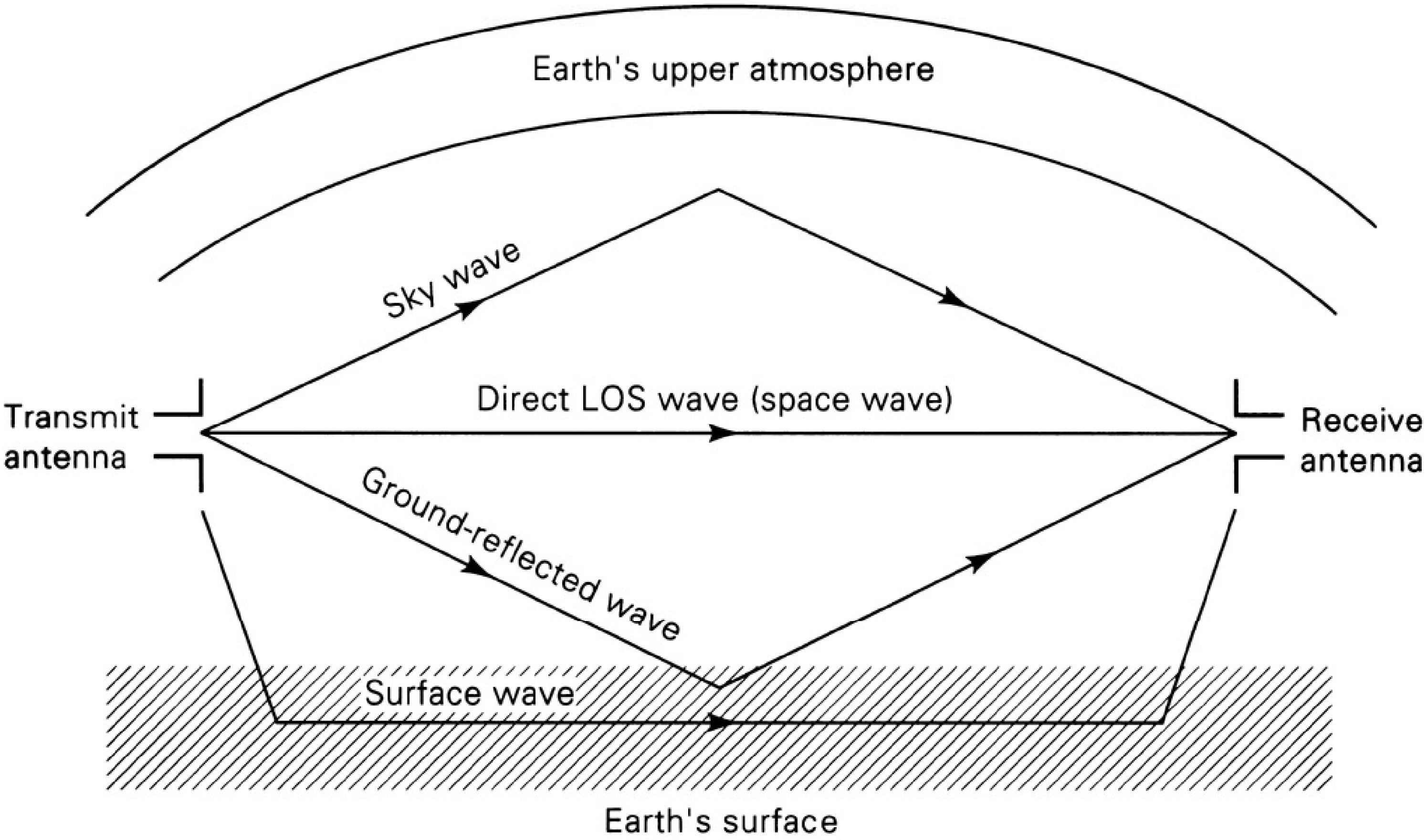
(b) finite wavefront through a slot



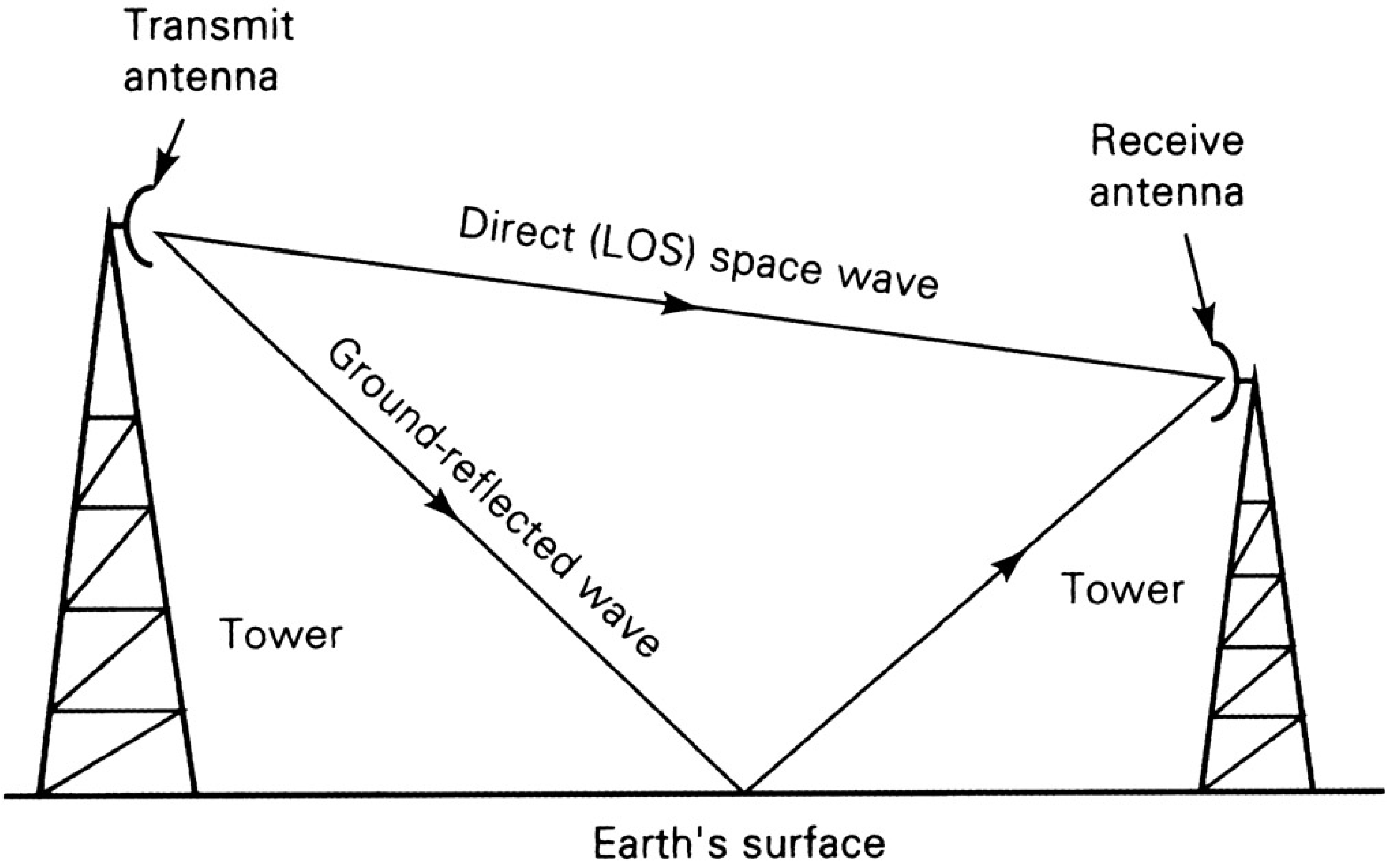
(c) around an edge



Normal modes of wave propagation

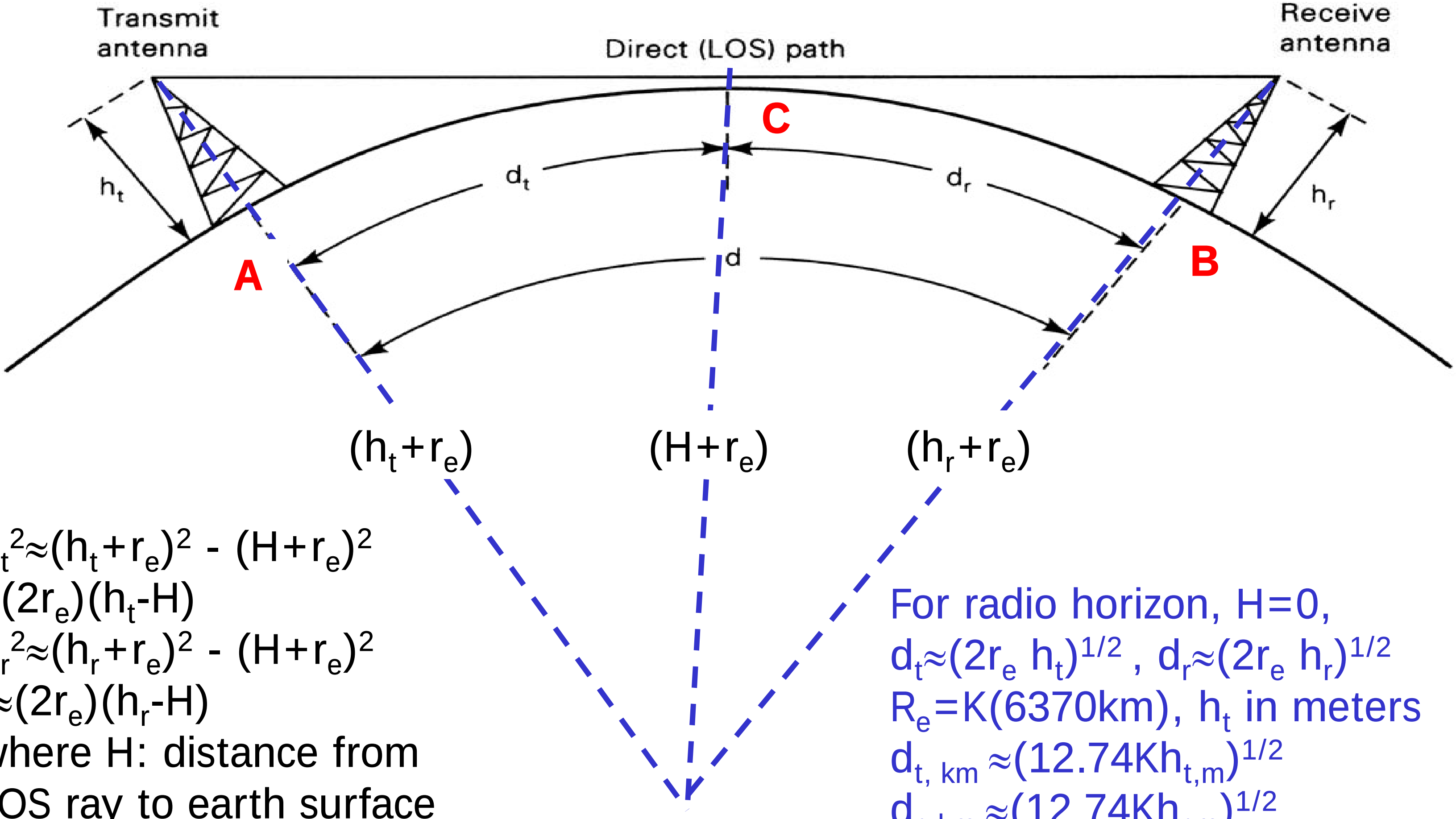


Space-wave propagation: line-of-sight (LOS)



Space waves and radio horizon

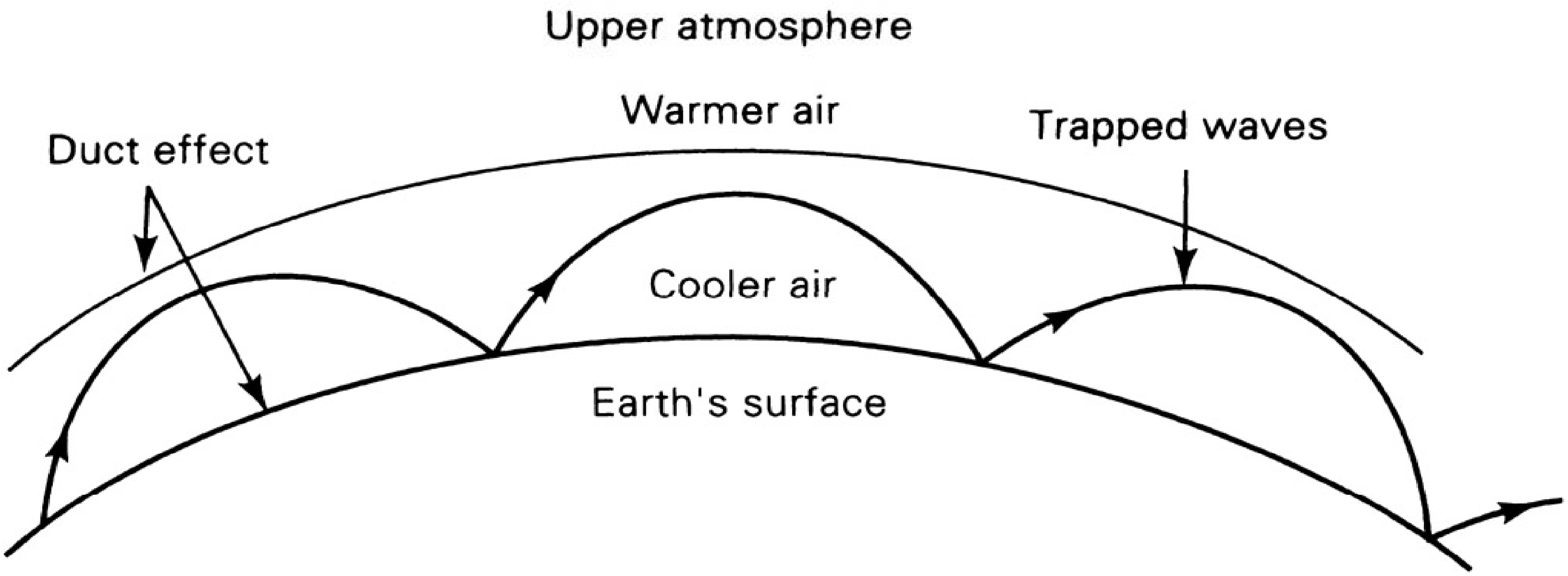
RADIO HORIZON= OPTICAL HORIZON for K=1



$d_t^2 \approx (h_t+r_e)^2 - (H+r_e)^2$
$\approx (2r_e)(h_t-H)$
$d_r^2 \approx (h_r+r_e)^2 - (H+r_e)^2$
$\approx (2r_e)(h_r-H)$
where H: distance from LOS ray to earth surface

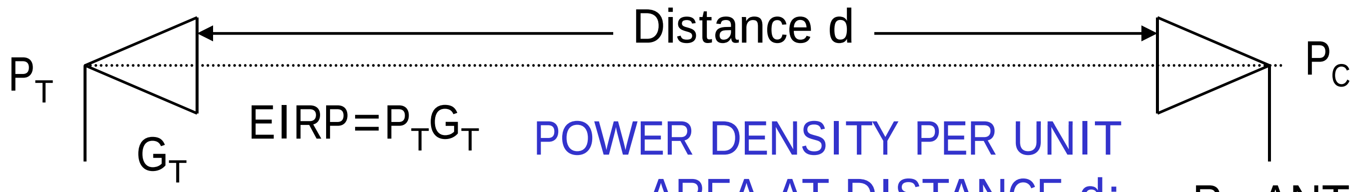
For radio horizon, H=0,
$d_t \approx (2r_e\, h_t)^{1/2}$, $d_r \approx (2r_e\, h_r)^{1/2}$
$R_e = K(6370\text{km})$, h_t in meters
$d_{t,\,km} \approx (12.74Kh_{t,m})^{1/2}$
$d_{r,\,km} \approx (12.74Kh_{r,m})^{1/2}$
Longest $d_{km} = d_{t,\,km} + d_{r,\,km}$
$\approx (12.74Kh_{t,m})^{1/2} + (12.74Kh_{r,m})^{1/2}$

Duct propagation



ATMOSPHERIC DUCTS: DIELECTRIC WAVE-GUIDE-LIKE REGION
CAN EXTEND HUNDREDS OF KM BEYOND NORMAL RADIO HORIZON

LOS: FREE-SPACE LOSS



$EIRP = P_T G_T$

POWER DENSITY PER UNIT AREA AT DISTANCE d: $p_d = (P_T G_T)/(4\pi d^2)$

Tx POWER P_T
Tx ANT POWER GAIN G_T

Rx ANT POWER GAIN G_R
Rx (CAPTURED) POWER P_C

p_d : AMOUNT OF POWER INCIDENT ON EACH UNIT AREA OF AN IMAGINARY SURFACE (PERPENDICULAR TO THE DIRECTION OF PROPAGATION OF THE ELECTROMAGNETIC WAVE).

EFFECTIVE CAPTURE AREA OF THE Rx ANTENNA: $A_C = (G_R \lambda^2)/(4\pi)$

where $\lambda = c/f$: wavelength

Rx CAPTURED POWER: $P_C = A_C\, p_C = (G_R P_T G_T \lambda^2)/(4\pi d)^2 = P_T(G_T G_R)/(4\pi df/c)^2$

FREE-SPACE LOSS: $L_{FREE\text{-}SPACE} = (4\pi df/c)^2$, i.,e., proportional to d^2 and f^2

$P_{C,dBm} = P_{T,dBm} + (G_{T,dB} + G_{R,dB}) - L_{FS,\,dB}$

$L_{FS,\,dB} = 10\log_{10}(L_{FREE\text{-}SPACE}) = 92.44 + 20\log_{10}(f_{GHz}) + 20\log_{10}(d_{km})$

LOS TRANSMISSION CONSIDERATION

The presence of the ground modifies the generation and propagation of radio waves so that the received power is ordinarily less than would be expected in free space (P_R)

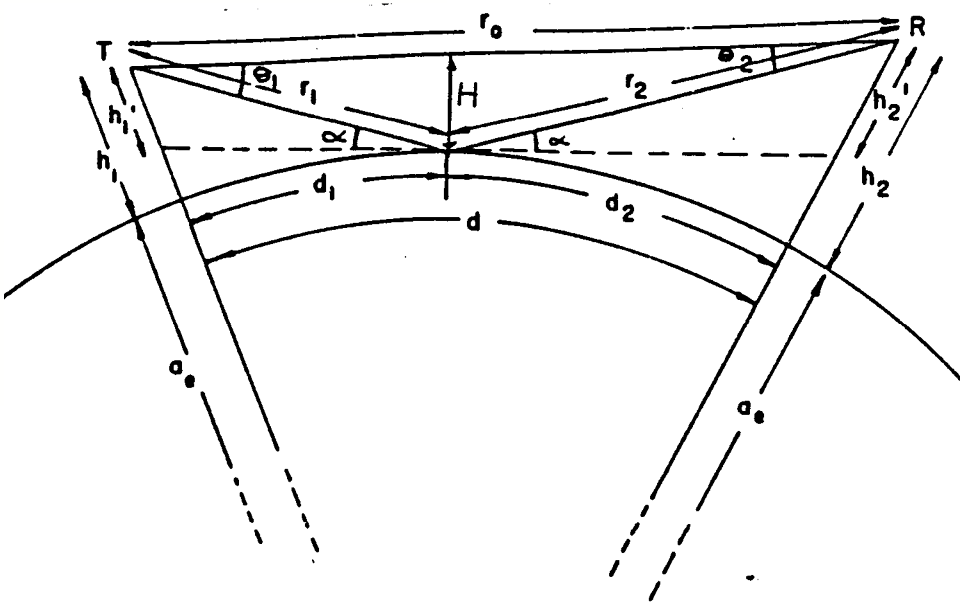
$$V_r = \sqrt{\frac{P_r}{P_R}} = |\underbrace{1}_{\text{direct wave}} + \underbrace{R\, e^{j\Delta}}_{\text{reflected wave}} + \underbrace{(1-R)A\, e^{j\Delta}}_{\text{surface wave}} + \underbrace{\cdots\cdots\cdots\cdots}_{\text{induction field and secondary effects of the ground}} |$$

where R :reflection coefficient of the ground

A :" surface wave " attenuation factor

$$\Delta = \frac{2\pi}{\lambda}(r_1 + r_2 - r_0) \simeq \left(\frac{\pi}{\lambda} \cdot \frac{dH^2}{d_1 . d_2}\right)$$

$$r_1 + r_2 - r_0 = \frac{dH^2}{2d_1 . d_2}$$;H :path clearance



FRESNEL ZONES

For near grazing paths and $h_1, h_2 > \lambda$,

$R \sim -1$ and $A \sim 0$, and

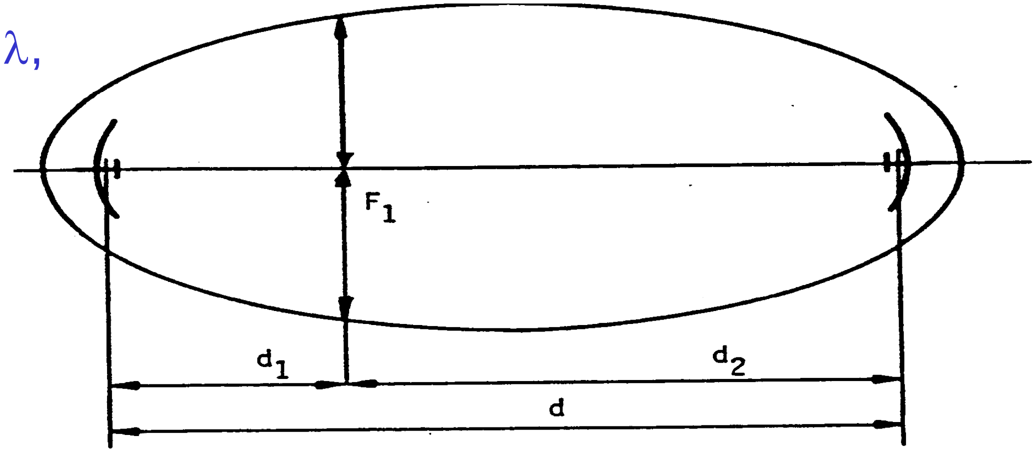
$V_r = 2 \sin \Delta/2$

$= 2 \sin((\pi/2\lambda) \cdot dH^2/(d_1 \cdot d_2))$

For $dH^2/(d_1 \cdot d_2) = n\lambda$,

$V_r = 2 \sin(n\pi/2)$

the received signal is enhanced for odd n and reduced (cancelled) for even n



FIRST FRESNEL ZONE

The regions in space where these reflections take place are called FRESNEL ZONES, i.e., n^{th} Fresnel zone clearance

$F_n = \{n\lambda d_1 \cdot d_2/d\}^{1/2}$, $F_n = F_1\, n^{1/2}$

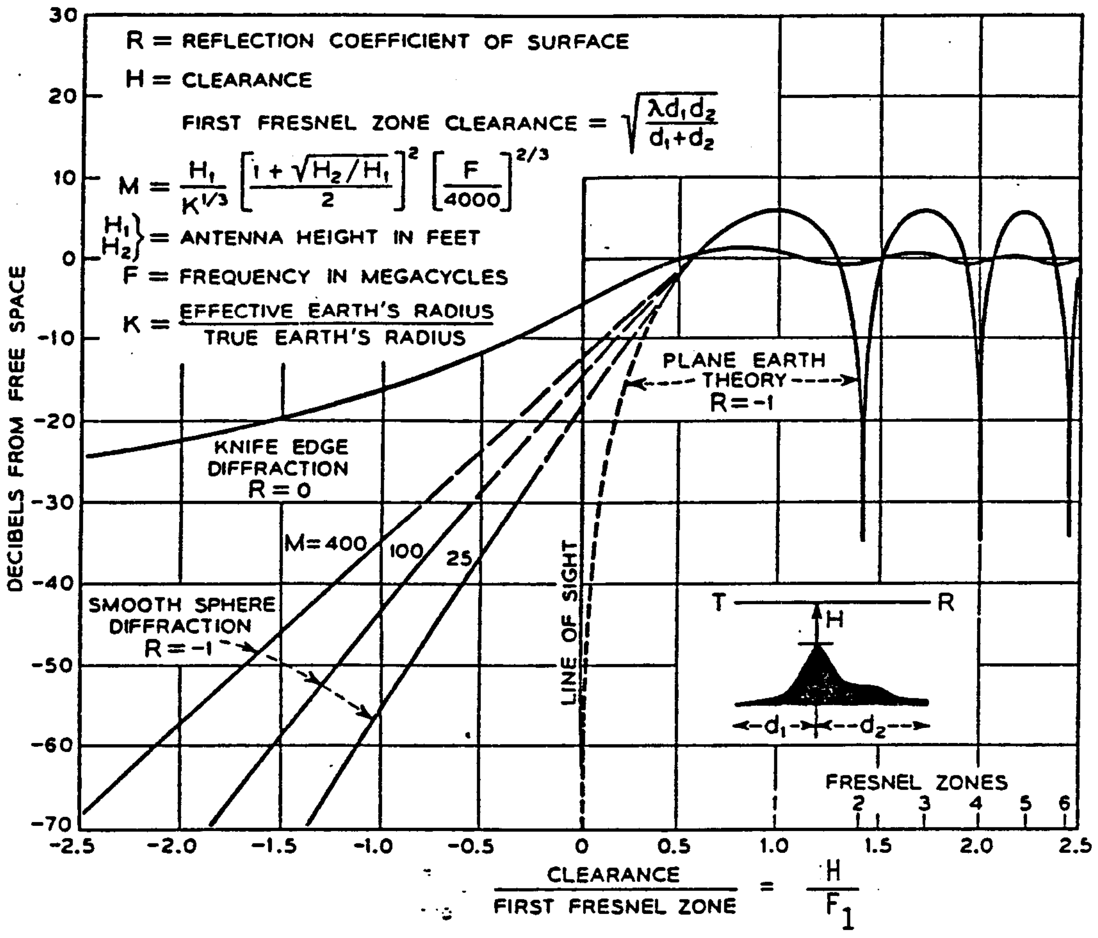
It is found in practice that only signals reflected within the first Fresnel zone have a large enough signal amplitude to produce significant interference. As much as possible, precautions are taken to keep this zone free of any obstacles.

TRANSMISSION LOSS VERSUS CLEARANCE

REQUIRED CLEARANCE

Heavy-route, or highest reliability systems:

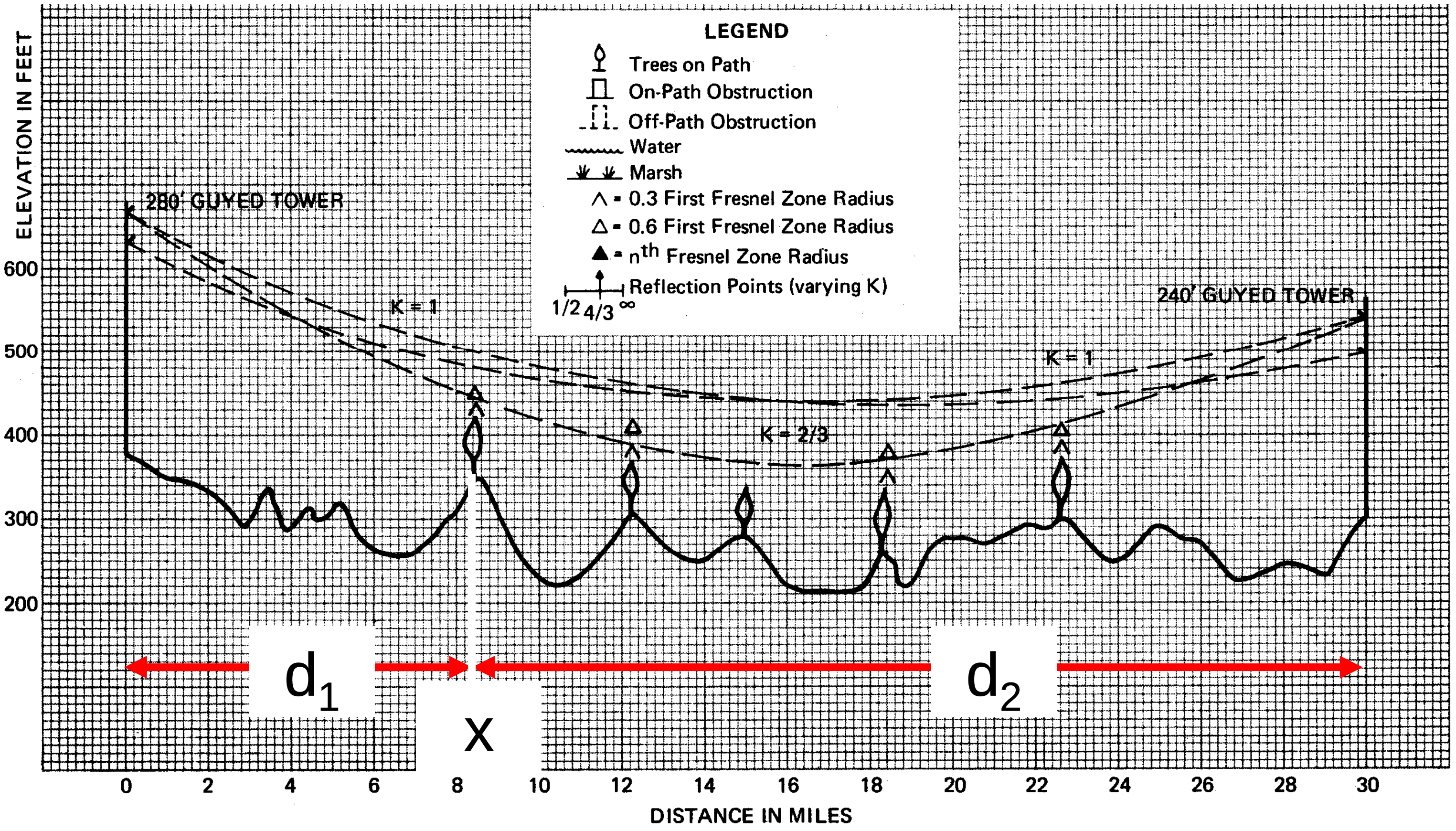
- At least 0.3 F_1 @ K=2/3 or
- At least 1.0 F_1 @ K=4/3
- whichever requires the greater heights.
- In areas of very difficult propagation, it may be necessary also to ensure a clearance of at least grazing at K=1/2.
- All criteria should be evaluated along entire path.



Light-route/ medium reliability systems: At least 0.6 F_1 + 10 feet @ K=1

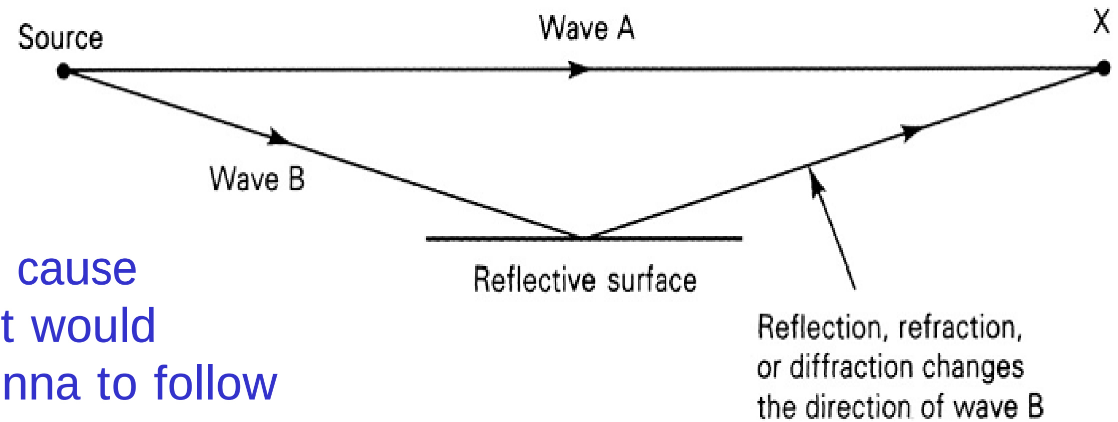
PATH ENGINEERING

FOR A GIVEN LINK, USING UP-TO-DATE MAP PLOT THE TERRAIN PROFILE
AT EACH POINT $x=(d_1,d_2)$ ALONG THE LINK, IDENTIFY REQUIRED CLEARANCE
PLOT THE CORRESPONDING LOS RAY AND DETERMINE THE ANTENNA HEIGHTS

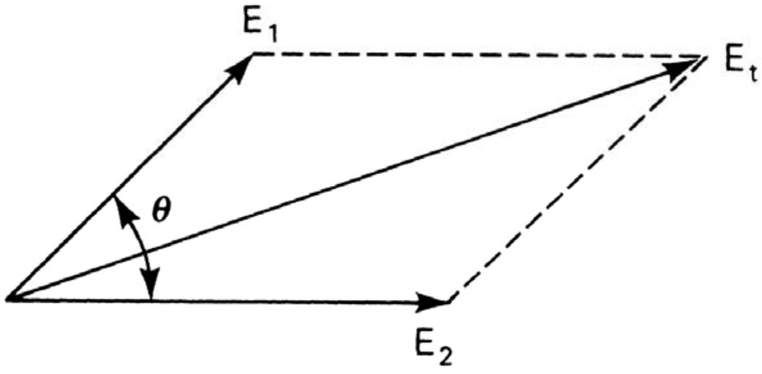


ATMOSPHERIC MULTIPATH

The multipath fading is caused by fluctuations in the index of refraction of the atmosphere as a function of time and altitude.



Varying index of refraction can cause portions of the main beam that would normally miss the receive antenna to follow longer curved paths to the receive antenna. A continuum of such paths may exist with the signal components arriving at the receive antenna with various phase angles.



It is statistically possible for these phase angles to be such as to cause a cancellation of all or a large portion of the signal power. When this happens a deep multipath fade occurs.

EXAMPLE OF 2-PATH MODEL

At receiver, the received signal is

$r(t)= x(t) + \beta\, x(t-\tau)$

where $x(t)$: the main path

β : relative level between the main and undesired paths

τ : relative time delay between the main and undesired paths

β, τ : random variables.

In frequency domain, $R(\omega) = T(\omega) \,.\, X(\omega)$

where $T(\omega)$ is the transfer function of the model

$T(\omega) = 1 + \beta e^{-j\omega\tau}$

Amplitude distortion:

$|T(\omega)|= 1 + \beta^2 + 2\beta\cos\omega\tau$

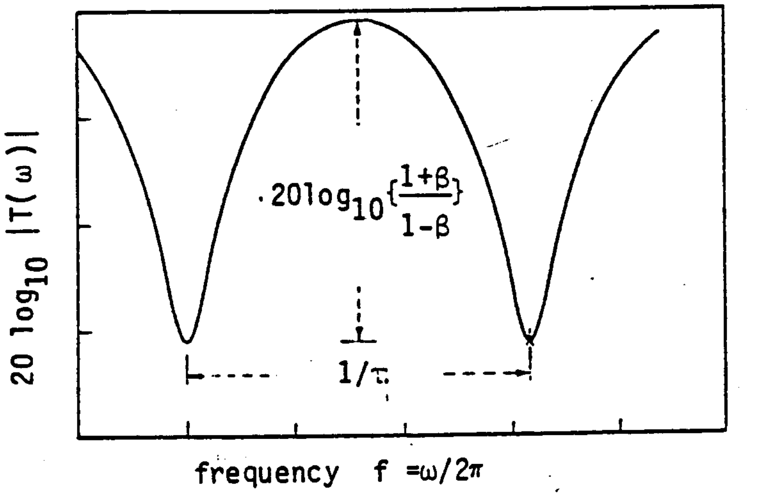
phase distortion:

$\Phi(\omega) = \tan^{-1} [\beta\sin\omega\tau/(1 + \beta\cos\omega\tau)]$

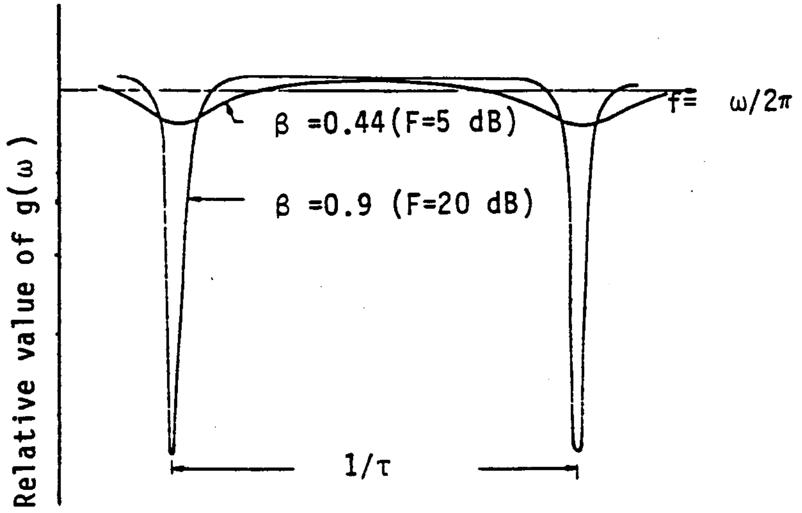
group delay distortion $g(\omega) = d\Phi/d\omega$

$g(\omega)=\beta\tau(\beta+\cos\omega\tau)/(1 + \beta^2 + 2\beta\cos\omega\tau)$

DIFFERENT ATTENUATION AT DIFFERENT FREQUENCY: FREQ-SELECTIVE FADING IN BROADBAND TRANSMISSION NEEDS EQUALIZATION.



(a) AMPLITUDE DISTORTION (| T(ω)| in dB)



(b) GROUP DELAY DISTORTION (g(ω))

RADIO PATH WITHOUT FADING

When paths are significantly shorter than 22 km, the standard, multipath model does not necessarily hold true.

C. L. Ruthroff developed a prediction model that indicates the path length below which no deep multipath fading will exceed 3 dB in fade depth for a given set of refractivity data. The distance (d_o) for which a path shorter than this will not produce multipath fading is:

$d_o=\{2.7E9[1-0.5\Delta_{med}/\Delta_{max}]^2/([1-\Delta_{med}/\Delta_{max}]^4\ [\Delta_{max}]^2 f)\}^{1/3}$, f = frequency in GHz

Δ_{med}= median refractivity gradient or median surface refractivity gradient

Δ_{max} = maximum refractivity gradient expected for the majority of the time

Example: Washington, D.C., area, 11-GHz band.

Δ_{med}= - 40 N-units for 50% of the time for the worst month

Δ_{max} = -350 N-units for 99.8% of the time for tile worst month

d = 14.25 km (8.9 mi)

PREDICTING FADE DEPTH

Rayleigh fading equation: P_r = Pr{ fade depth ≥FdB} = $10^{-F/10}$

Empirical formula (CCIR, Vol.V, Rep. 338-3, Geneva 1978)

For F ≥ 15 dB and clear LOS path with negligible earth reflection

$P_r = (K.Q.f^B.d^C)10^{-F/10}$

d : path length (km), f : frequency (GHz)

K : factor for climatic condition, Q : factor for terrain condition

In Japan and for the worst season: B= 1.2 , C=3.5 , K=0.97E-9

Q = 0.4 (over mountain), 1.0 (over plain), or $72/[0.5(h_1 + h_2)]^{1/2}$ (over sea and coast)

h_1,h_2 :antenna heights in meters.

Where earth reflection is not negligible, Rayleigh formula is used.

For N.W. Europe and for worst month: B=1, C=3.5, K=1.4E-8, Q=1

For United States and for worst month: B=1, C=3

K= 1.2E-6 (equatorial, maritime temperate, mediterranean, coastal or high humidity and temperate climatic regions),

K= 9E-7 (maritime sub tropical climatic regions)

K= 6E-7 (continental temperate climates or mid-latitude inland climatic regions)

K= 3E-7 (polar climates or high dry mountains climatic regions)

$Q=(15.2/S)^{1.3}$ where S is the terrain roughness measured in meters by the standard deviation of terrain elevations at 1 km intervals; 3.35 (smooth terrain, S ≥ 6km), 1 (average terrain,S=15.2 km), 0.27 (rough terrain, S≤42 m)

PREDICTING FADE DURATION

(CCIR Vol V Rep. 338-3s Geneva 1978)
long-term measurements on LOS paths of 40 to 70 km in the United States have shown that multipath median fade durations t_{fade} can be expressed for a non-diversity signal as follows.

$t_{fade} = 56.6\text{x}10^{-F/20}\ [d/f]^{1/2}$ (in sec)

where

d : path length (km)

f : frequency (GHz)

F : fade depth in dB ($F \geq 20$ dB)

PATH AVAILABILITY & FADE MARGIN

Fade Margin (FM): extra power budget to compensate the fade

1. Propagation reliability (path availability) during the worst month of the year is $R_m = 1 – P_r$, where P_r is the Pr {fade depth> **FM**} during the worst month of the year.
2. An annual path availability may be determined by applying an annualization factor (A_n) that is a climatic measure of the duration of the fading season

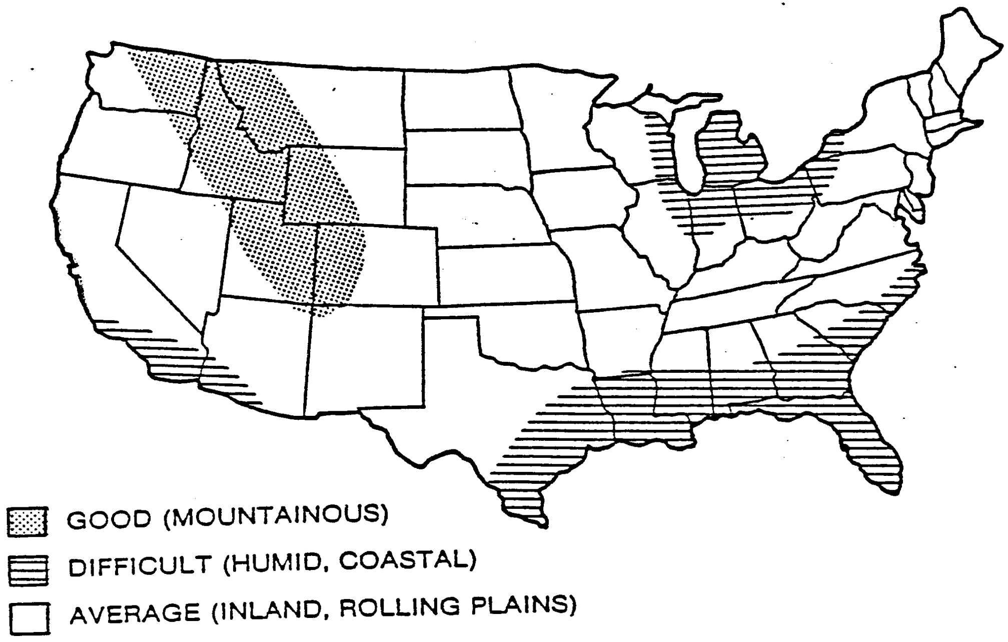
$R_{annual} = 1 – A_n P_r$

A_n= 0.50 for low latitude tropical Gulf Coast regions or areas with high humidity and temperature

A_n = 0.375 for mid-latitude Gulf Coast regions or areas with high humidity and temperature

A_n = 0.25 for average inland regions

A_n = 0.175 for high and dry mountainous regions.



PROPAGATION CONDITIONS: EXAMPLE OF USA

Path availability: an example @ 2GHz

Required path availability: 99.99%, i.e., outage Pr{fade depth>**FM**}$\leq$0.0001=1E-4

From Rayleigh equation: Pr{ fade depth $\geq$FdB} = $10^{-F/10}$, FM=40dB

Using $P_r = (K.Q.f^B.d^C)10^{-F/10}$, $FM=40+10\log_{10}(KQ)+10B\log_{10}(f)+10C\log_{10}(d)$ with B=1, C=3,

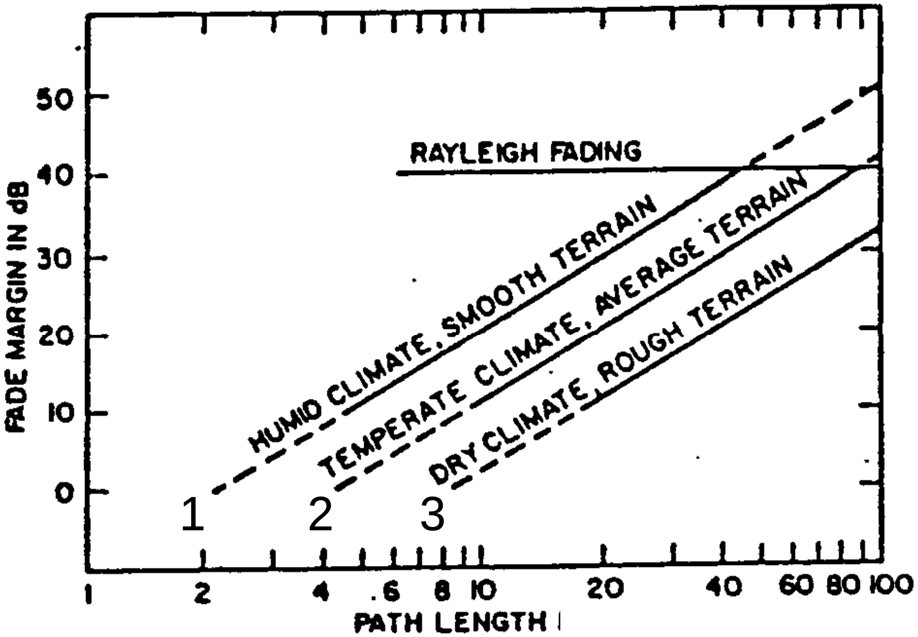
d : path length (km),

f : frequency (GHz)

CASE	K	Q	$10\log_{10}(KQ)$
1	12E-7	3.35	-53.95
2	6E-7	1	-62.21
3	3E-7	0.27	-70.91

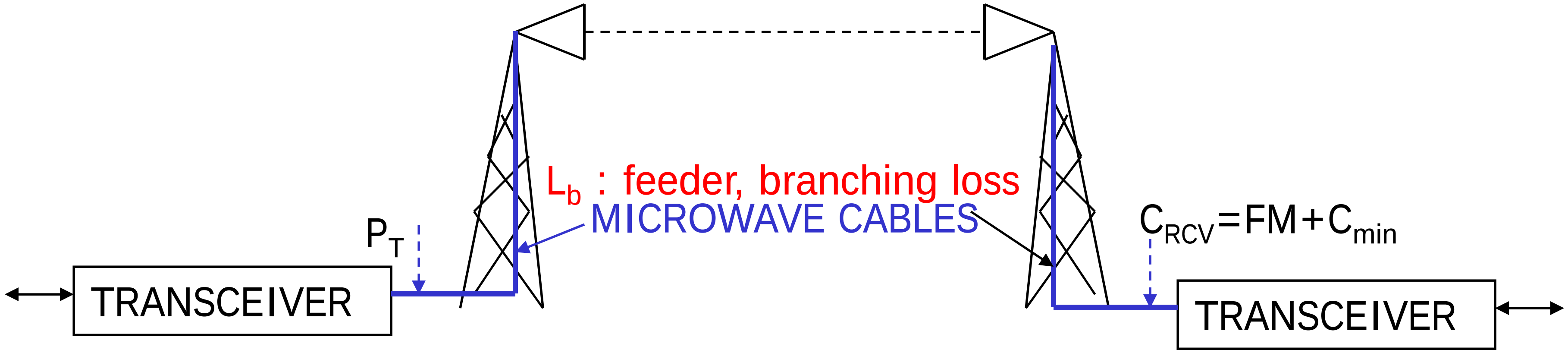
CASE:	FM CURVE:
1	$-10.94+30\log_{10}(d)$
2	$-19.20+30\log_{10}(d)$
3	$-27.90+30\log_{10}(d)$

ONLY VALID FOR FM=10dB OR MORE



- FOR 99 999 % ADD 10dB MARGIN
- FOR 4 GHz ADD 3dB MARGIN
- FOR 6 GHz ADD 4.8 dB MARGIN
- FOR 11 GHz ADD 7.4 dB MARGIN

LOS TRANSMISSION EQUATIONS FOR DIGITAL COMMUNICATIONS



System gain: $G_s = P_T - C_{min}$ in dB

P_T : Transmitter output power excluding antenna gains. (in dBm)

C_{min} : min received power (in dBm) for required quality objective (in BER)

Fade margin: $FM = G_s + G_T + G_R - L_{FS} - L_b$

G_T , G_R (in dB) :Tx and Rx antenna gains, L_b : feeder, branching loss.

L_{FS} : free-space loss $L_{FS,\,dB} = 92.44 + 20\log_{10}(f_{GHz}) + 20\log_{10}(d_{km})$

Minimum received power: $C_{min} = 10\log_{10}(kT) + NF + 10\log_{10}(f_b) + E_b/N_o$

$10\log_{10}(kT) = -174$ dBm/Hz; NF: noise figure of the receiver (dB)

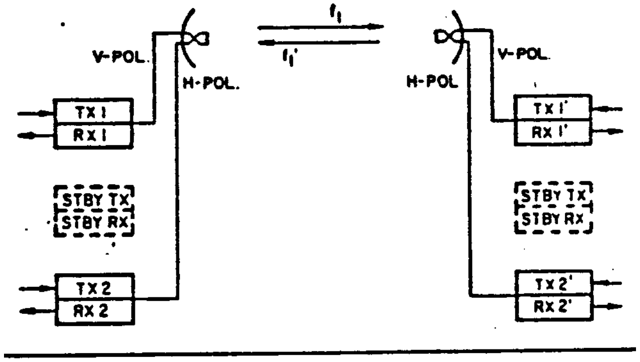
f_b: transmission bit rate E_b/N_o: required for certain threshold BER.

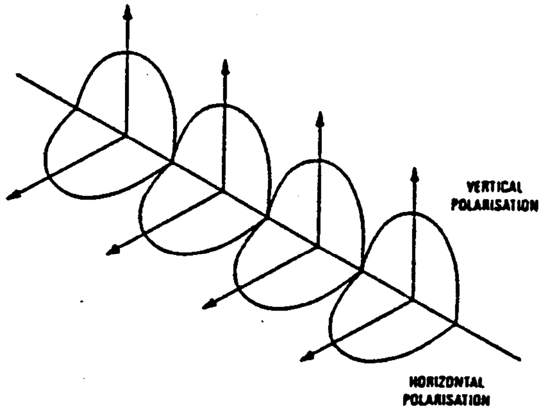
CROSS-POLARIZED OPERATION (XPD)

Linear orthogonal-polarized transmissions are normally used for radio-relay systems, so that interference between adjacent channels can be controlled by the cross-polar discrimination (XPD) of the antenna system.

For high spectrum efficiency, use two channels on the same frequency assignment in both horizontal and vertical plan polarization of the microwave signals.

The capacity of each frequency assignment can be doubled and hot standby equipment protection can be utilized.





XPD DEGRADATION

Typical XPD of 30 to 45 dB should be quite adequate for digital operation under normal propagation conditions.

During conditions of multipath fading or degraded obstruction clearance the XPD can be reduced. (The amount of XPD degradation is not predicted readily. The XPD might drop from 35 dB to as low as 20dB in a 15dB multipath fade. .

Using the reasonable (but unproven) assumption, the worst-case XPD degradation equal to FdB will occur 10% as often as a fade of F dB.

The XPD degradation can be predicted using the following equation:

$XPD_{degradation} = XPD_{faded} - XPD_{unfaded}$ (in dB)

$= 10 \log(KQ.f^{B}.d^{C}) - 10 \log[10(1-R)]$

where R is the path reliability objective.

XPD degradation also can result from depolarization due to rainfall particularly at 11 GHz.

FCC MASK

FCC SPECTRUM EMISSION REQUIREMENTS

(DOCKET No.19311, for frequencies below 12 GHz)

Relative power spectral density measured in 4 kHz

$A_{dB}(x) = 0$ for $0 < x < 0.5$

$A_{dB}(x) = 35 + 80(x-0.5) + 10 \log B$ for $x \geq 0.5$

$A_{dB}(x) = 80$ for large x

where 0dB is the reference for total Tx power measured by unmodulated signal

B: allowable bandwidth in MHz

$x = |f-f_c|/B$

f_c: carrier frequency

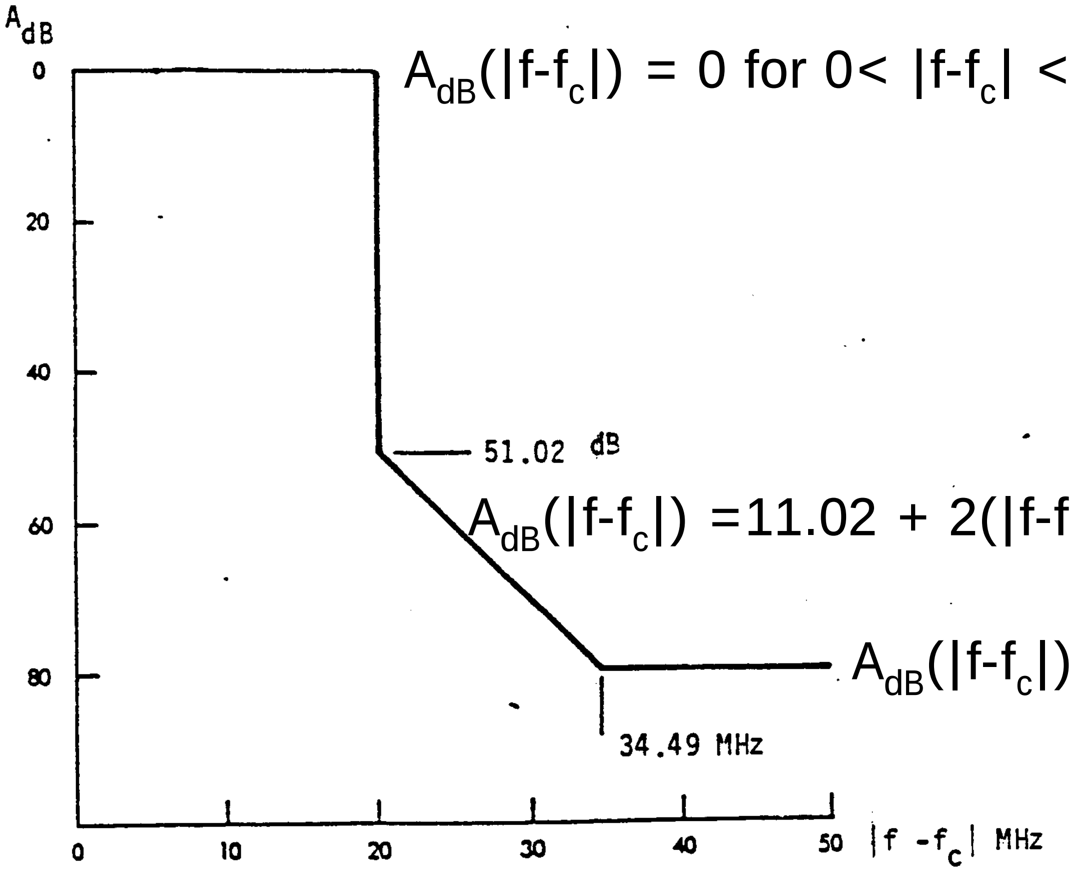
f : frequency at which the attenuation specification is being evaluated.

EXAMPLE:

Freq. Band (MHz)	**BW(MHz)**	**#of 64kb/s voice channels**
2,110-2,130	3.5	96
2,160-2,180	3.5	96
3,700-4,200	20.0	1152
5,925-6,425	30.0	1152
10,700-11,700	40.0	1152

EXAMPLE OF FCC MASK

Frequency band: 10.7-11.7GHz, Allowable bandwidth: 40 MHz FCC Mask



$A_{dB}(|f-f_c|) = 0$ for $0 < |f-f_c| < 0.5B = 20\text{MHz}$

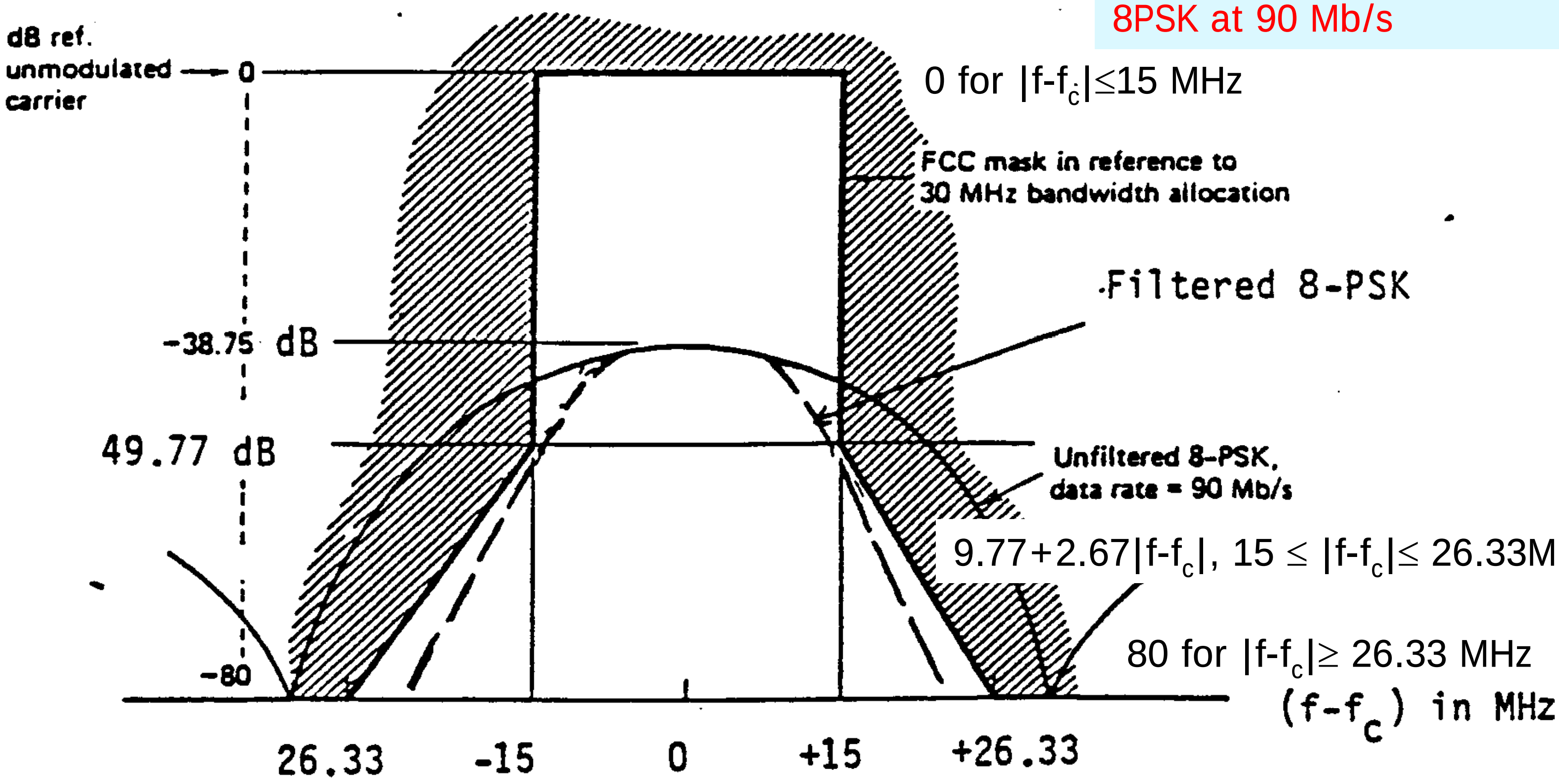
$A_{dB}(|f-f_c|) = 11.02 + 2(|f-f_c|)$ for $20\text{MHz} \leq |f-f_c| \leq 34.49\text{MHz}$

$A_{dB}(|f-f_c|) = 80$ for $|f-f_c| \geq 34.49\text{MHz}$

EXAMPLE OF FCC MASK AND FILTERING REQUIREMENT

Relative power spectral density measured in 4 kHz, centered at carrier frequency is 10log(4kHz/30MHz) = -38.75 dB.
Frequency band: 5.925-6.425 GHz, Allowable BW: 30 MHz

Minimum capacity: 1152 voice channels The min transmission efficiency is (1152X64kb/s)/30MHz = 2.4576 b/s/Hz We can use 8PSK at 90 Mb/s



0 for $|f-f_c| \le 15$ MHz

$9.77+2.67|f-f_c|$, $15 \le |f-f_c| \le 26.33$MHz

80 for $|f-f_c| \ge 26.33$ MHz

INTRASYSTEM INTERFERENCE AND FREQUENCY PLANS

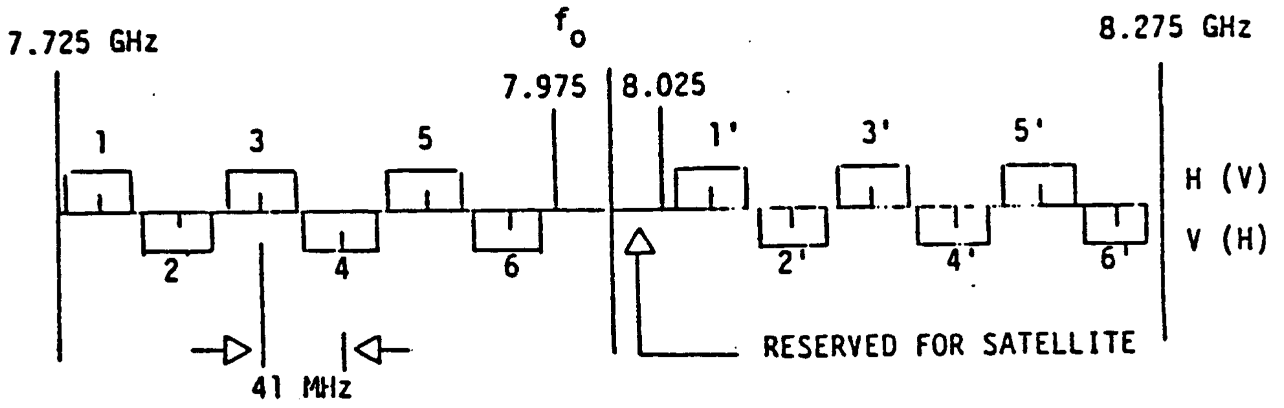
Several mechanisms can produce co-channel (same channel) or adjacent channel interference. This intra-system interference is unavoidable, since the usable frequency spectrum in practice is limited and, hence, the same frequency carrier allocations have to be re-used along the microwave route.

Adjacent channel interference occurs when two modulated carriers are close in frequency so that the side bands of one signal extend over the other. This interference effect can be reduced by filtering the higher-order sidebands, but this only can be done at the expense of causing **signal distortion**. It is apparent, then, that frequency spectrum separation between carriers (and therefore maximum channel bandwidth) has an important influence on the problem of filtering overlapping sidebands. A frequency plan shall, therefore, optimize spectrum efficiency (maximum number of channels within the frequency band) keeping at the same time distortions below acceptable levels.

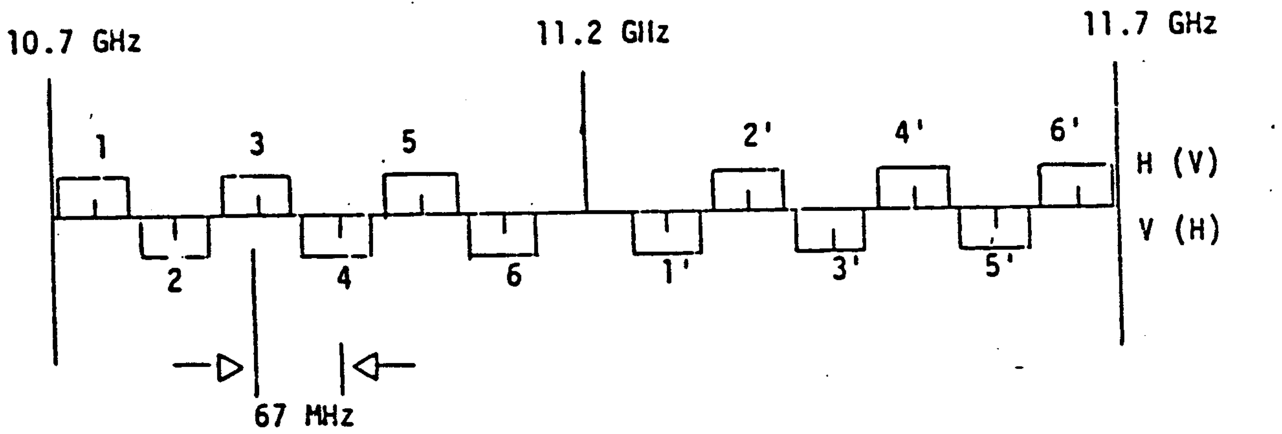
Co-channel interference can be caused by reflections of the microwave signal (e.g. buildings), overreach, image channel interference, and limited discrimination of the antennas. The harmful effects of co-channel interference can be reduced by using an adequate frequency plan and careful selection of the microwave sites.

To rationalize the use of the frequency spectrum, international organizations and national administrations have subdivided it into frequency bands. Subsequently every frequency band is subdivided into Radio Frequency (RF) channels. A frequency plan, in general, establishes the center frequency of each RF channel, the polarization of the signal (vertical and horizontal), and the preferred growth pattern.

EXAMPLE OF FREQUENCY PLAN



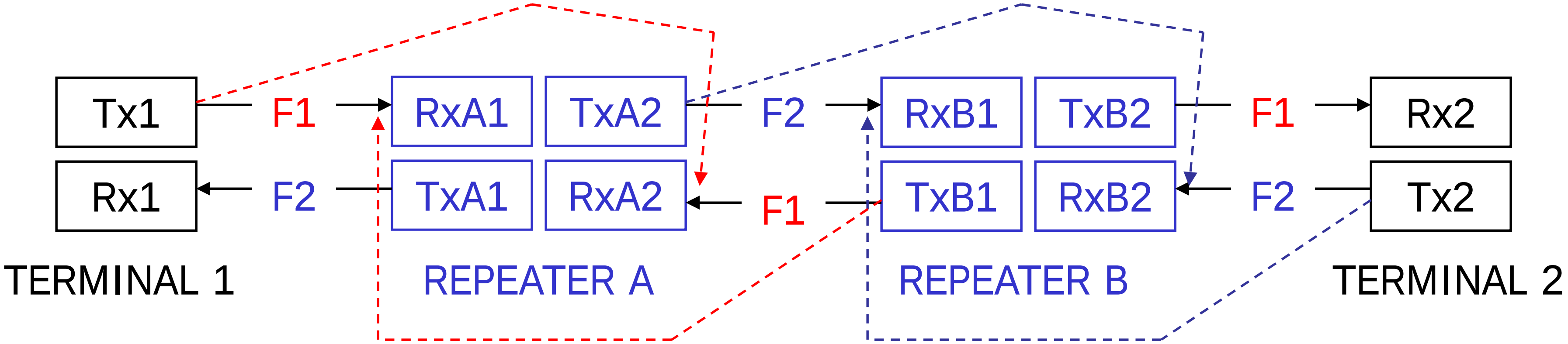
CANADA RD-3 PLAN



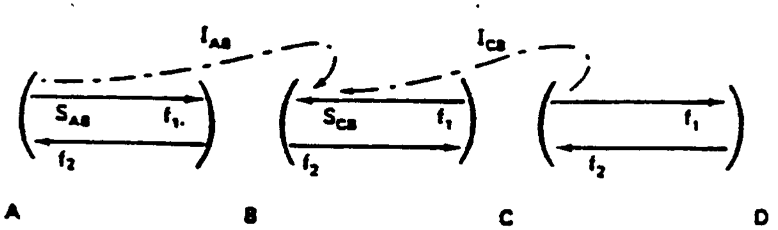
BRITISH 140 MB SYSTEM

TWO-FREQUENCY PLAN

Advantage: it allows for full usage of the frequency band capacity.
Disadvantage: the possibilities of intrasystem interference are higher than in the four-frequency plan.
Both receivers facing East and West, in the repeaters operate at the same frequency. Therefore, the receiver facing East in Repeater A, for example, will be protected against interference from transmitter at Terminal 1 only by the receiving antenna discrimination. The actual value of the antenna discrimination (attenuation of the unwanted signal) will depend on the angle between the main beam of the transmitting antenna at Terminal 1 and the main beam of the receiving antenna facing East at Repeater A



EXAMPLE OF 2-FREQUENCY PLAN

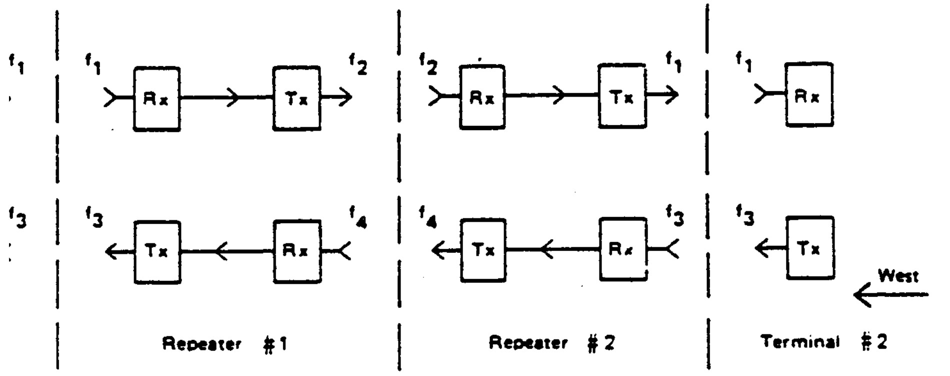


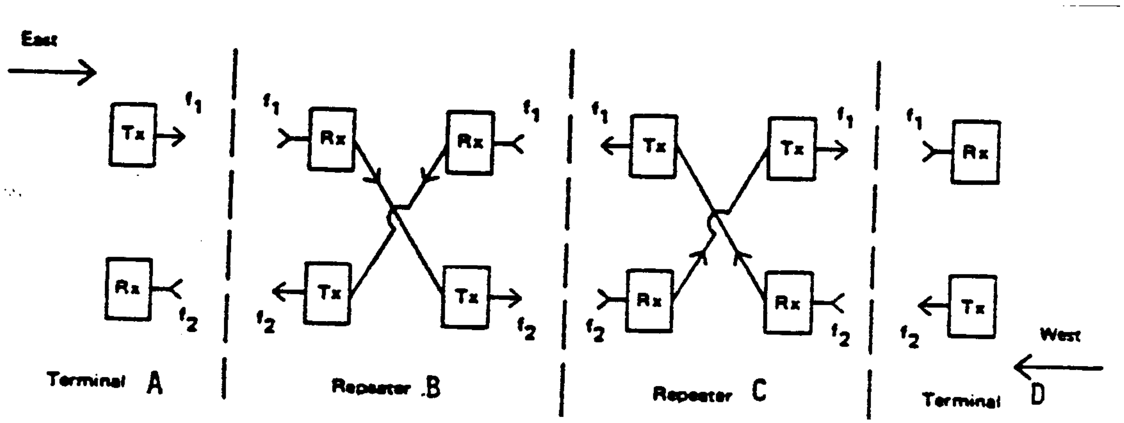
f_1, f_2: carrier frequencies

S_{CB}: victim carrier at site B from site C

I_{AB}: interfering carrier from site A (on frequency f_1)

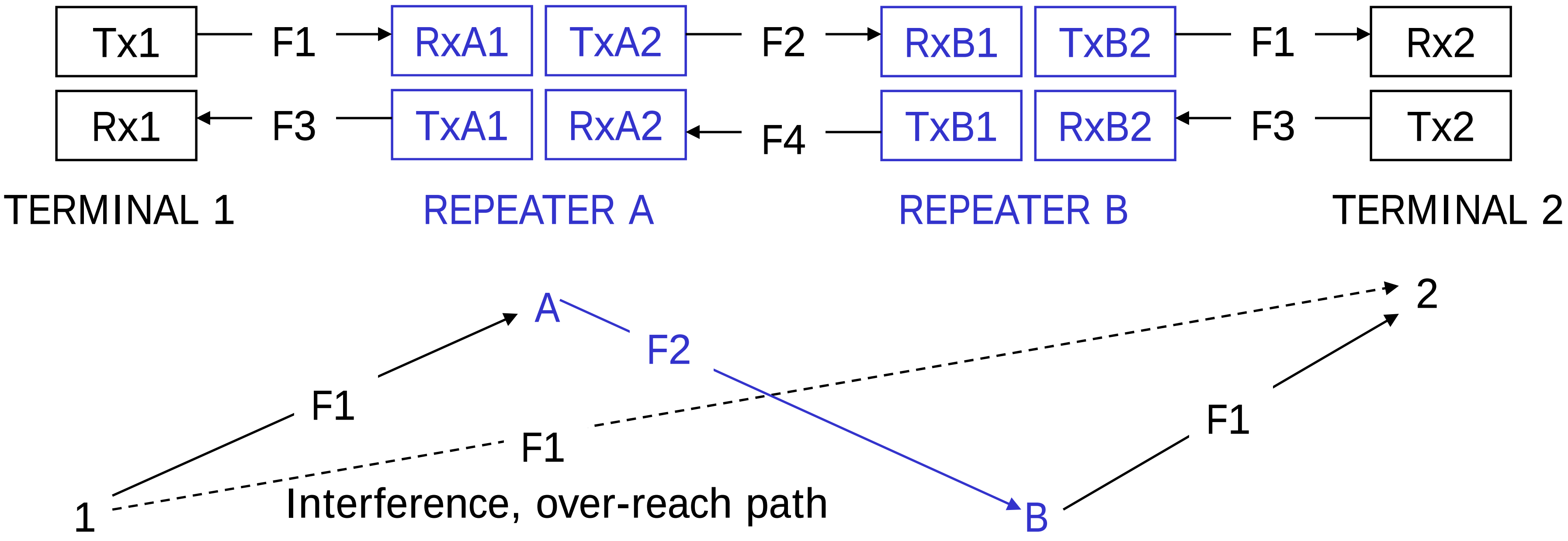
I_{CB}: interfering carrier from site C (on frequency f_1)



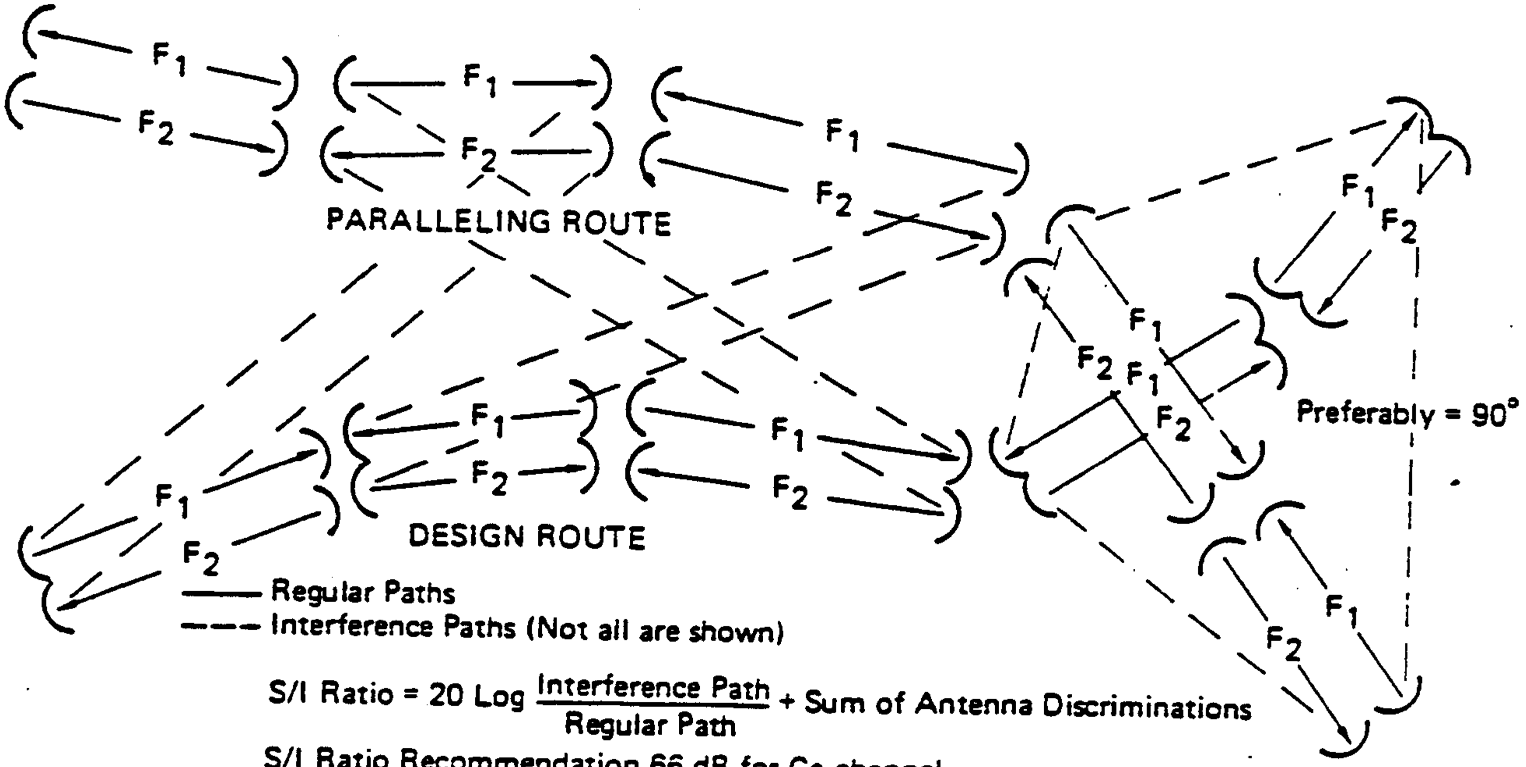


FOUR-FREQUENCY PLAN

The advantage of the four-frequency plan is that the receivers operating at the same frequency are two hops apart. The transmitter at Terminal #1, for example, could interfere with the receiver at Terminal #2. This is known as overreach. The probability of this happening is low because they are 3 hops apart and terrain obstructions (or earth bulge) would block the interfering signal. The route should be designed to ensure that potentially interfering hops are not in a straight line. The obvious disadvantage of this plan is the inefficient use of the frequency spectrum (the band can be used only to one half of its capacity).



INTERFERENCE COORDINATION OF PARALLEL SYSTEMS



——— Regular Paths

– – – Interference Paths (Not all are shown)

$$S/I \text{ Ratio} = 20 \text{ Log} \frac{\text{Interference Path}}{\text{Regular Path}} + \text{Sum of Antenna Discriminations}$$

S/I Ratio Recommendation 66 dB for Co-channel

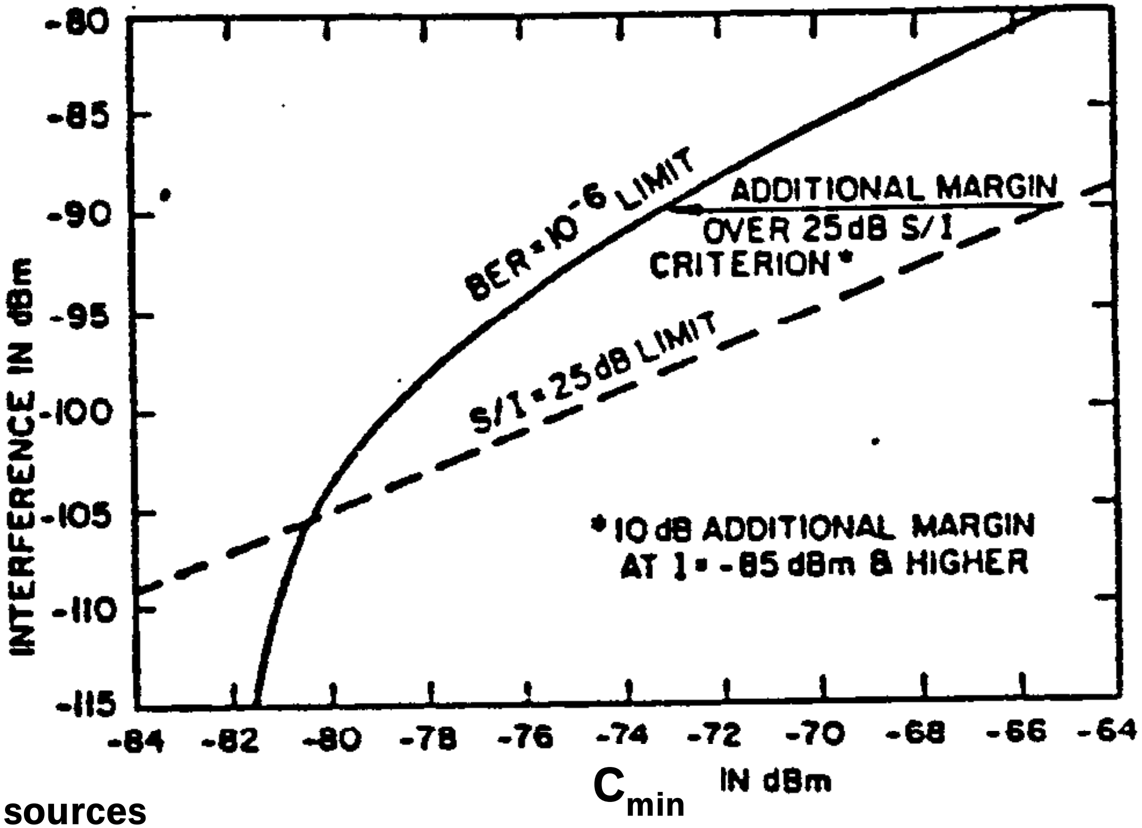
NOTE

Cross polarization advantage at angles close to 90° is zero and may be negative in some combinations.

EFFECTS OF INTERFERENCE ON C_{min}

Interference is observed when its level, along with the noise and distortion is high enough to cause bit errors. It causes an increase in the C_{min} required for threshold BER. Actual numbers to be used depend upon the equipment involved and the type of modulation employed.

EXAMPLE: for BER=1E-6
With no interference,
C_{min} = -82 dBm.
For I= -100 dBm
C_{min}. = -79 dBm
Therefore 3 dB more unfaded signal level is required to maintain the same fade margin.



References: materials from various sources