UNIT-5

Advanced Communication Techniques

Satellite communications

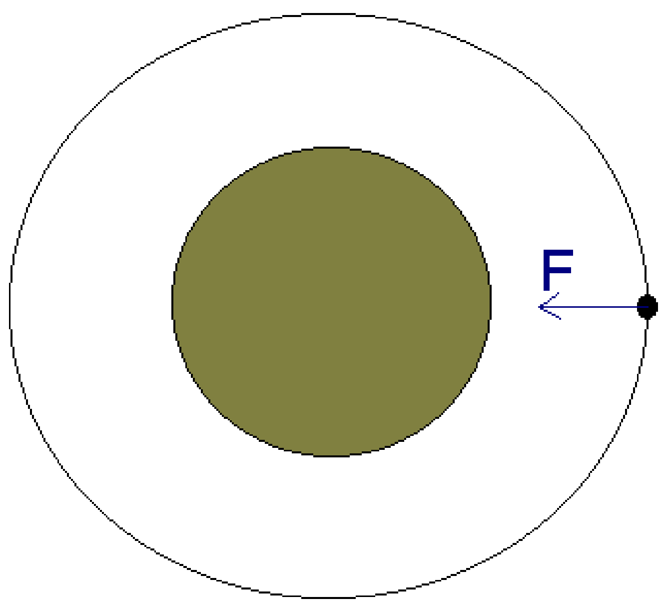
Introduction

A few reasons of satellite revolution:

- A single satellite can provide coverage to over 30% of Earth's surface.
- It is often the only solution for developing areas.
- It is ideal for broadcast applications.
- It can be rapidly deployed.
- It is scalable.
- Depending on application, there is no need for the local loop.
- Transmission cost is independent on distance.
- One hop from the backbone, wherever you are.
- Wide bandwidths (155 Mbps) are available now.

What is a satellite?

- Isaac Newton noticed first, that if we throw an object on Earth horizontally with big enough velocity, it will not fall down, but will circulate around Earth indefinitely.



$$F = \frac{GMm}{r^2}$$

$$v = \sqrt{\frac{GM}{r}}$$

$$T = \sqrt{\frac{2\pi}{r}}$$

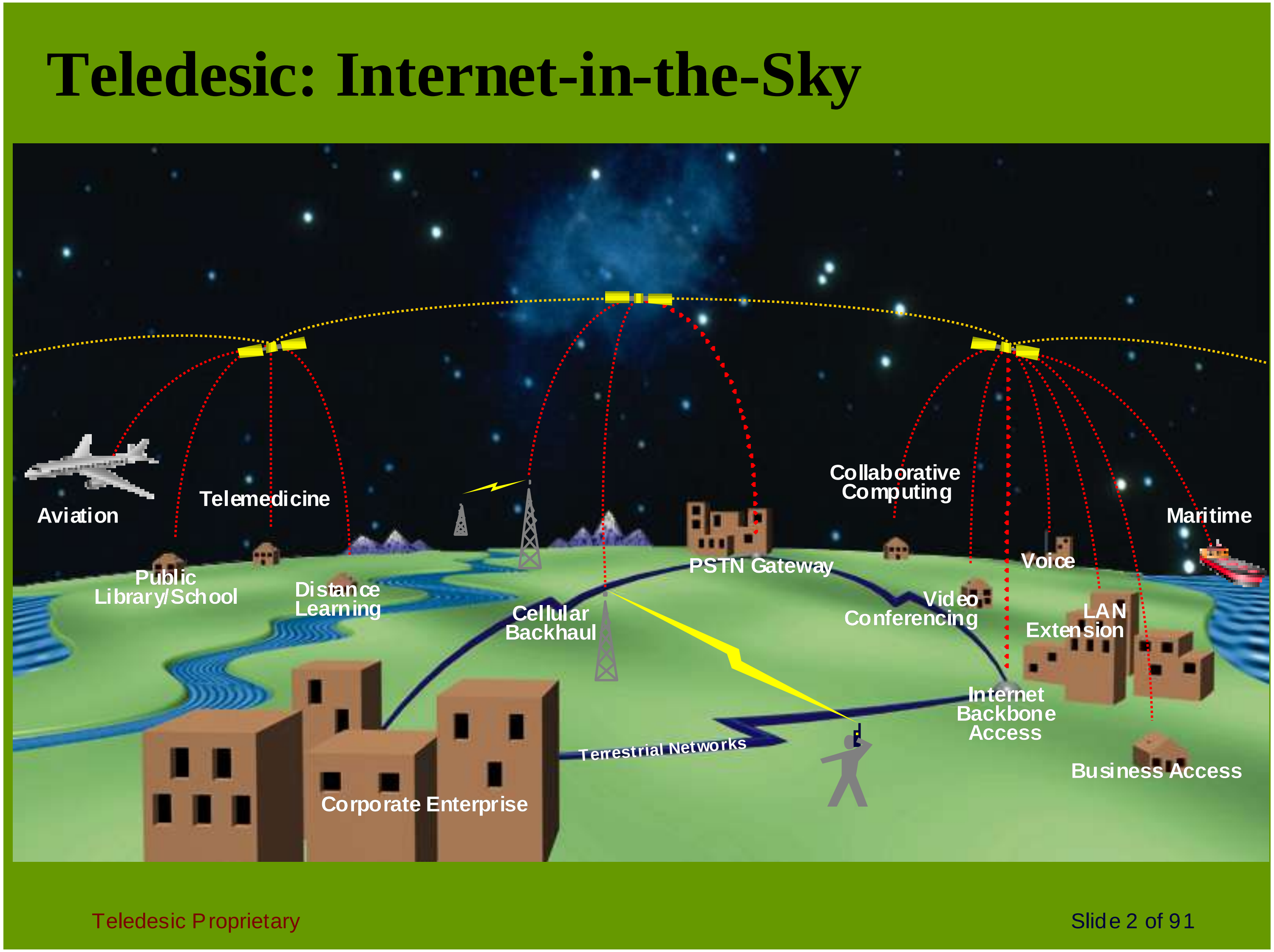
- R=6400 km T=84 minutes
- R=7100 km T=99 minutes (LEO)
- R=11400 km T=201 minutes (MEO)
- R=42350 km T=24 hrs (GEO)

So, an object placed at the orbit approx. 36 000 km above the equator will be seen at the same position in the sky from Earth.

But roundtrip time will be more than half a second!

Is this position actually stable?

a few remarks about LEO and MEO satellites(Teledesic, Iridium)



but …

- omnidirectional antenna vs directional one

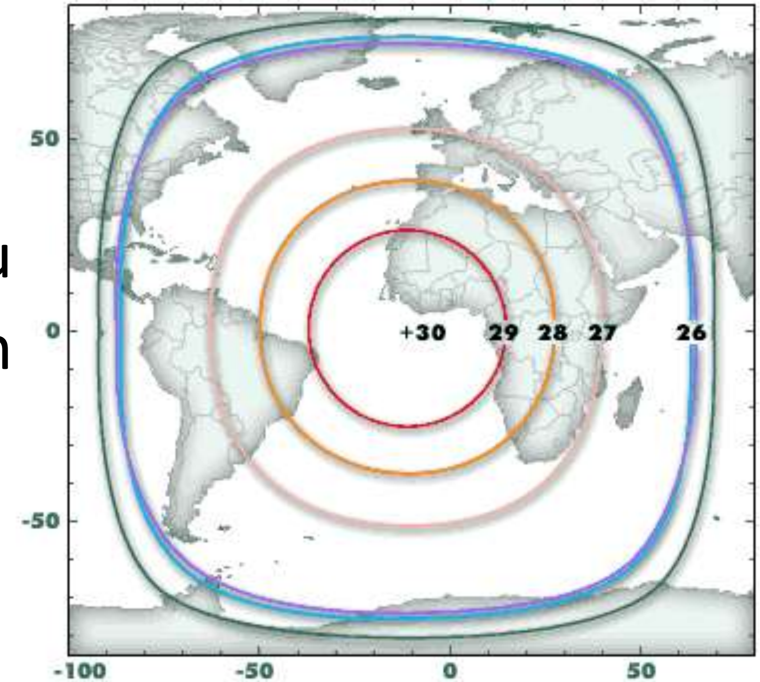
- what does it mean in terms of available frequency spectrum?

  There are (in general) three bands of spectrum available for GEO satellite communication: C, Ku, Ka.

C	-	4-7 GHz	(5 cm wavelength)
Ku	-	10-14 GHz	(2.3 cm wavelength)
Ka	-	18-30 GHz	(1 cm wavelength)

Properties of spectrum bands

- C band:
  - large beams
    - The actual footprint of Intersputnik Express 3A
  - little rain fade (but sand storms affect it as well!)
  - large antennas
  - expensive amplifiers
  - lots of noise on the grou
  - also circular polarization
  - Rx: 3625 to 4200 MHz
  - Tx: 5850 to 6435 MHz



Properties of spectrum bands (contd)

- Ku-band
  - most widely used today
  - smaller beams (even spot bea
  - smaller antennas
  - stronger rain fade
  - cheaper amplifiers
  - suitable for home users as wel
  - noise on the ground is already often a problem
  - steerable spot beams
  - Rx: 10.95 to 12.75 GHz
  - Tx: 14 to 14.5 GHz
- Ka band (still at development phase)

Satellites

- Several types
- LEOs - Low earth orbit
- MEOs - Medium earth orbit
- GEOs - Geostationary earth orbit

GEOs

- Originally proposed by Arthur C. Clarke
- Circular orbits above the equator
- Angular separation about 2 degrees - allows 180 satellites
- Orbital height above the earth about 23000 miles/35000km
- Round trip time to satellite about 0.24 seconds

GEOs (2)

- GEO satellites require more power for communications
- The signal to noise ratio for GEOs is worse because of the distances involved
- A few GEOs can cover most of the surface of the earth
- Note that polar regions cannot be “seen” by GEOs

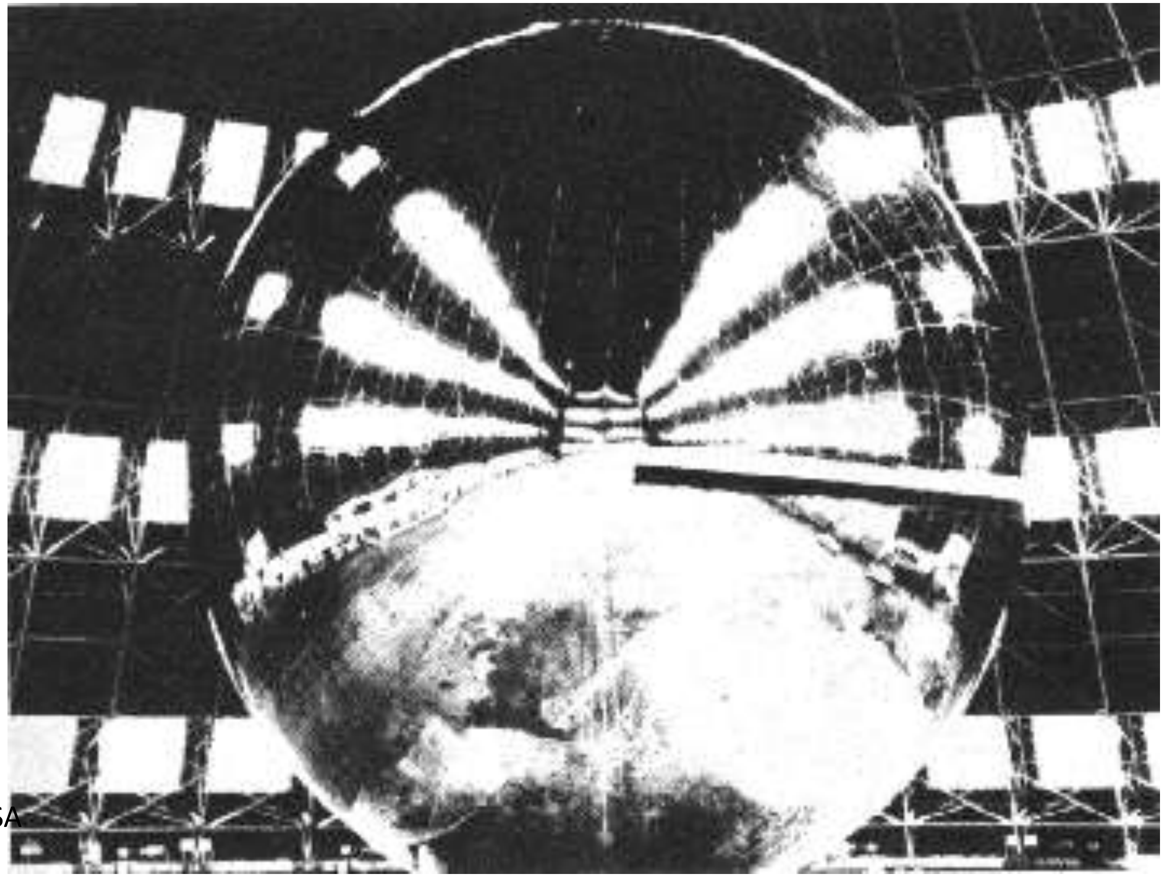
GEOs (3)

- Since they appear stationary, GEOs do not require tracking
- GEOs are good for broadcasting to wide areas

Early experiments

- US Navy bounced messages off the moon
- ECHO 1 “balloon” satellite - passive
- ECHO 2 - 2nd passive satellite
- All subsequent satellites used active communications

ECHO 1

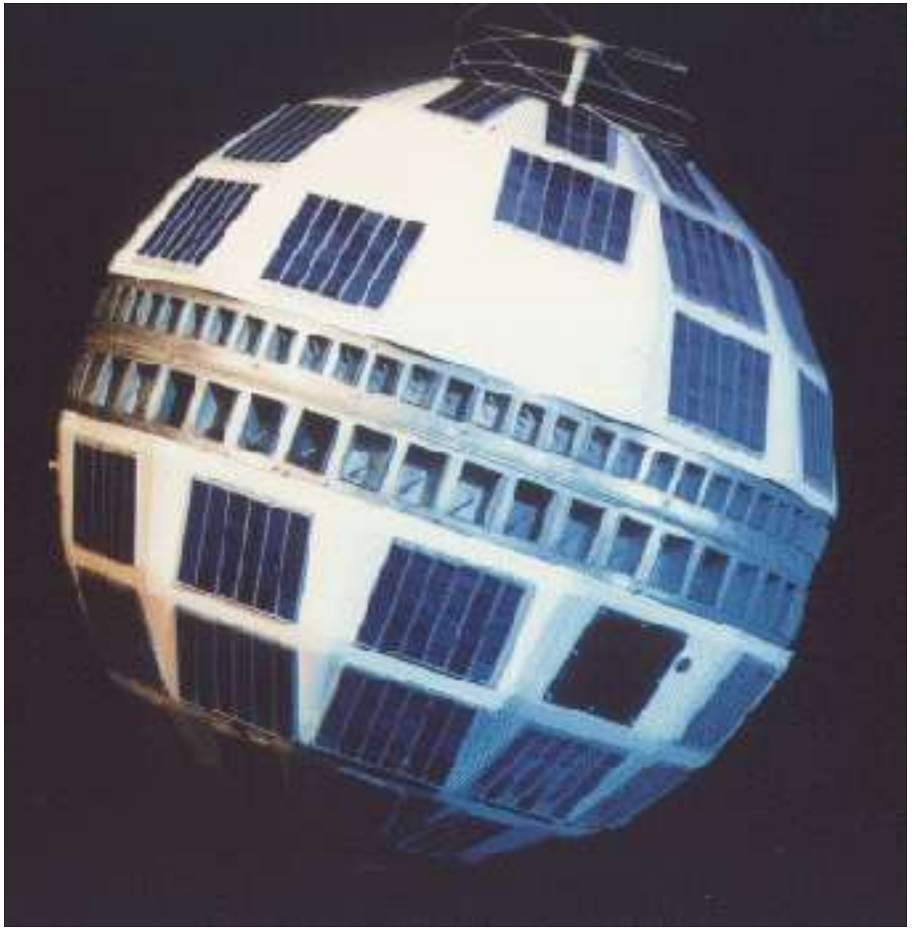


- Photo from NASA

Early satellites

- Relay
  - 4000 miles orbit
- Telstar
  - Allowed live transmission across the Atlantic
- Syncom 2
  - First Geosynchronous satellite

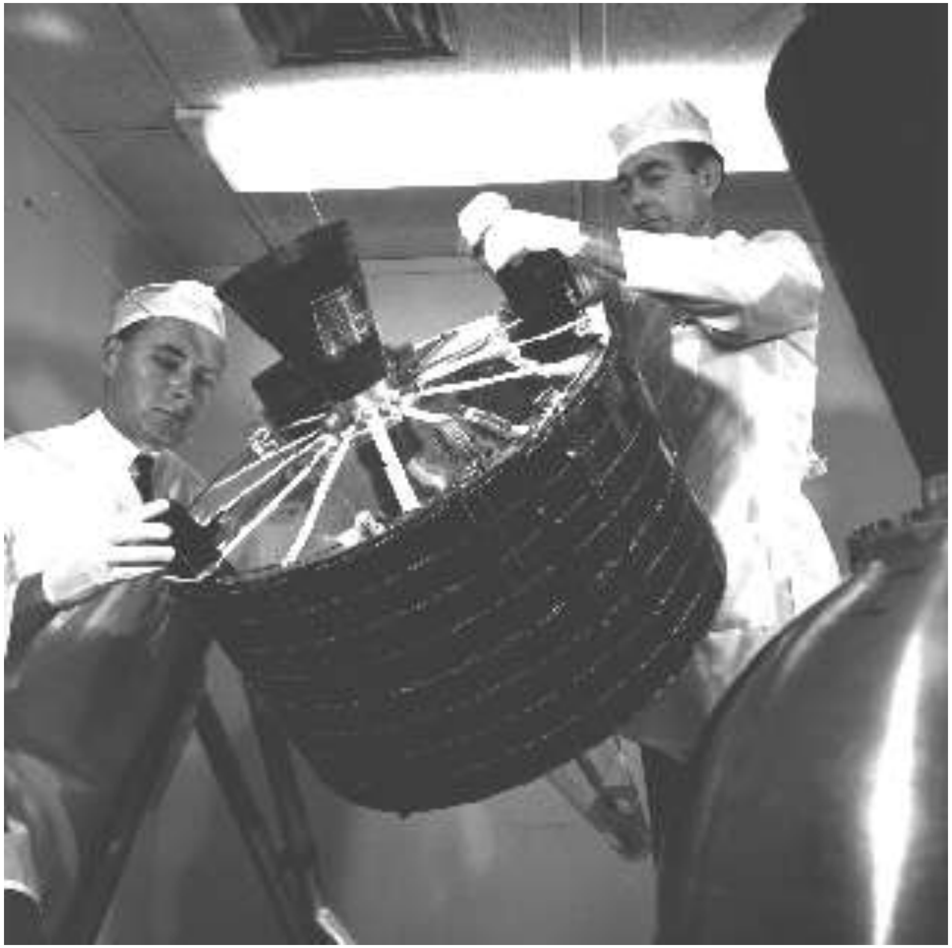
TELSTAR



- Picture from NASA

SYNCOM 2

- Picture from NASA



Major problems for satellites

- Positioning in orbit
- Stability
- Power
- Communications
- Harsh environment

Positioning

- This can be achieved by several methods
- One method is to use small rocket motors
- These use fuel - over half of the weight of most satellites is made up of fuel
- Often it is the fuel availability which determines the lifetime of a satellite
- Commercial life of a satellite typically 10-15 years

Stability

- It is vital that satellites are stabilised
  – to ensure that solar panels are aligned properly
  – to ensure that communications antennae are aligned properly
- Early satellites used spin stabilisation
  – Either this required an inefficient omni-directional aerial
  – Or antennae were precisely counter-rotated in order to provide stable communications

Stability (2)

- Modern satellites use reaction wheel stabilisation - a form of gyroscopic stabilisation Other methods of stabilisation are also possible
- including:
  – eddy currrent stabilisation
  – (forces act on the satellite as it moves through the earth’s magnetic field)

Reaction wheel stabilisation

- Heavy wheels which rotate at high speed - often in groups of 4.
- 3 are orthogonal, and the 4th (spare) is a backup at an angle to the others
- Driven by electric motors - as they speed up or slow down the satellite rotates
- If the speed of the wheels is inappropriate, rocket motors must be used to stabilise the satellite - which uses fuel

Power

- Modern satellites use a variety of power means
- Solar panels are now quite efficient, so solar power is used to generate electricity
- Batteries are needed as sometimes the satellites are behind the earth - this happens about half the time for a LEO satellite
- Nuclear power has been used - but not recommended

Harsh Environment

- Satellite components need to be specially "hardened"
- Circuits which work on the ground will fail very rapidly in space
- Temperature is also a problem - so satellites use electric heaters to keep circuits and other vital parts warmed up - they also need to control the temperature carefully

Alignment

- There are a number of components which need alignment
  - Solar panels
  - Antennae
- These have to point at different parts of the sky at different times, so the problem is not trivial

Antennae alignment

- A parabolic dish can be used which is pointing in the correct general direction
- Different feeder “horns” can be used to direct outgoing beams more precisely
- Similarly for incoming beams
- A modern satellite should be capable of at least 50 differently directed beams

Satellite - satellite communication

- It is also possible for satellites to communicate with other satellites
- Communication can be by microwave or by optical laser

LEOs

- Low earth orbit satellites - say between 100 - 1500 miles
- Signal to noise should be better with LEOs
- Shorter delays - between 1 - 10 ms typical
- Because LEOs move relative to the earth, they require tracking

Orbits

- Circular orbits are simplest
- Inclined orbits are useful for coverage of equatorial regions
- Elliptical orbits can be used to give quasi stationary behaviour viewed from earth
  - using 3 or 4 satellites
- Orbit changes can be used to extend the life of satellites

Communication frequencies

- Microwave band terminology
  - L band 800 MHz - 2 GHz
  - S band 2-3 GHz
  - C band 3-6 GHz
  - X band 7-9 GHz
  - Ku band 10-17 GHz
  - Ka band 18-22 GHz

Early satellite communications

- Used C band in the range 3.7-4.2 GHz
- Could interfere with terrestrial communications
- Beamwidth is narrower with higher frequencies

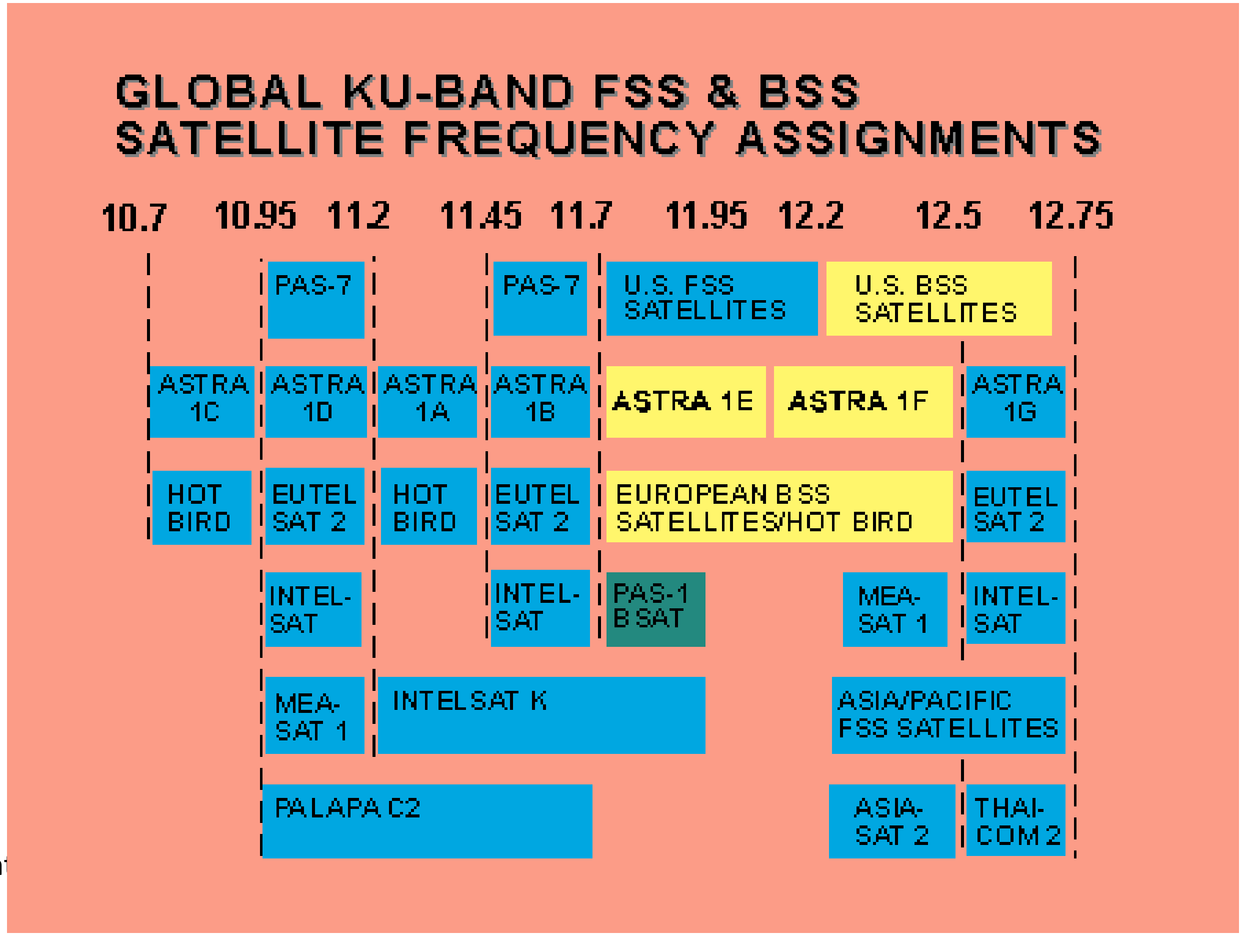
More recent communications

- Greater use made of Ku band
- Use is now being made of Ka band

Rain fade

- Above 10 GHz rain and other disturbances can have a severe effect on reception
- This can be countered by using larger receiver dishes so moderate rain will have less effect
- In severe rainstorms reception can be lost
- In some countries sandstorms can also be a problem

Ku band assignments



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Satellite management

- Satellites do not just “stay” in their orbits
- They are pushed around by various forces
- They require active management

Systems of satellites

- Example - Iridium
- Deploy many satellites to give world wide coverage - including polar regions
- So far have not proved commercially viable
- Other systems “coming along” - Teldesic

The future

- Because Iridium has not been a commercial success the future of satellites is uncertain
- Satellites still have major advantages for wide area distribution of data

Link Budgets

What Is a Link Budget

- It is a theoretical calculation of end-to-end performance for a communications path under a specific set of conditions.
- Sometimes the conditions are stated; most often at least some of them are implied or assumed.
- Every link budget implies everything not included is irrelevant.
  - Sometimes this is true

Why is a Link Budget Important

- A link budget is used to predict performance before the link is established.
  - Show in advance if it will be acceptable
  - Show if one option is better than another
  - Provide a criterion to evaluate actual performance

Link Budget Components

- A satellite link budget should include the following parts:
  1. UPLINK
  2. DOWNLINK
  3. COMBINE 1 AND 2
  4. DEFINE PERFORMANCE LIMIT(S)
  5. COMPARE CALCULATED AND DESIRED PERFORMANCE

EXAMPLE PART 1

Parameter	Value in dB
Uplink transmit EIRP	48.0
Net uplink losses	-177.3
Satellite receive G/T	-17.0
Boltzmann’s constant	(-198.6)
Uplink receive C/N_0	52.3

EXAMPLE PART 2

Parameter	Value in dB
Downlink transmit EIRP	22.5
Net downlink losses	-190.1
Satellite receive G/T	15.0
Boltzmann's constant	(-198.6)
Downlink receive C/N_0	46.0

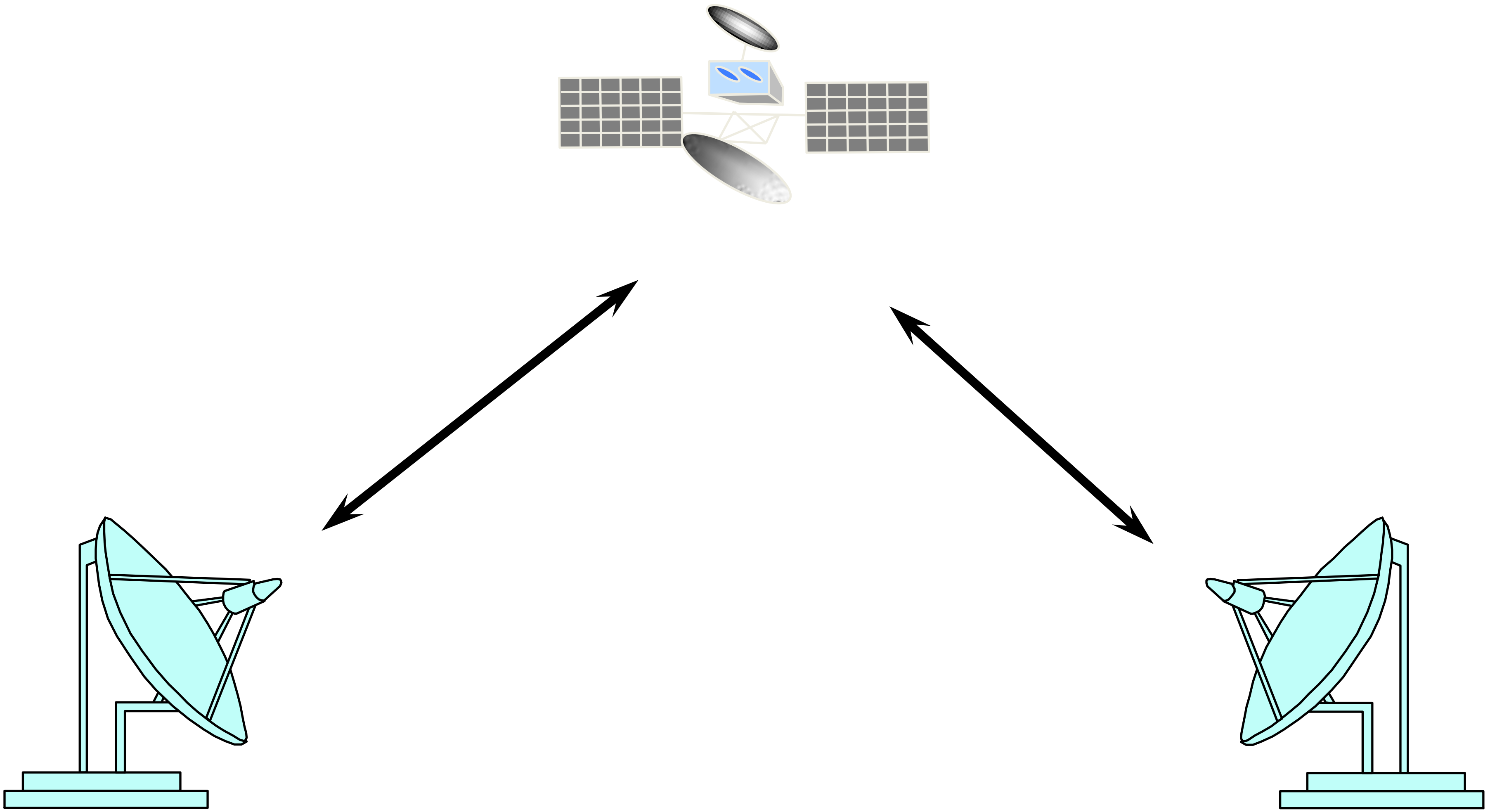
EXAMPLE PART 3

Parameter	Value in dB
Uplink receive C/N_0	52.3
Downlink receive C/N_0	46.0
Combined C/N_0	45.1
Data rate in dB (1200 bps)	30.8
Calculated link E_B/N_0	14.3

EXAMPLE PARTS 4 & 5

Parameter	Value in dB
Calculated link E_B/N_0	14.3
Required E_B/N_0	11.7
Operating margin	2.6

LINK BUDGET



LINK BUDGET

- A satellite link is defined as an Earth station - satellite - Earth station connection. The Earth station - satellite segment is called the uplink and the satellite - Earth station segment is called the downlink.
- The Earth station design consists of the Transmission Link Design, or Link Budget, and the Transmission System Design.
- The Link Budget establishes the resources needed for a given service to achieve the performance objectives.

LINK BUDGET

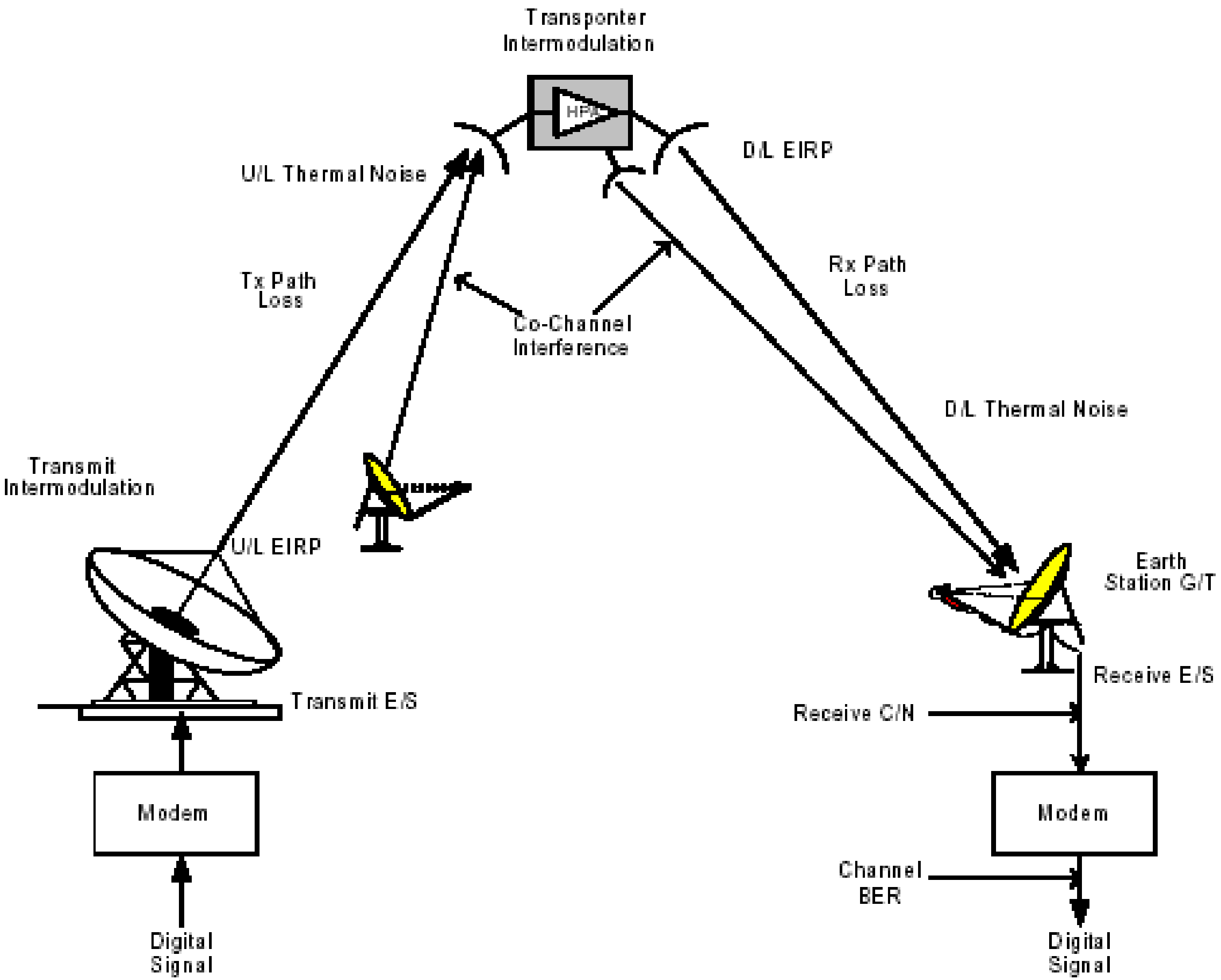
- Performance objectives for digital links consist of:

- BER for normal operating conditions

- Link Availability, or percentage of time that the link has a BER better than a specified threshold level

LINK BUDGET

- The satellite link is composed primarily of three segments:
- (i) the transmitting Earth station and the uplink media;
- (ii) the satellite; and
- (iii) the downlink media and the receiving Earth station.
- The carrier level received at the end of the link is a straightforward addition of the losses and gains in the path between transmitting and receiving Earth stations.



Typical Satellite Link

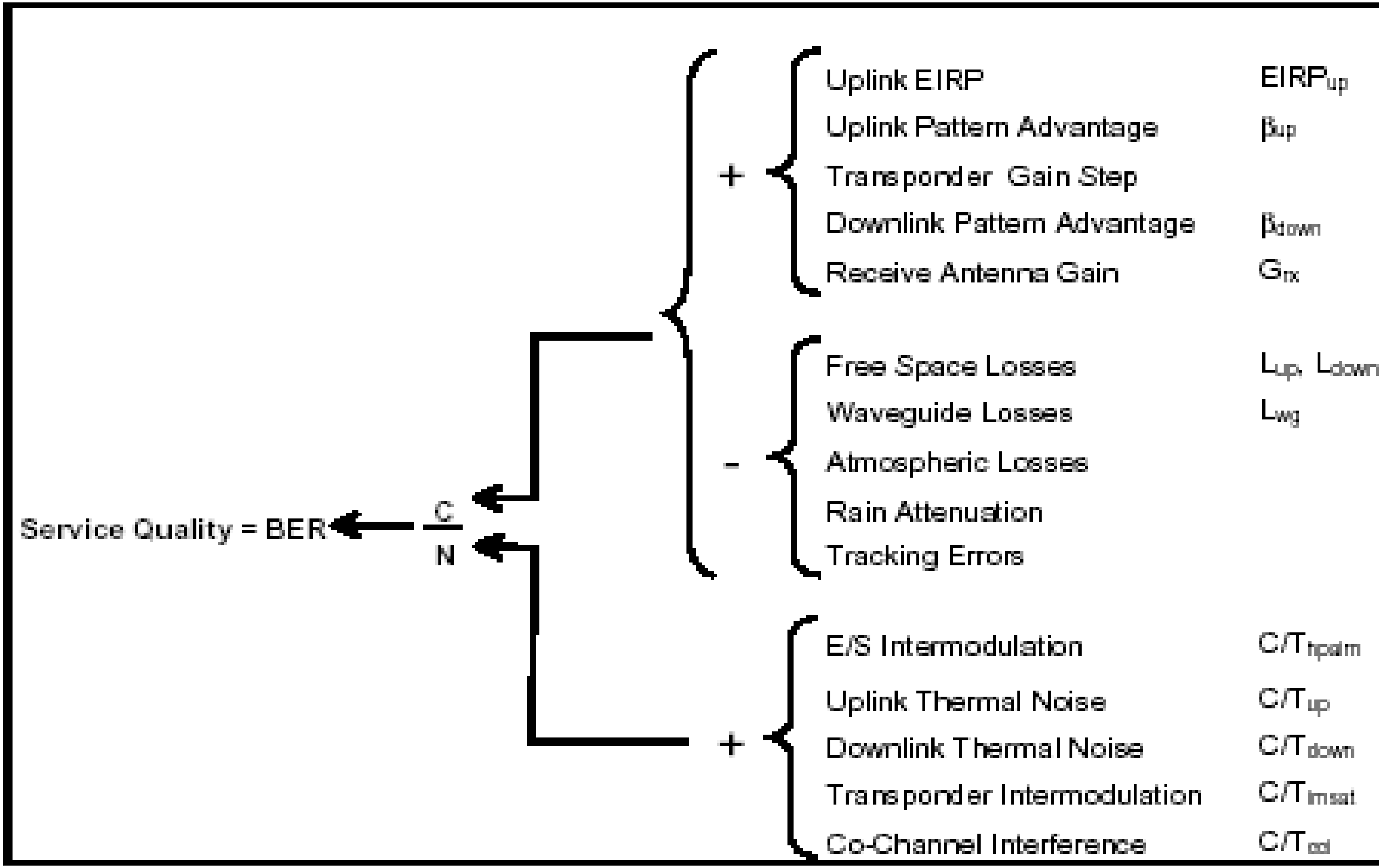
LINK BUDGET

- The basic carrier-to-noise relationship in a system establishes the transmission performance of the RF portion of the system, and is defined by the receive carrier power level compared to the noise at the receiver input. For example, the downlink thermal carrier-to-noise ratio is:

$$C/N = C - 10\log(kTB) \qquad (1)$$

- Where:
- C = Received power in dBW
- k = Boltzman constant, $1.38 * 10^{-23}$ W/°K/Hz
- B = Noise Bandwidth (or Occupied Bandwidth) in Hz
- T = Absolute temperature of the receiving system in °K

Link Parameters' Impact on Service Quality



LINK BUDGET

- The link equation in its general form is:

$$C/N = EIRP - L + G - 10\log(kTB) \qquad (2)$$

Where:

- EIRP = Equivalent Isotropically Radiated Power (dBW)
- L = Transmission Losses (dB)
- G = Gain of the receive antenna (dB)

LINK BUDGET

Equivalent Isotropically Radiated Power:

The gain of a directive antenna results in a more economic use of the RF power supplied by the source. Thus, the EIRP is expressed as a function of the antenna transmit gain G_T and the transmitted power PT fed to the antenna.

$$EIRP_{dBW} = 10 \log P_{T\,dBw} + G_{T\ \ dBi} \qquad (3)$$

Where:

PT_{dBw} = antenna input power in dBW

GT_{dBi} = transmit antenna gain in dBi

LINK BUDGET

Equivalent Isotropically Radiated Power:

Maximum power flux density at distance r from a transmitting antenna of gain G:

$$\Psi_M = (G*Ps) / (4\pi r^2)$$

An isotropic (omnidirectional) radiator would generate this flux density

EIRP is defined as G*Ps

When expressed as dBW, Ps in W, G in dB:

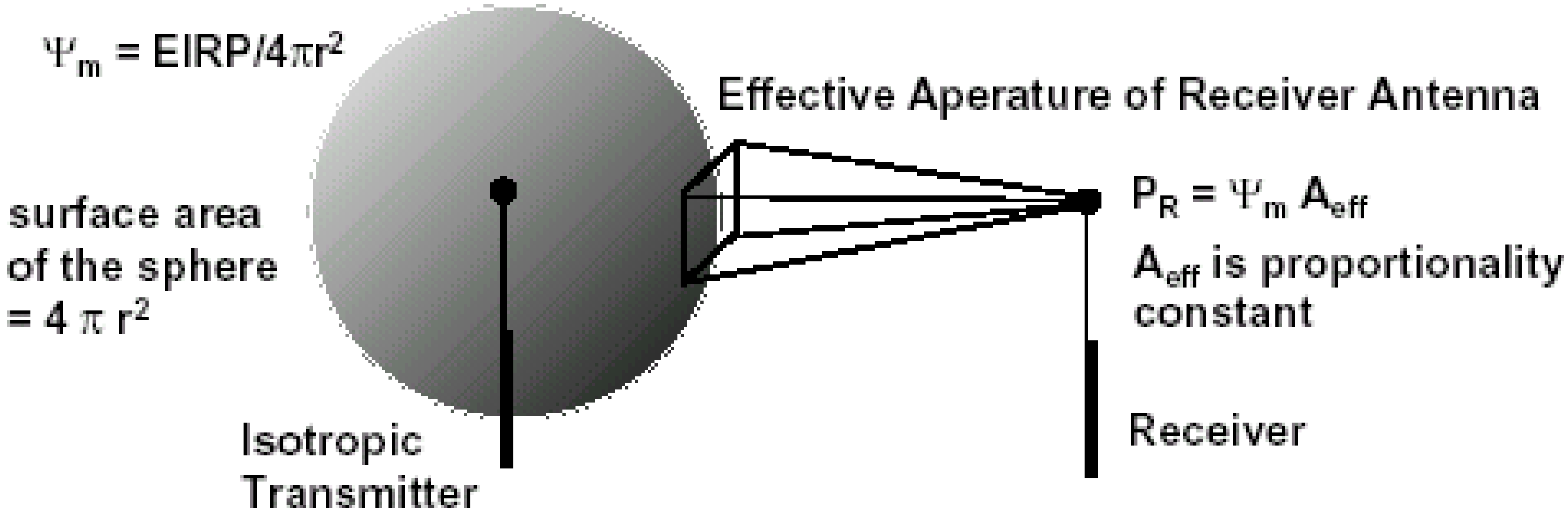
$$EIRP = Ps + G$$

e.g., transmit power of 6 W and antenna gain of 48.2 dB:

$$EIRP = 10 \log 6 + 48.2 = 56 \text{ dBW}$$

Free Space Loss: $P_R = EIRP + G_R - 10 \log (4\pi r/\lambda)^2$ **(dBW)**

Receiver Power Equation



Gain measures directionality of receiver antenna

$$G = \frac{\text{Max Flux Den}}{\text{Isotropic Flux Den}} = \frac{\Psi_m}{\Psi_i}$$

$A_{eff} = G\,\lambda^2 / 4\,\pi$ (antenna efficiency x aperature area)

$$P_R = \frac{EIRP \;\; G_R \;\; \lambda^2}{4\,\pi\, r^2 \;\; 4\,\pi} \;:\; EIRP + G_R - 10\log(4\,\pi\, r / \lambda)^2 \text{ in dB}$$

"Free Space Loss"

Antenna Gain.

The antenna gain, referred to an isotropic radiator, is defined by:

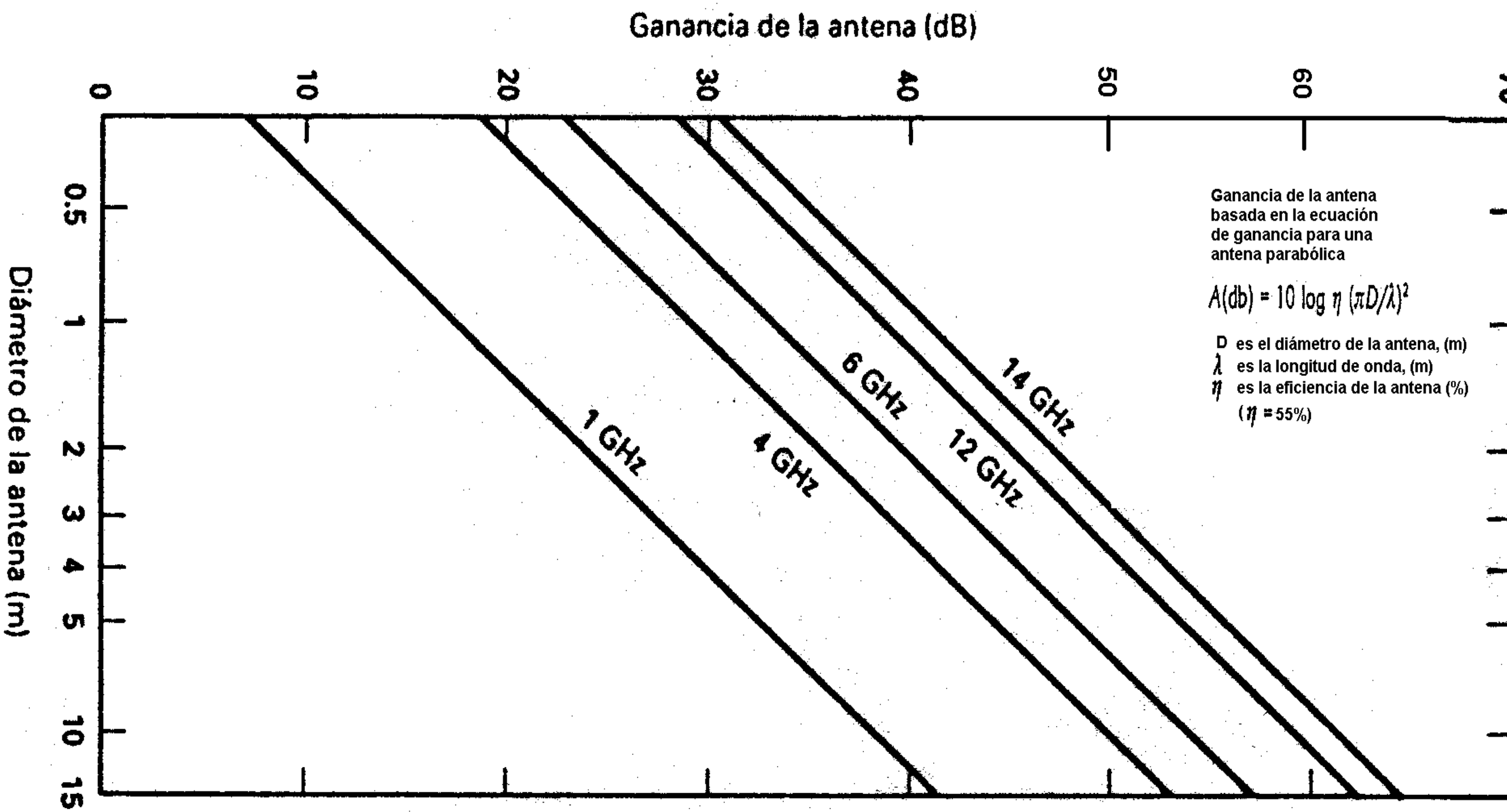
$$G_{dBi} = 10\log(\eta)+20\log(f)+20\log(d)+20.4 \text{ dB} \quad (4)$$

Where:

η = antenna efficiency (Typical values are 0.55 - 0.75)

d = antenna diameter in m

f = operating frequency in GHz



Ganancia de la antena (dB)
0
10
20
30
40
50
60
70
Diámetro de la antena (m)
0.5
1
2
3
4
5
10
15
1 GHz
4 GHz
6 GHz
12 GHz
14 GHz
Ganancia de la antena basada en la ecuación de ganancia para una antena parabólica
A(db) = 10 log η (πD/λ)²
D es el diámetro de la antena, (m)
λ es la longitud de onda, (m)
η es la eficiencia de la antena (%)
(η = 55%)

Transmission losses,

generally consist of four components:

$$L = L_o + L_{atm} + L_{rain} + L_{track} \qquad (5)$$

Where:

L_o = free Space Loss

L_{atm} = atmospheric losses

L_{rain} = attenuation due to rain effects

L_{track} = losses due to antenna tracking errors

LINK BUDGET

If an isotropic antenna radiates a power P_T, the beam power will spread as a sphere in which the antenna is the center. The power at a distance "D" from the transmission point is given by the next equation.

$$\mathbf{W = P_T/4\pi D^2 \ldots\ldots (W/m^2)} \qquad (6)$$

As the transmit antenna focuses the energy (i.e., has a gain), the equation changes to:

$$W = G_T P_T/4\pi D^2 \ldots\ldots (W/m^2) \qquad (7)$$

LINK BUDGET

or

$$W_{dBW/m^2} = EIRP_{dBW} - 20 \log D - 71\ dB \qquad (8)$$

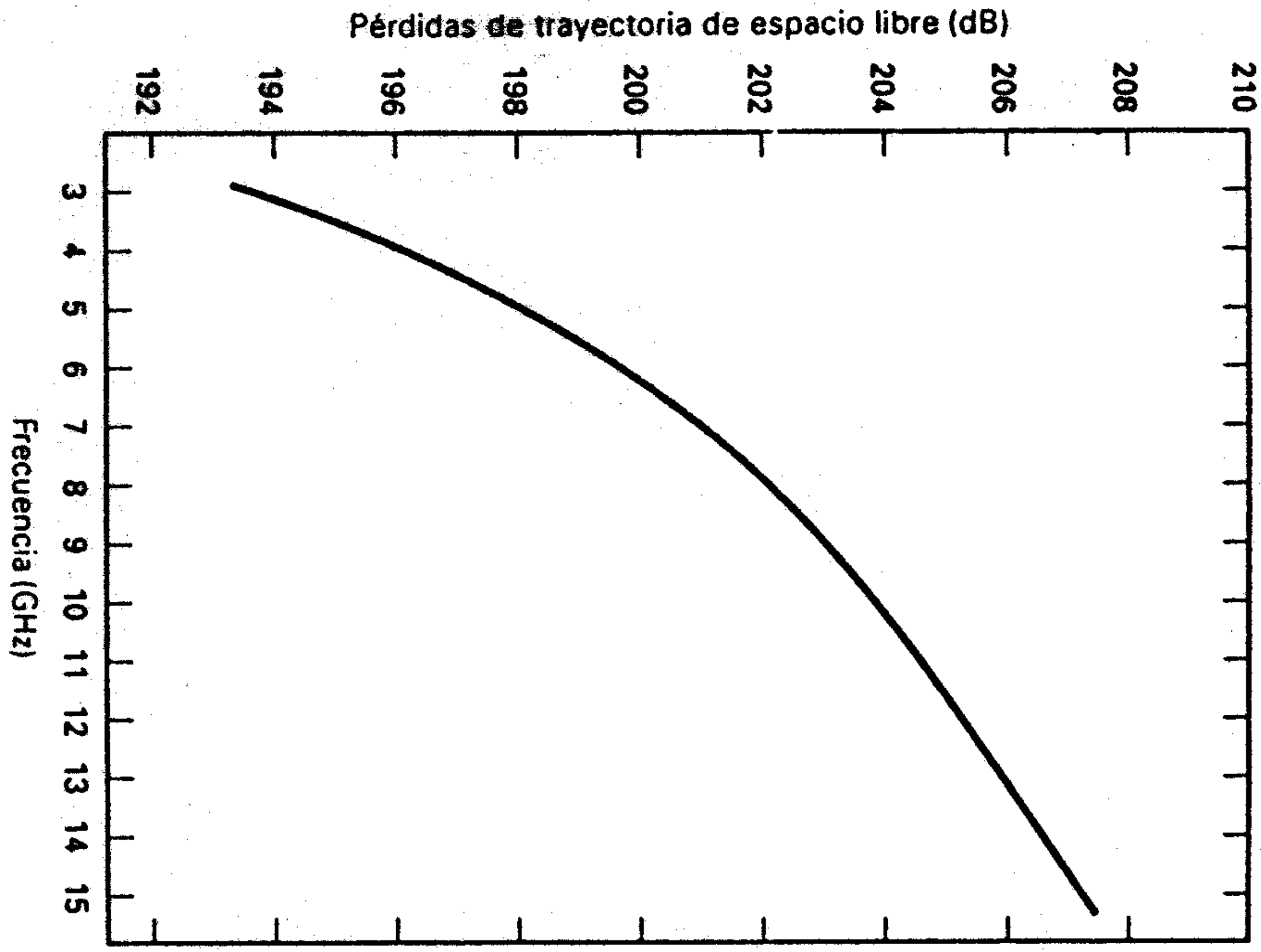
Where:

$G_T P_T = EIRP$

W = illumination level

D = distance in km

$71\ dB = 10 \log (4\pi * 10^6)$



Pérdidas de trayectoria de espacio libre (dB)
192
194
196
198
200
202
204
206
208
210
Frecuencia (GHz)
3
4
5
6
7
8
9
10
11
12
13
14
15

LINK BUDGET

As a receiver antenna 'collects' the signal, the amount of 'collected' signal will depend on the receiver antenna size. The received power P_R will be:

$$P_R = W*Ae \qquad (9)$$

Where:

Ae = effective aperture of the receive antenna

$= (\lambda^2/4\pi)/G_R$

Then,

$$P_R = [G_T P_T/4\pi D^2]*[(\lambda^2/4\pi)/G_R] \qquad (10)$$

$$P_R = G_T P_T*(\lambda/4\pi D)^2*G_R \qquad (11)$$

LINK BUDGET

The expression $[4\pi D/\lambda]^2$ is known as the basic free space loss Lo. The basic free space loss is expressed in decibels as:

$$Lo = 20\log(D) + 20\log(f) + 92.5 \text{ dB} \qquad (12)$$

Where:

D = distance in km between transmitter and receiver, or slant range

f = frequency in GHz

$92.5 \text{ dB} = 20 \log \{(4\pi * 10^9 * 10^3)/c\}$

Free Space Loss

$FSL = 10 \log (4\pi r/\lambda)^2$

in dBW , $FSL = 32.4 + 20 \log r + 20 \log f$

e.g., ES **to satellite is 42,000 km, f is 6 GHz, what is FSL?**

» **FSL = 32.4 + 20 log 42000 + 20 log 6000 = 200.4 dB**

» **Very large loss!!**

e.g., EIRP = 56 dBW, receive antenna gain 50 dB

» **PR = 56 + 50 - 200.4 = -94.4 dBW = 355 pW**

- **Other sources of losses**

– **Feeder losses**

– **Antenna misalignment losses**

– **Fixed atmospheric and ionospheric losses**

– **Effects of rain**

- **PR = EIRP + GR - Losses, in dBW**

Path Loss

- Depends on:
  - Distance and frequency
  - About 200 dB at C-band
  - About 206 dB at Ku-band

LINK BUDGET

Expressing equation (11) in dB:

$$P_{R\,dBW} = EIRP - Lo + G_R \qquad (13)$$

In equation (13), if GR were the gain for a $1m^2$ antenna with 100 percent efficiency, P_R will become the illumination level per unit area in dBW/m^2; therefore, the illumination level in equation (8) can also be expressed as:

$$W_{dBW/m^2} = EIRP - Lo + G_{1m^2} \qquad (14)$$

Atmospheric Losses

Losses in the signal can also occur through absorption by atmospheric gases such as oxygen and water vapor. This characteristic depends on the frequency, elevation angle, altitude above sea level, and absolute humidity. At frequencies below 10 GHz, the effect of atmospheric absorption is negligible.

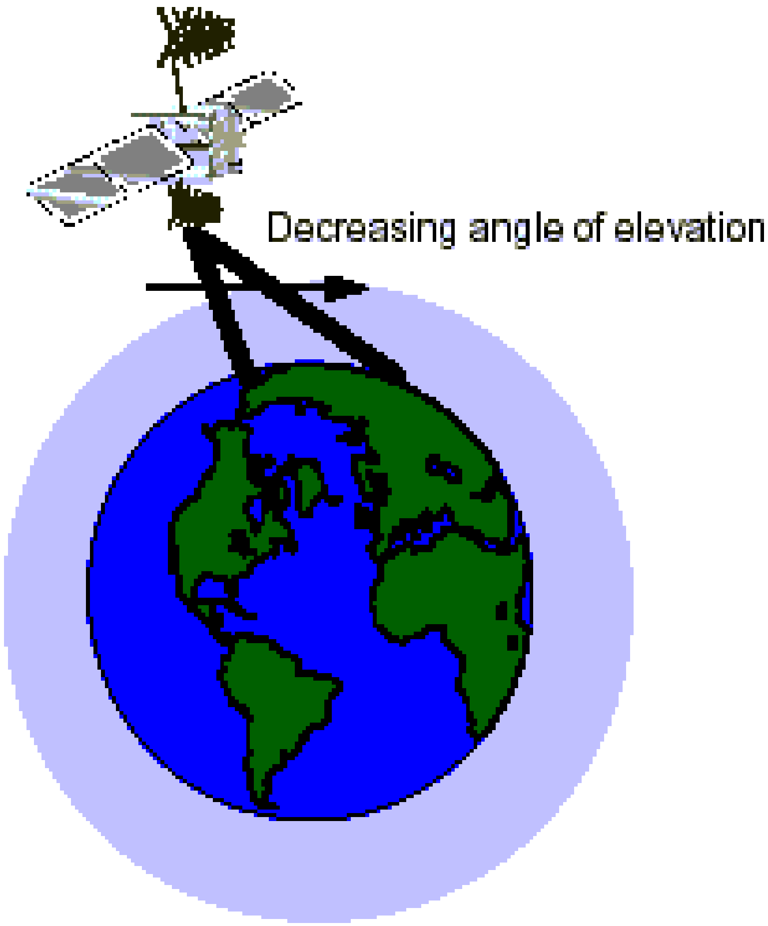
Its importance increases with frequencies above 10 GHz, especially for low elevation angles.

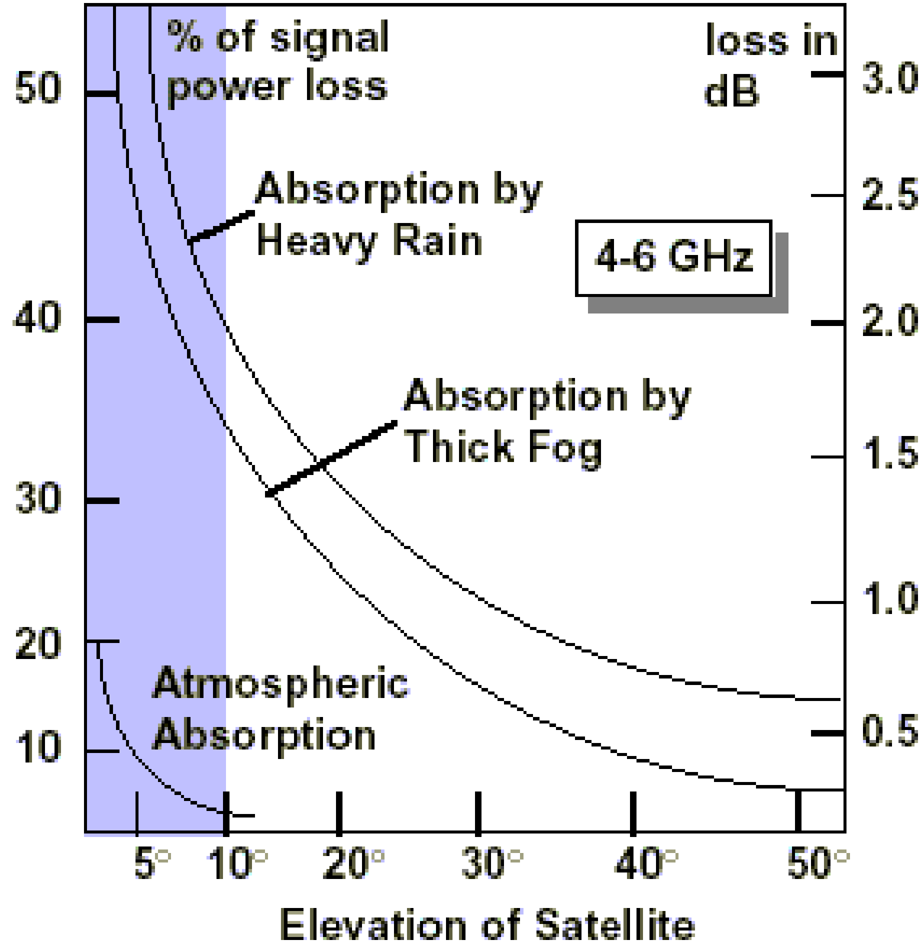
Atmospheric Losses

- Table shows an example of the mean value of atmospheric losses for a 10-degree elevation angle.

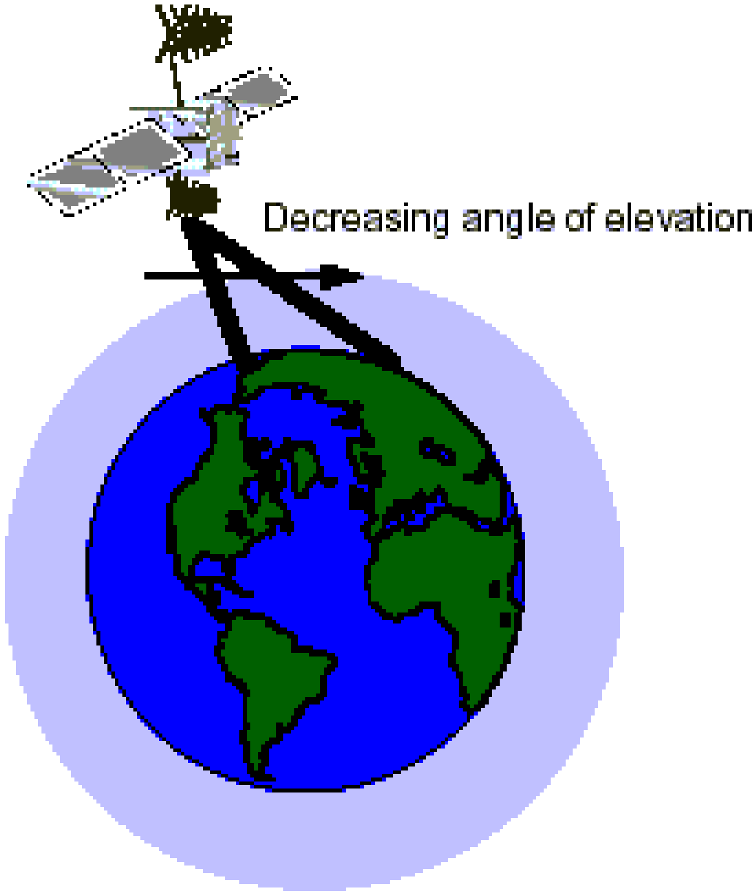
Atmospheric Loss	Frequency (f) in GHz
0.25	2 < f < 5
0.33	5 < f < 10
0.53	10 < f <13
0.73	13 < f

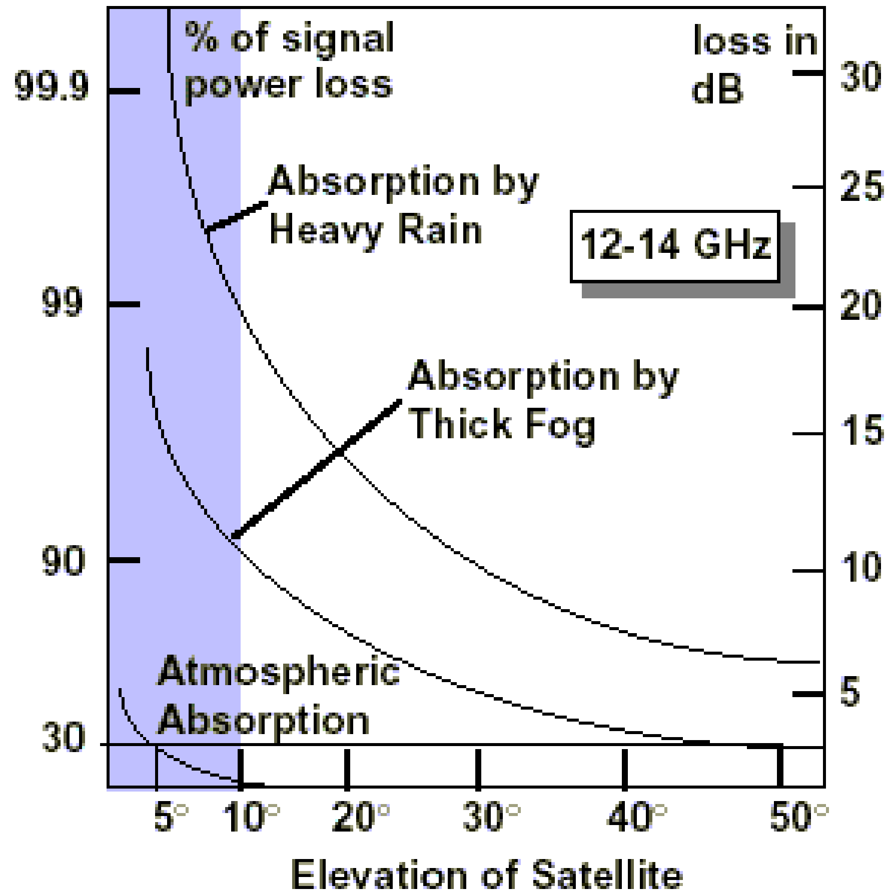
Atmospheric Attenuation





Atmospheric Attenuation





Atmospheric Absorption

Contributing Factors:

– **Molecular oxygen** **Constant**

– **Uncondensed water vapor**

– **Rain**

– **Fog and clouds** **Depend on weather**

– **Snow and hail**

- **Effects are frequency dependent**

– **Molecular oxygen absorption peaks at 60 GHz**

– **Water molecules peak at 21 GHz**

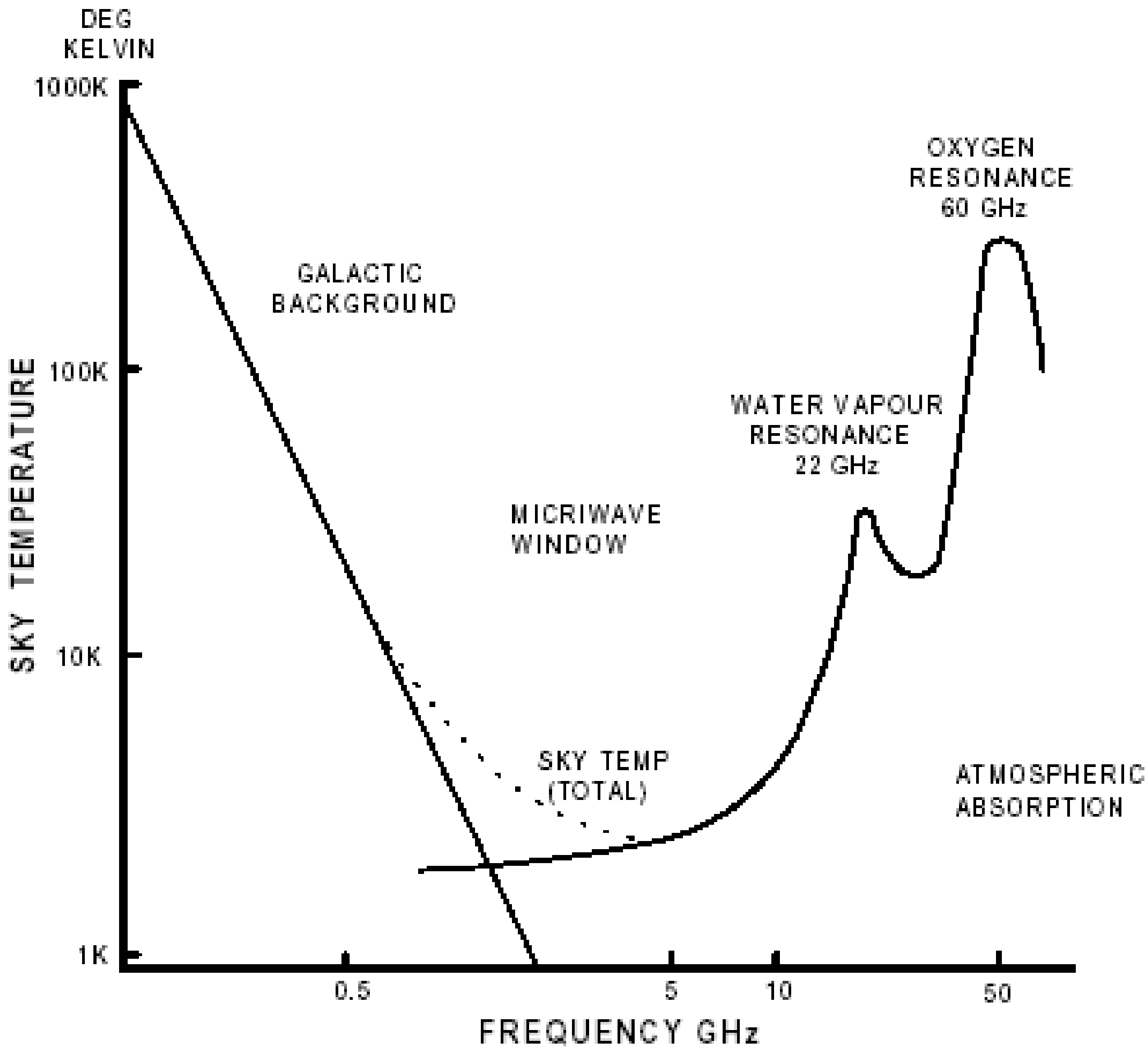
- **Decreasing elevation angle will also increase absorption loss**

Atmospheric Absorption

Location	Rain Attenuation, dB 1%	0.5%	0.1%	Atmos Absorp dB, Summer	Sat Ant Pointing Loss, dB 1/4 Canada Coverage	1/2 Canada Coverage
Ottawa	0.3	0.5	1.9	0.2	0.6	0.2
Toronto	0.2	0.6	1.8	0.2	0.3	0.4

1% of the time, rain attenuation exceeds 0.3 dB
(99% of the time, it is less than or equal to 0.3 dB)
0.5% of the time, it exceeds 0.5 dB
0.1% of the time, it exceeds 1.9 dB

Sky-Noise and Frequency Bands



Transmission Losses

Up-Link (Geosync)

– **Up-link f = 6.175 GHz, D = 36,000 km**

– **Path loss is a function of frequency and distance minus transmitter and receiver antenna gain**

– **Loss = 132.7 - 20 log dt - 20 log dr**

dt transmitter antenna: 30 m

dr satellite receiver antenna: 1.5 m

– **Loss = 132.7 - 29.5 - 3.5 = 94.7 dB**

Transmitted pwr/received pwr = 2.95 x 109

- **Down-Link**

– **Down-link f = 3.95 GHz**

– **Footprint of antenna affects its gain; wide area footprint yields a lower gain, narrow footprint a higher gain**

– **Loss = 136.6 - 20 log dt - 20 log dr**

Loss = 136.6 - 3.5 - 29.5 = 103.6 dB

Rain Effects

- An important climatic effect on a satellite link is the rainfall. Rain results in attenuation of radio waves by scattering and by absorption of energy from the wave.
- Rain attenuation increases with the frequency, being worse for Ku-band than for C-band. Enough extra power must be transmitted to overcome the additional attenuation induced by rain to provide adequate link availability.

Tracking Losses

When a satellite link is established, the ideal situation is to have the Earth station antenna aligned for maximum gain, but normal operation shows that there is a small degree of misalignment which causes the gain to drop by a few tenths of a dB. The gain reduction can be estimated from the antenna size, the tracking type, and accuracy.

- This loss must be considered for the uplink and downlink calculations.

Tracking Losses

Earth Station Performance Characteristic (C-band, Antenna Efficiency 70%)

ANTENNA DIAMETER (m)	TX GAIN 6 GHz (dBi)	RX GAIN 4 GHz (dBi)	UPLINK LOSSES dB	DOWN-LINK LOSSES dB	TRACKING
1.2	35.6	32.1	0	0	FIXED
1.8	39.2	35.6	0	0	FIXED
2.4	41.7	38.1	0.4	0.2	FIXED
3.6	45.6	42.1	0.7	0.4	FIXED
7	51	47.4	0.9	0.9	MANUAL*
11	54.9	51.4	0.5	0.5	STEP TRACK

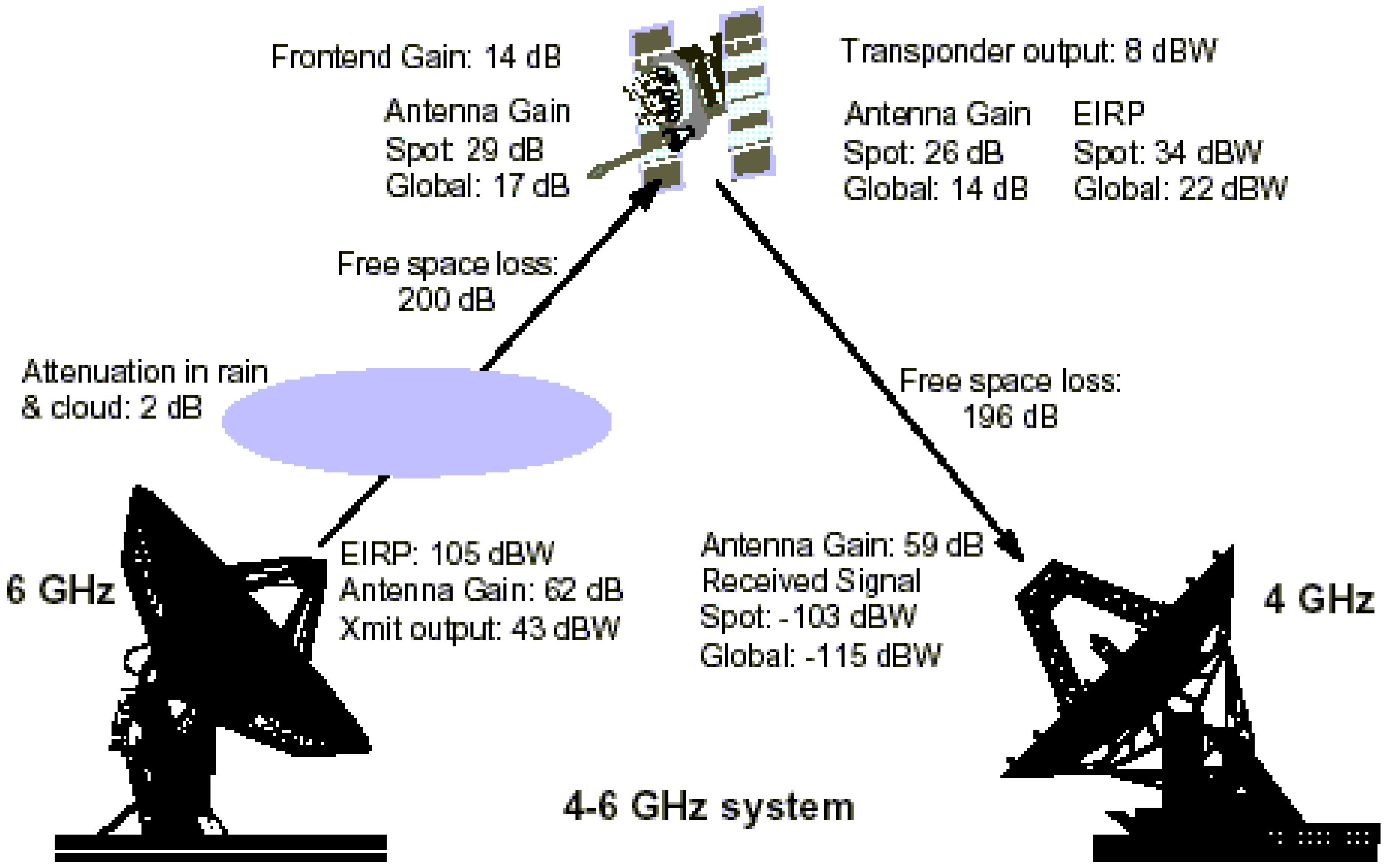
* Manual tracking requires weekly E-W angle adjustments.

Tracking Losses

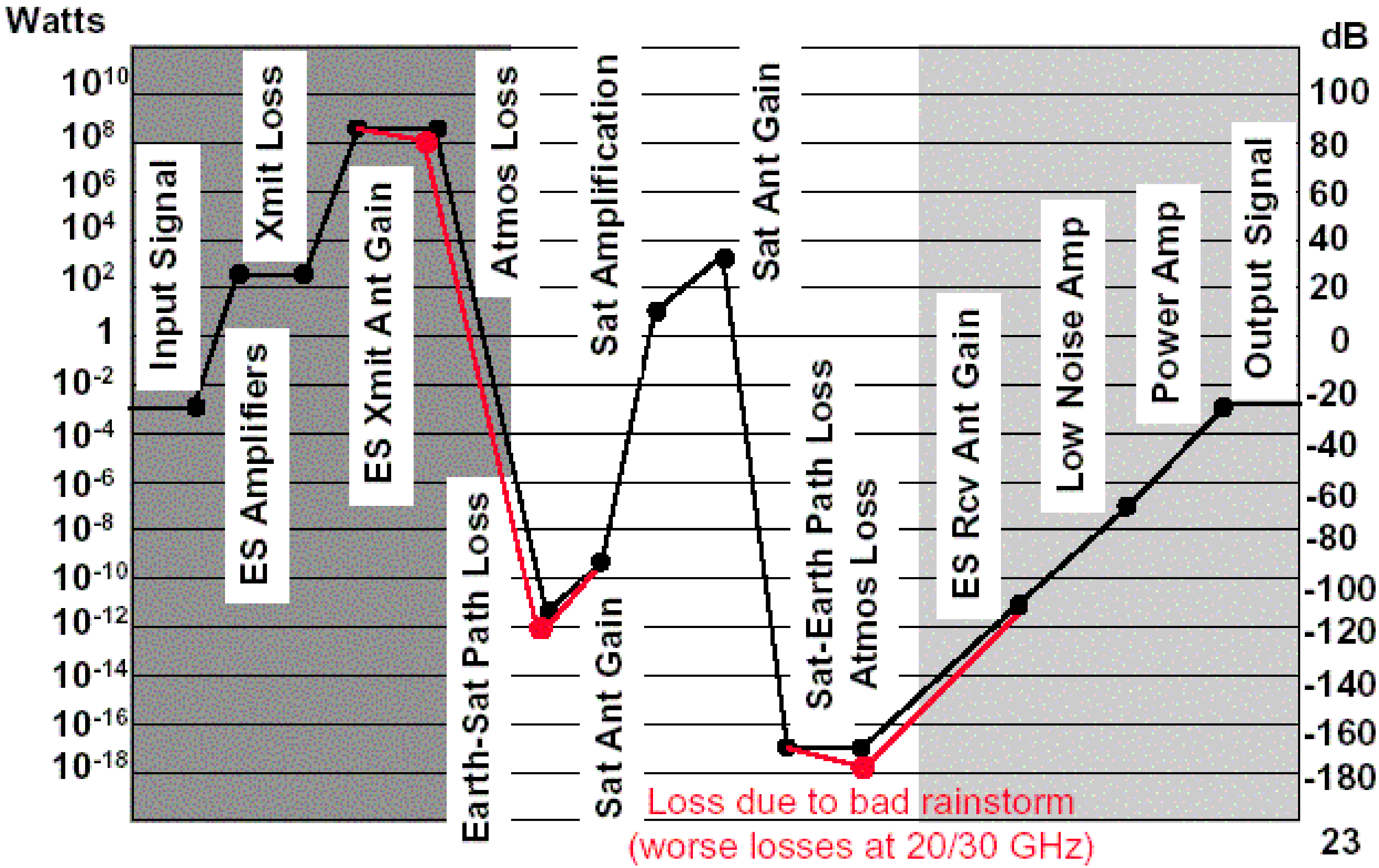
Earth Station Performance Characteristic (Ku-band, Antenna Efficiency 60%)

ANTENNA DIAMETER (m)	TX GAIN 14 GHz (dBi)	RX GAIN 11 GHz (dBi)	UPLINK LOSSES dB	DOWN-LINK LOSSES dB	TRACKING
1.2	42.6	40.5	0.4	0.2	FIXED
1.8	46.1	44	0.7	0.5	FIXED
2.4	48.7	46.6	1.1	0.8	FIXED
3.7	52.5	50.3	1.2	0.9	MANUAL*
5.6	56.1	53.9	0.8	0.7	MANUAL*
7	58	55.8	0.5	0.5	STEP TRACK
8	59.2	57	0.5	0.5	STEP TRACK

Typical Losses



Typical Losses (4/6 GHz)



System Noise Temperature

The system noise temperature of an Earth station consists of the receiver noise temperature, the noise temperature of the antenna, including the feed and waveguides, and the sky noise picked up by the antenna.

$$T_{system} = T_{ant}/L + (1 - 1/L)To + Te \qquad \textbf{(15)}$$

Where:

L = feed loss in numerical value

Te= receiver equivalent noise temperature

To= standard temperature of 290°K

T_{ant} = antenna equivalent noise temperature as provided by the manufacturer

Noise

- **Shannon's Law: $B = BN \log_2 (PR / PN + 1)$**
- **Where B = information-carrying capacity of the link (bits/unit bandwidth)**
- **BN = usable bandwidth (hertz)**
- **PR/PN must not get too small!**
- **Noise power usually quoted in terms of noise temperature: PN = k TN BN**
- **The noise temperature of a noise source is that temperature that produces the same noise power over the same frequency range: TN = PN / k BN**
- **Noise density (noise per hertz of b/w): N0 = PN / BN = k TN**
- **Carrier-to-Noise: C/N0 = PR / N0 = PR / k TN : EIRP + G/T - k - Losses in dB**
- **Receiver antenna figure of merit: increases**
- **with antenna diameter and frequency;**
- **More powerful xmit implies cheaper receiver**
- **Sun, Moon, Earth, Galactic**
- **Noise, Cosmic Noise, Sky**
- **Noise, Atmospheric Noise,**
- **Man-made Noise**

Noise Sources

System Noise

– Received power is very small, in picowatts

– Thermal noise from random motion of electrons

– Antenna noise: antenna losses + sky noise (background microwave radiation)

– Amplifier noise temperature: energy absorption manifests itself as heat, thus generating thermal noise

- **Carrier-to-Noise Ratio**

– C/N = PR - PN in dB

– PN = k TN BN

– C/N = EIRP + GR - LOSSES - k -TS - BN

where k is Boltzman's constant, TS is system noise temperature, TN is equivalent noise temperature, BN is the equivalent noise bandwidth

– Carrier to noise power density (noise power per unit b/w):

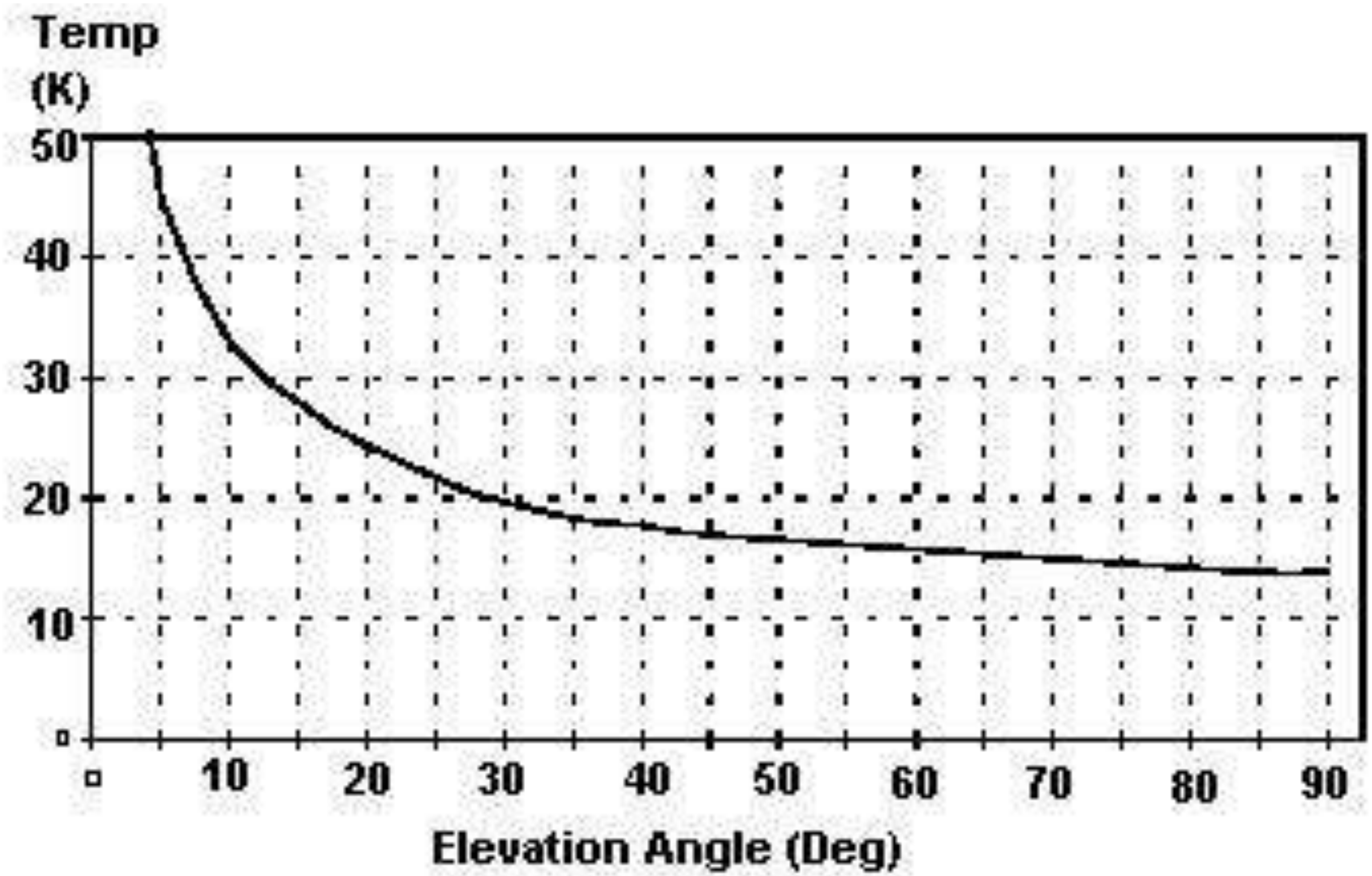
C/N0 = EIRP + G/T - Losses - k

Antenna Noise Temperature

- The noise power into the receiver, (in this case the LNA), due to the antenna is equivalent to that produced by a matched resistor at the LNA input at a physical temperature of $\mathbf{T_{ant}}$.
- If a body is capable of absorbing radiation, then the body can generate noise. Thus the atmosphere generates some noise. This also applies to the Earth surrounding a receiving ground station antenna. If the main lobe of an antenna can be brought down to illuminate the ground, the system noise temperature would increase by approximately 290°K.

Antenna Noise Temperature

Noise Temperature of an Antenna as a Function of Elevation Angle



Antenna Temperature

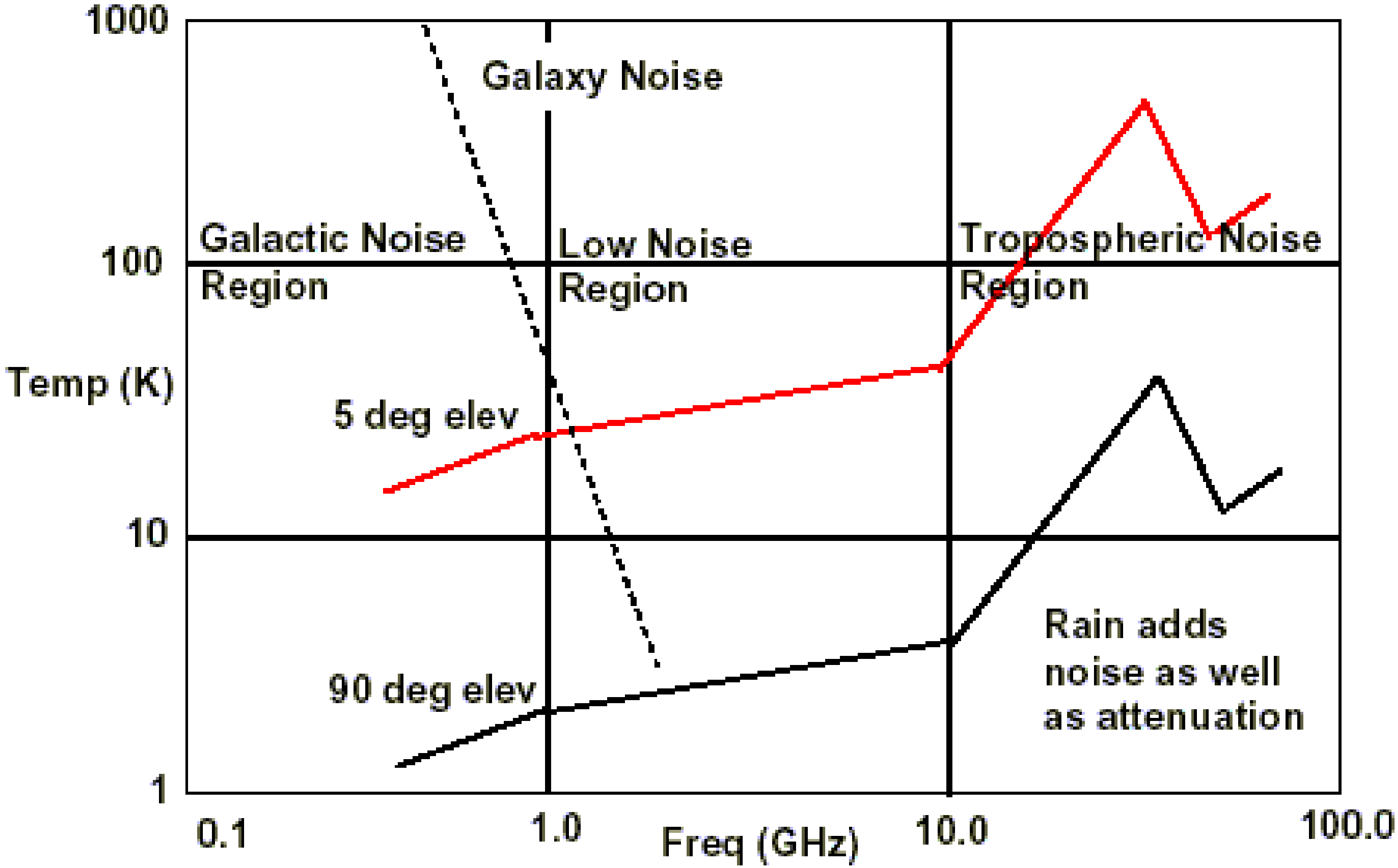


Figure of Merit (G/T)

In every transmission system, noise is a factor that greatly influences the whole link quality.

The G /$T_{\mathbf{dBK}}$ is known as the "goodness" measurement of a receive system.

This means that providing the Earth station meets the required G/T specification, INTELSAT will provide enough power from the satellite to meet the characteristic of every service.

Figure of Merit (G/T)

G/T is expressed in dB relative to 1°K. The same system reference point, such as the receiver input, for both the gain and noise temperature must be used.

$$G/T = G_{rx} - 10\log(T_{sys}) \qquad (16)$$

Where:

G_{rx} = receive gain in dB

T_{sys} = system noise temperature in °K

Carrier to Noise Ratio

In the link equation, by unfolding the kTB product under the logarithm, the link equation becomes:

$C/N = EIRP - L + G - 10\log(k) - 10\log(T) - 10\log(B)$ (17)

The difference, **$G - 10\log T$**, is the figure of merit:

$C/N = EIRP - L + G/T - 10\log(k) - 10\log(B)$ (18)

Where:

L = transmission losses

G/T = figure of merit of the receiver

k = Boltzmann constant

B = carrier occupied bandwidth

Carrier to Noise Ratio

Because the receiver bandwidth (B) is often dependent on the modulation format, isolate the link power parameters by normalizing out the bandwidth dependence. The new relation is known as Carrier-to-Noise Density ratio (C/No).

$$C/No = EIRP - L + G/T - 10\log(k) \quad \textbf{(19)}$$

Note that:

$$C/N = C/T - 10\log kB \quad \textbf{(20)}$$

Expressing C/T as a function of C/N, and replacing C/N with the right side of the link equation, results:

$$C/T = EIRP - L + G/T \quad \textbf{(21)}$$

Carrier to Noise Ratio

The ratio C/No allow us to compute directly the receiver Bit energy-to-noise density ratio as:

$$E_b/N_o = C/N_o - 10\log(\text{digital rate}) \qquad (22)$$

The term "digital rate" is used here because E_b/N_o can refer to different points with different rates in the same modem.

Carrier-to-Noise Ratio

Example Calculation

– 12 GHz frequency, free space loss = 206 dB,
antenna pointing loss = 1 dB,
atmospheric absorption = 2 dB
– Receiver G/T = 19.5 dB/K,
receiver feeder loss = 1 dB
– EIRP = 48 dBW

• Calculation:
– $C/N0 = -206 - 1 - 2 + 19.5 - 1 + 48 + 228.6 = 86.1$
(Note that Boltzmann's constant k
$= 1.38 \times 10^{-23}$ J/K = -228.6 dB)

Link Budget

The interpretation of equation (21) is that a given C/T required by a certain type of carrier and quality of service, can be obtained for different combinations of EIRP and G/T.

EIRP represents the resource usage and finally is reflected in the operating costs because higher satellite EIRP means higher operating costs. On the other hand the G/T represents the capital expenditure, because higher G/T means larger antenna and/or better LNA, reflected in the cost of the equipment.

Link Budget

Note that in some cases the Earth station G/T could be improved by using a better LNA. For example, an Earth station with a receive gain of 53 dBi,
antenna noise of 25°K at 25° in C-band, feeder noise temperature of 5°K and LNA noise temperature of 80°K would have:

$$G/T = Gant - 10\log(T_{\mathbf{ant}}+T_{\mathbf{feed}}+T_{\mathbf{LNA}}) \qquad (23)$$

$$G/T = 53 - 10\log(25 + 5 + 80) = 32.6 \text{ dB/°K}$$

This antenna would be classified as a standard B antenna.

Link Budget

Removing the LNA and replacing it with a 30°K LNA, the G/T is:

$G/T = 53 - 10\log(25 + 5 + 30) = 35.2$ dB/°K

This reclassifies the antenna as a standard A.

For elevation angles below 25°, the antenna noise would increase and the overall G/T would be too low for standard A.

Simplified Link Equation

$10 \log (C/N_0) = P_S + G_S - FSL + G_R - T_R - k - L$ (dB) where:

- **C/N_0: ratio of signal pwr to noise pwr after being received (Hz)**
- **P_S: RF pwr delivered to transmitting antenna (dBW)**
- **G_S: Gain of the transmitting antenna relative to isotropic rad (dBi)**
- **FSL: Free space loss (dB)**
- **G_R: Gain of the receiving antenna (dBi)**
- **T_R: Composite noise temperature of the receiver (dBK)**
- **k: Boltzmann's constant (-288.6 dBW/K-Hz)**
- **L: Composite of propagation loss (dB)**

- **$G = 10 \log (\eta\pi^2 D^2/\lambda^2)$ dBi**
  - **η: antenna efficiency, D: diameter**
- **$FSL = 10 \log [(4\pi r)^2/\lambda^2]$ dB**
  - **r is distance**

Path loss and antenna gain increase with square of radio frequency

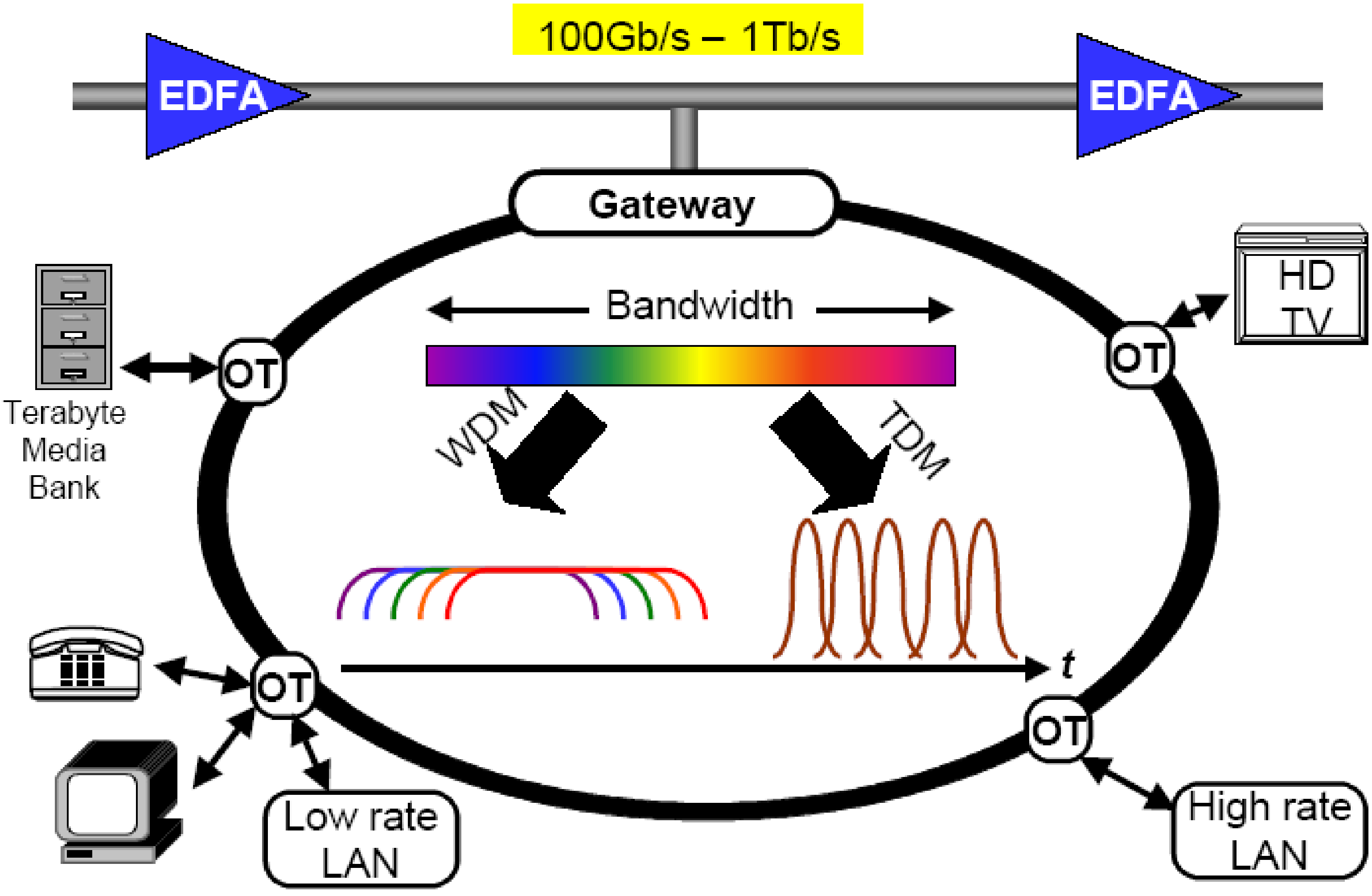
Fiber-Optic Communication Systems

Why Optical Communications?

- Optical Fiber is the backbone of modern communication networks
  - Voice (SONET/Telephony) - The largest traffic
  - Video (TV) over Hybrid Fiber Coaxial (HFC)
  - Fiber Twisted Pair for Digital Subscriber Loops (DSL)
  - Multimedia (Voice, Data and Video) over DSL or HFC

Information revolution wouldn’t have happened without the Optical Fiber

Introduction



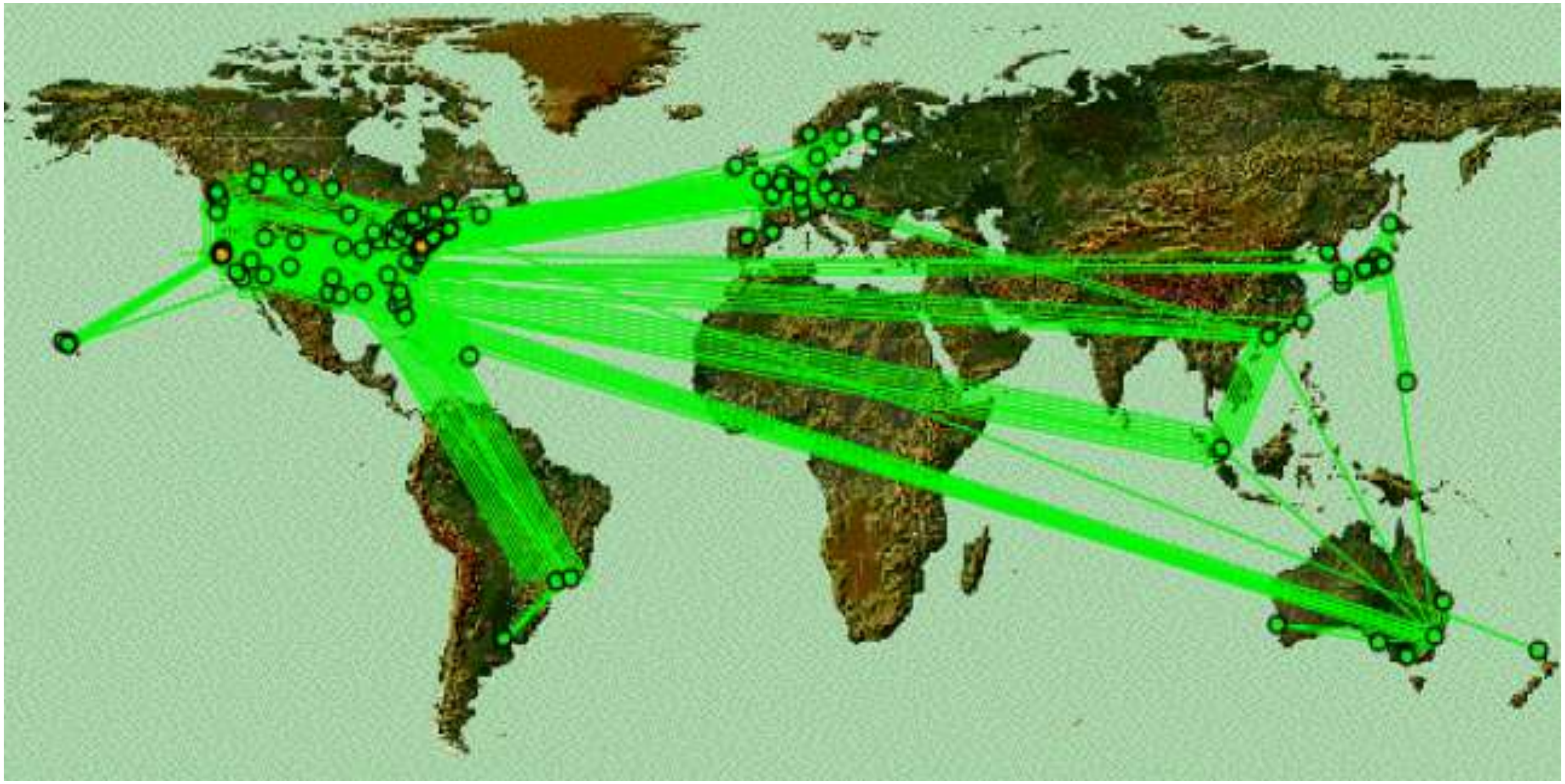
Why Optical Communications?

- Lowest attenuation → attenuation in the optical fiber (at 1.3 μm and 1.55 μm bands) is much smaller than electrical attenuation in any cable at useful modulation frequencies
  - Much greater repeater-less distances are possible
  - Optical attenuation is independent of modulation frequency
- Bandwidth/ broadband → high-speed →rich content
  - Single Mode Fiber (SMF) offers the lowest dispersion → highest bandwidth
- An SMF optical communication system can be upgraded to higher bandwidth by replacing only the transmitters and receivers

Why Optical Communications for you?

- Most Electrical and Computer Engineers will eventually work in Information and Communications Technology (ICT) area
- Canada produces 40% of the worlds optoelectronic products
- Some of the worlds leading Photonic Facilities are located in this region (Ottawa, Quebec…)

The UUNet Commercial Internet



Optical Communication Systems

- Digital fiber optic (SONET) systems
- Microwave (analog) fiber optic (MFO) Systems
- Radio over fiber systems for wireless communications (ROF)
- Line of sight Infrared fixed wireless systems (Free Space Optics)
- Diffused infrared indoor wireless systems

Digital Fiber Optic Systems (SONET/SDH)

High speed inter-city, intra-city, WAN type network with well defined standards and bit rates up 6.4 Tb/s

(Nortel Networks OPTera 5000)

Synchronous Optical Networks

- **SONET is the TDM optical network standard for North America (called SDH in the rest of the world)**
- **We focus on the physical layer**
- **STS-1, Synchronous Transport Signal consists of 810 bytes over 125 us**
- **27 bytes carry overhead information**
- **Remaining 783 bytes: Synchronous Payload Envelope**

SONET/SDH Bit Rates

SONET	Bit Rate (Mbps)	SDH
OC-1	51.84	-
OC-3	155.52	STM-1
OC-12	622.08	STM-4
OC-24	1244.16	STM-8
OC-48	2488.32	STM-16
OC-96	4976.64	STM-32
OC-192	9953.28	STM-64

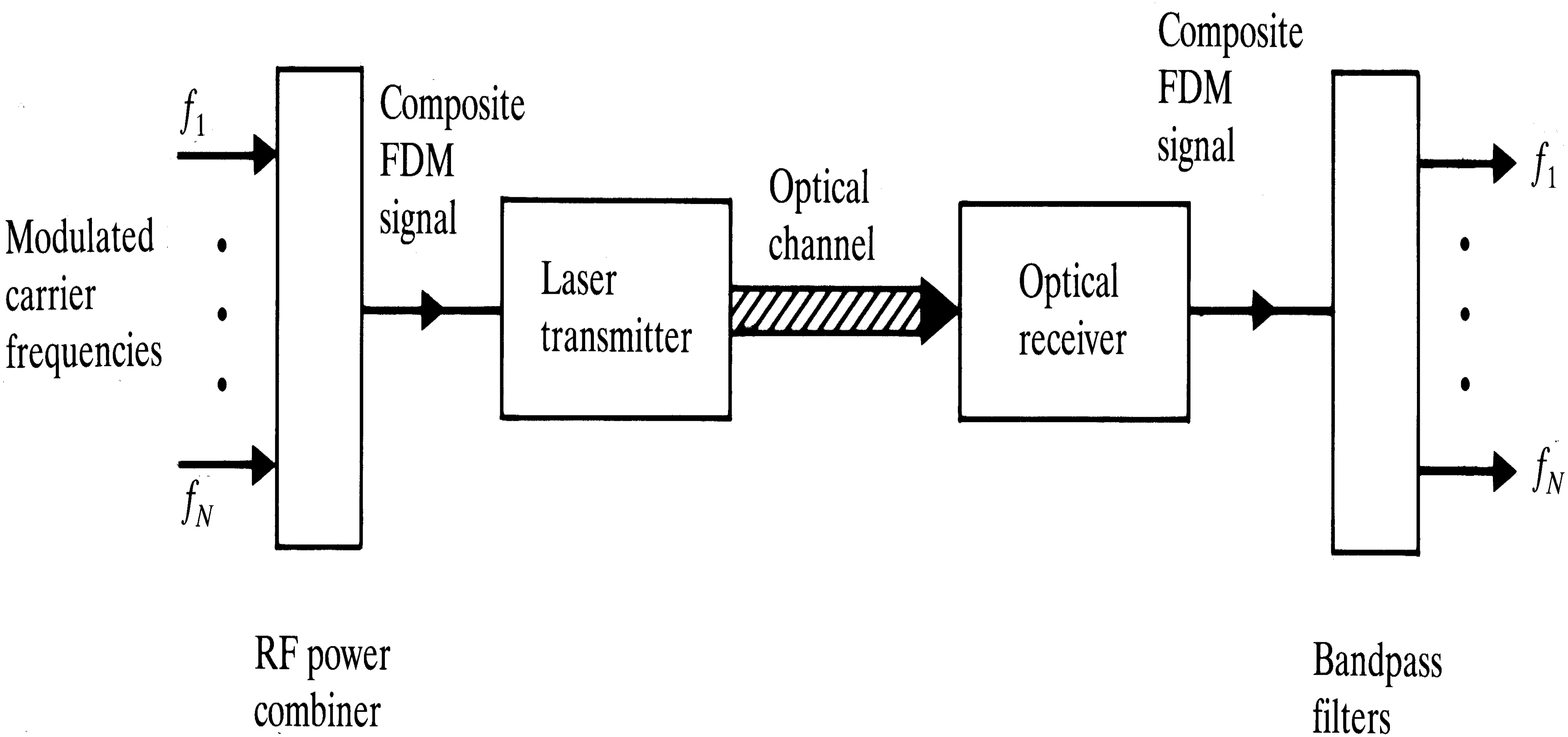
Microwave Fiber Optic (MFO) Analog Systems

Conventionally used for CATV Distribution (Fiber-Coax Systems) and recently for multimedia delivery via high-speed internet cable modems

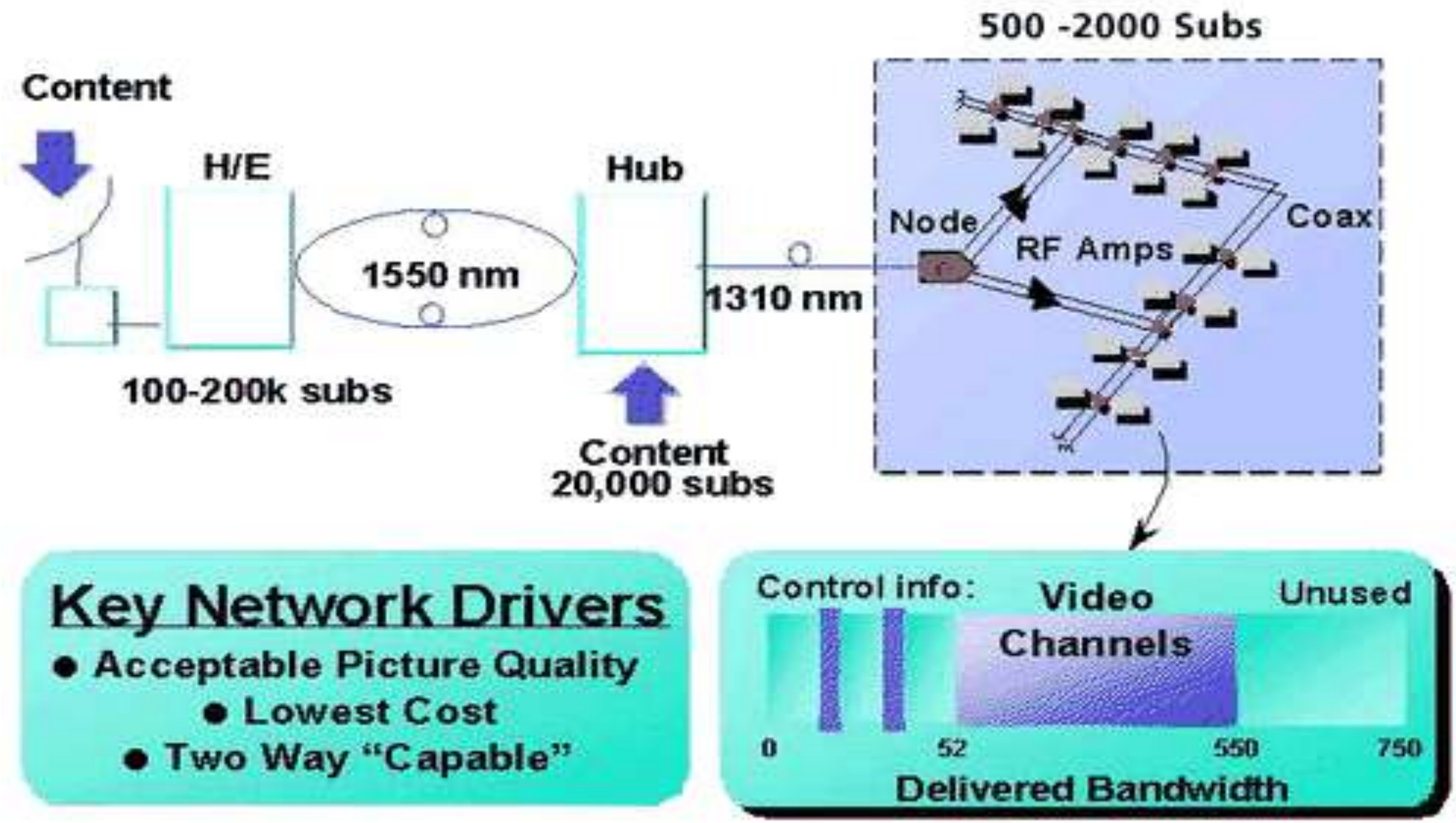
Analog Systems

- Modulating signal is analog (RF)
- Several RF carriers can be transmitted over a single fiber in FDM manner called Sub Carrier Multiplexing
- Each RF Carrier is an independent communication channel
  - Ex: CATV Systems
- Linearity is the biggest concern

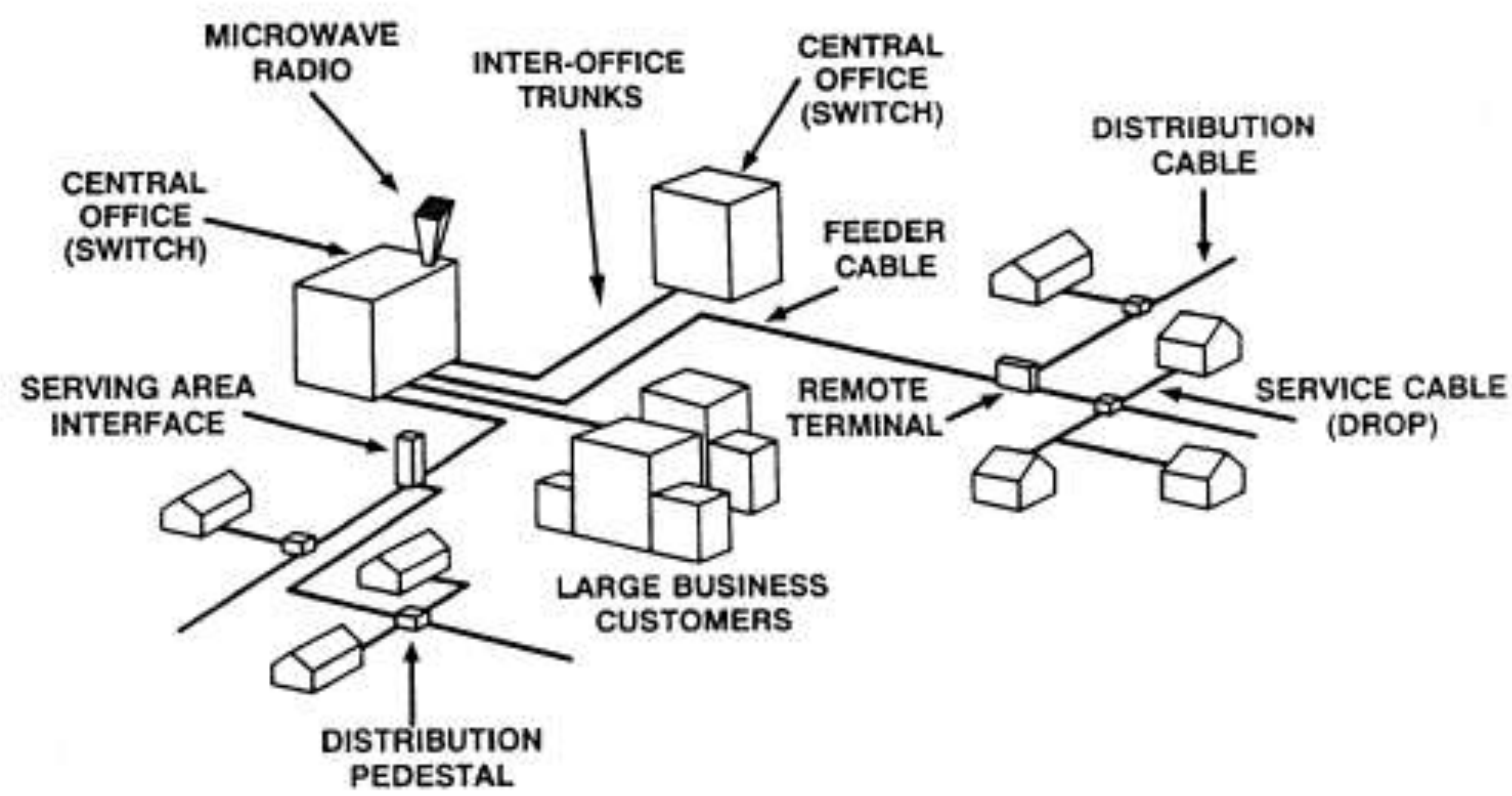
Sub-Carrier Multiplexing



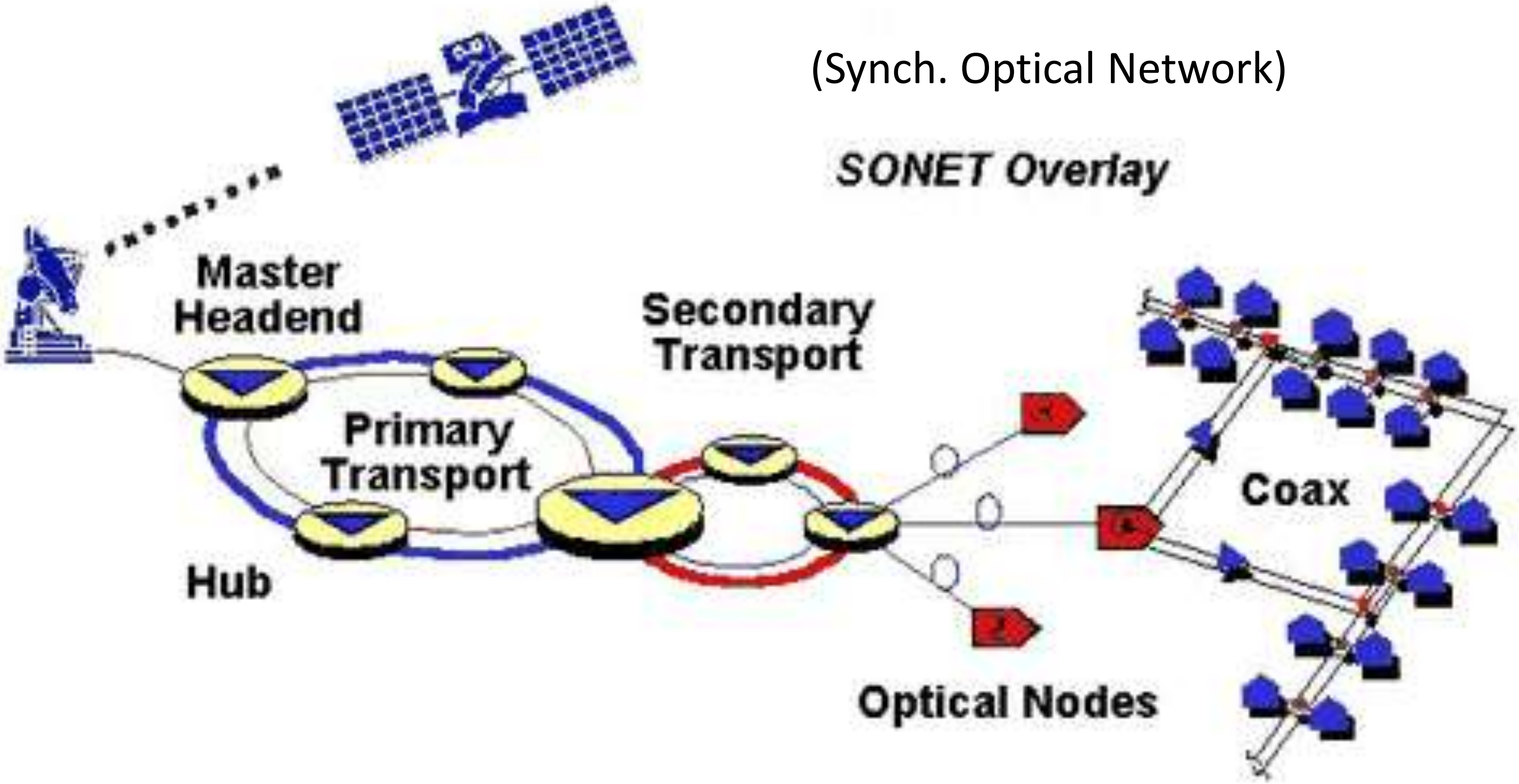
Hybrid/Fiber Coax (HFC) TV Networks



Public Switched Telephone Network (PSTN)



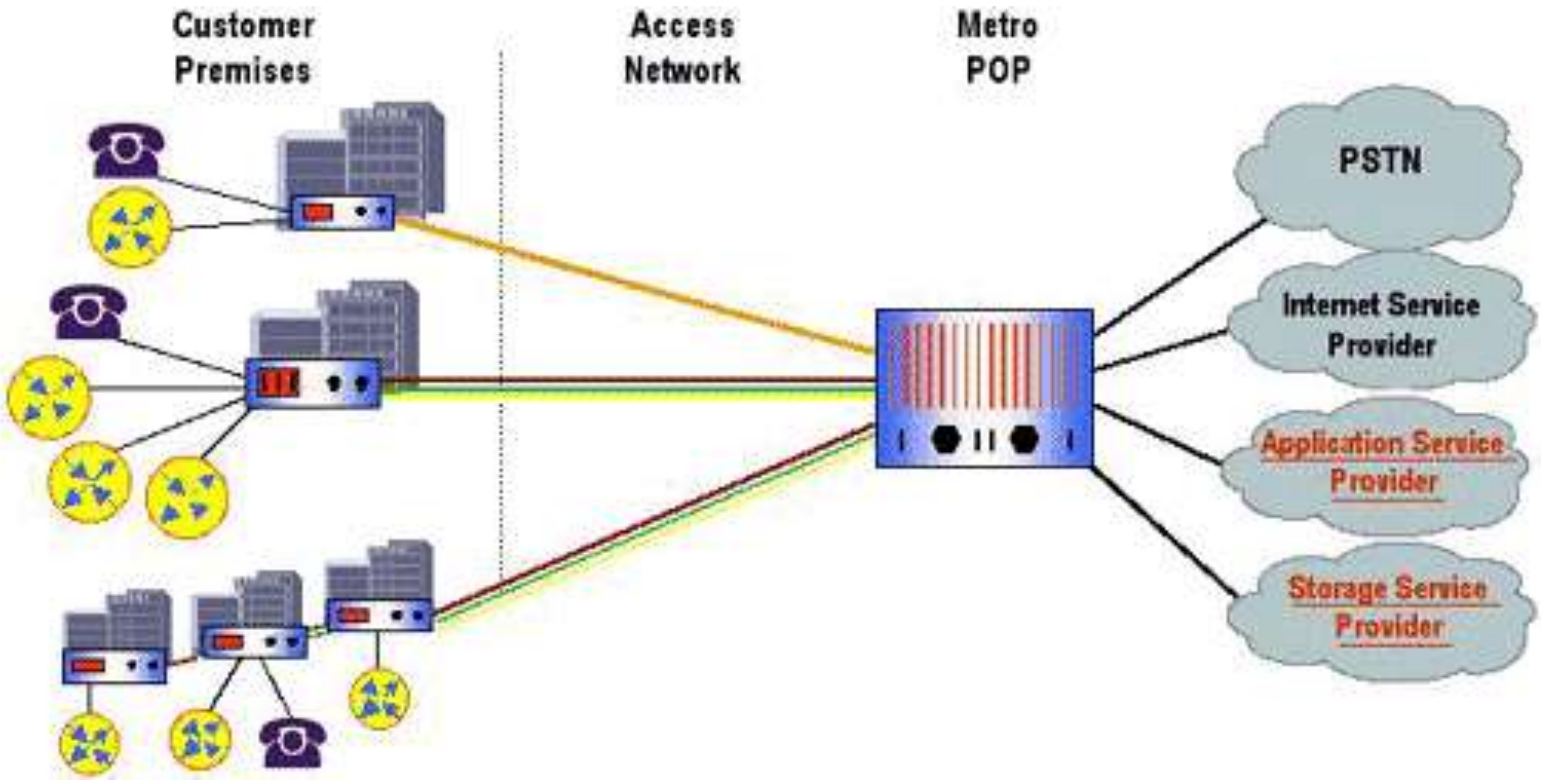
Multimedia over Fiber



Prisma DT is a multiservice OC-48 multiplexer optimized for regional interconnection and transport of:

- **Linear Broadcast Video**
- **Interactive Data and Voice Services**

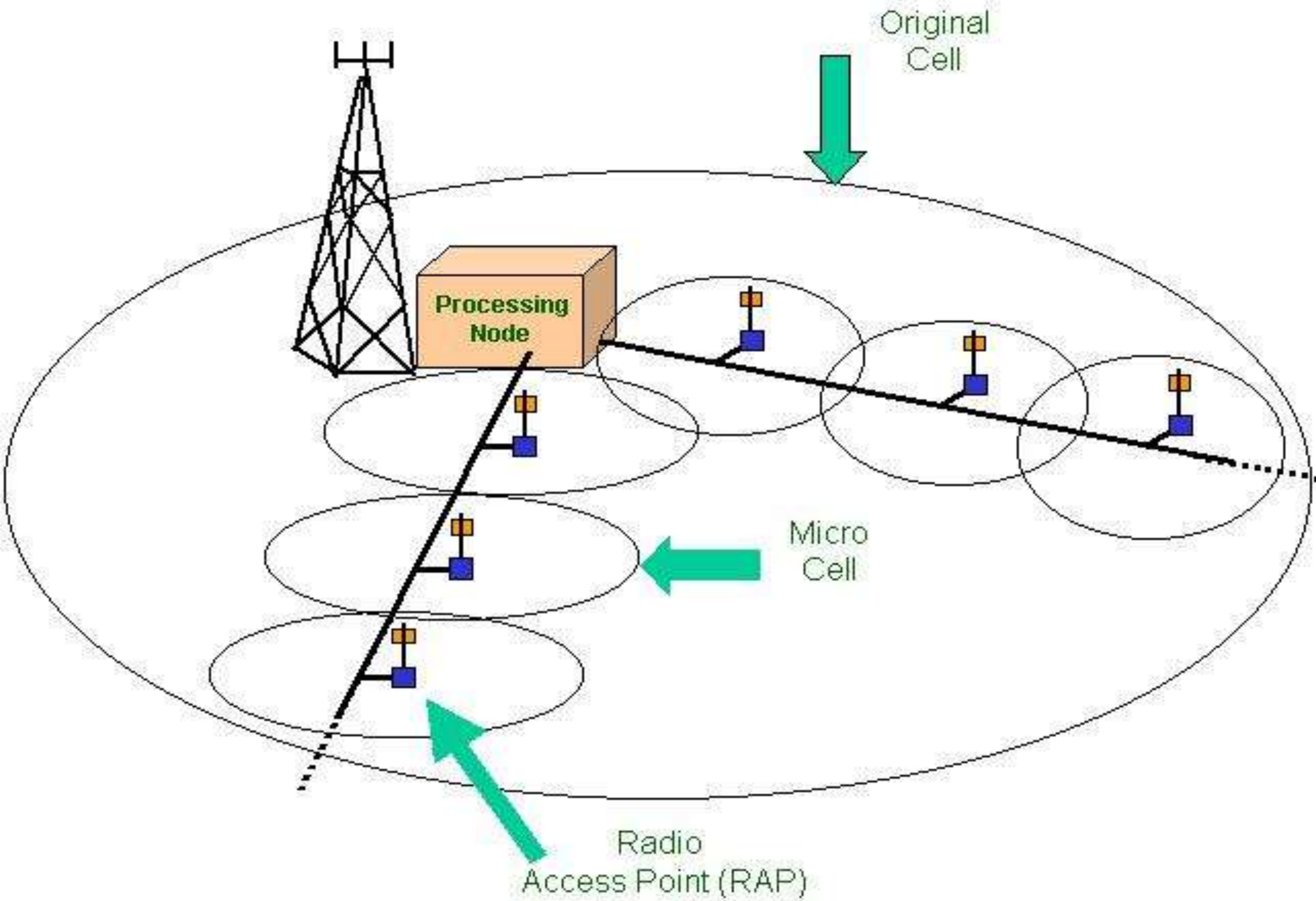
Optical Access Network

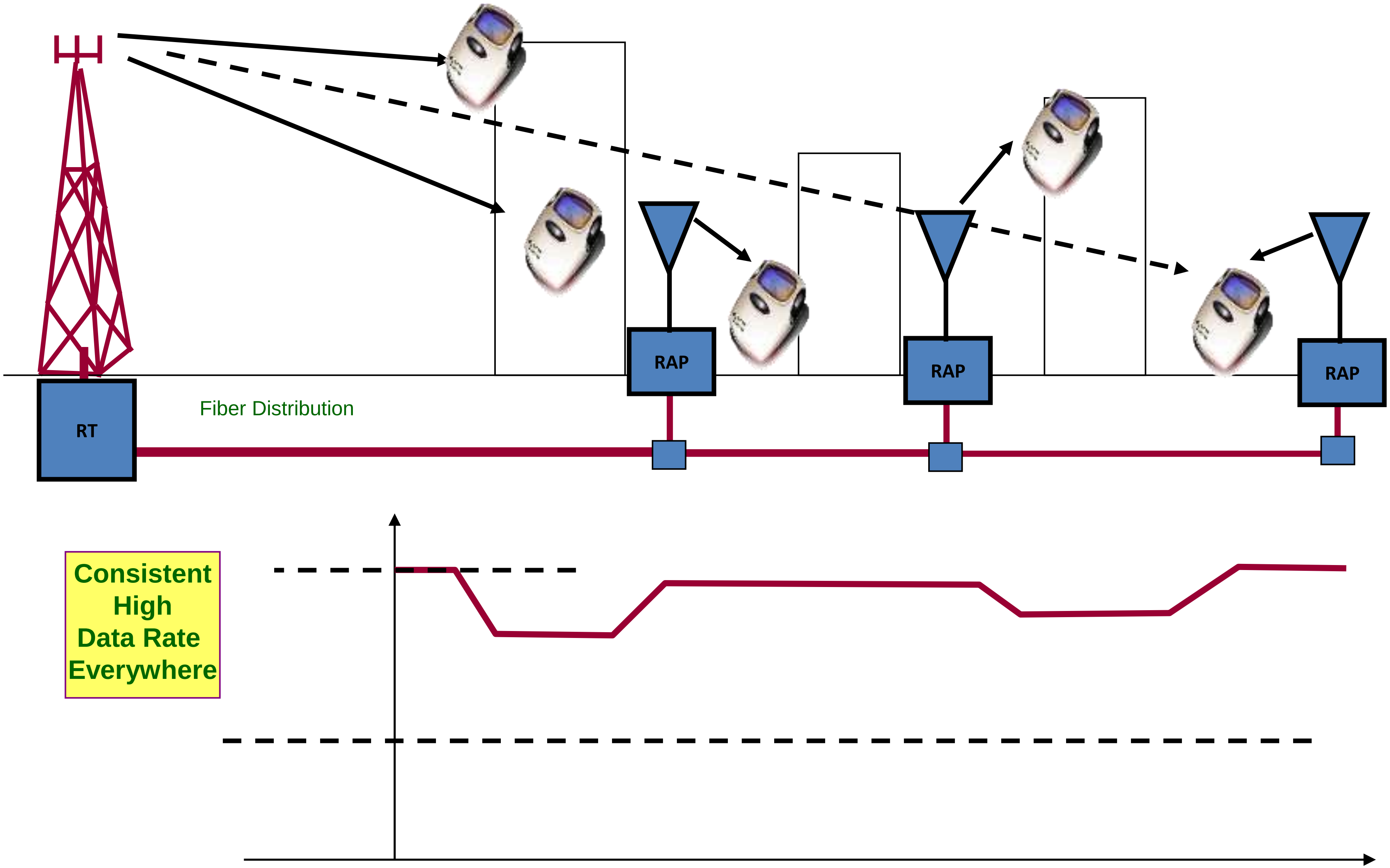


Radio over Fiber (ROF) for Wireless Systems

A subset of MFO systems – However, the microwave signal is transmitted into the free-space to give wireless access and mobility. Gives unique challenges.

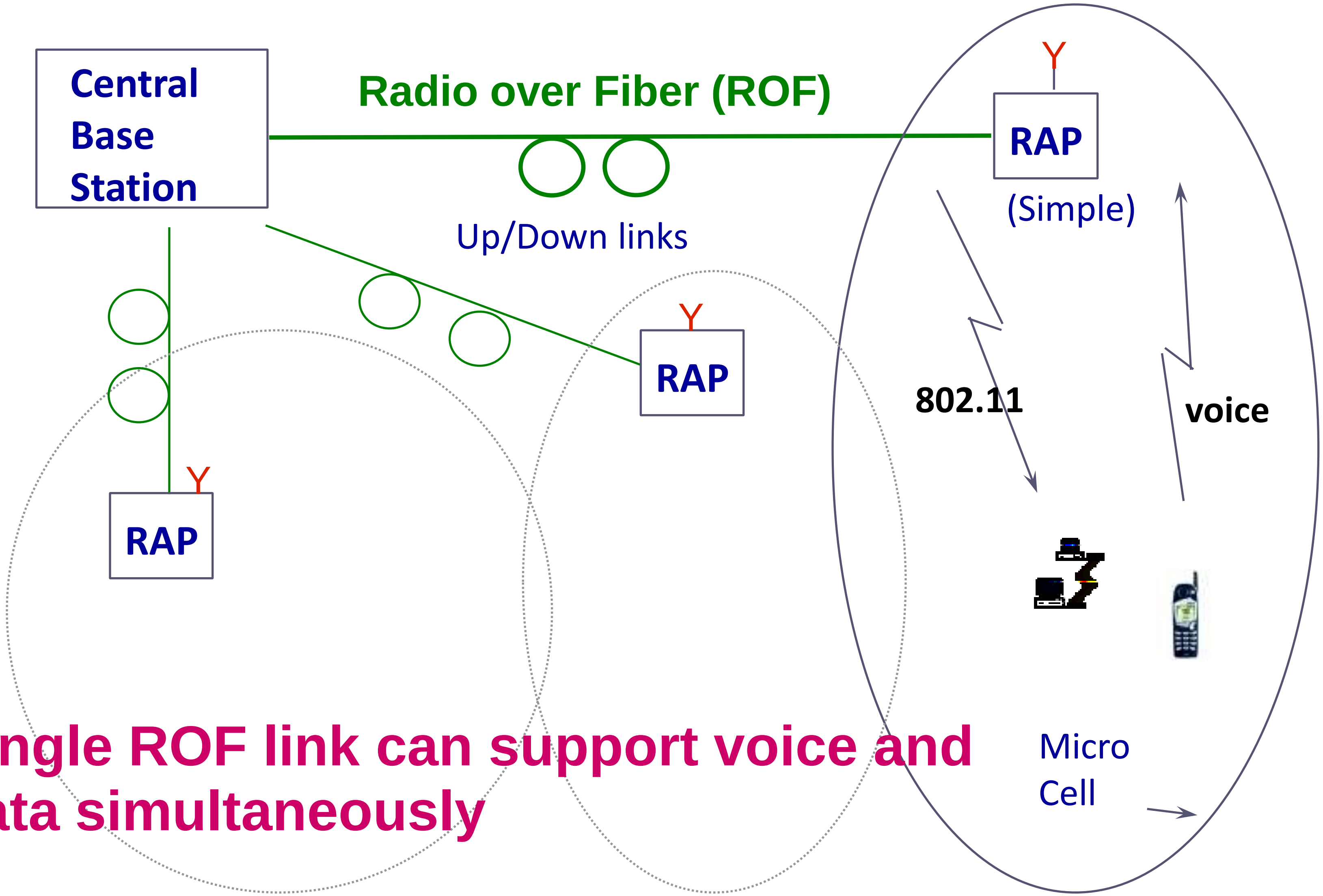
The Technology





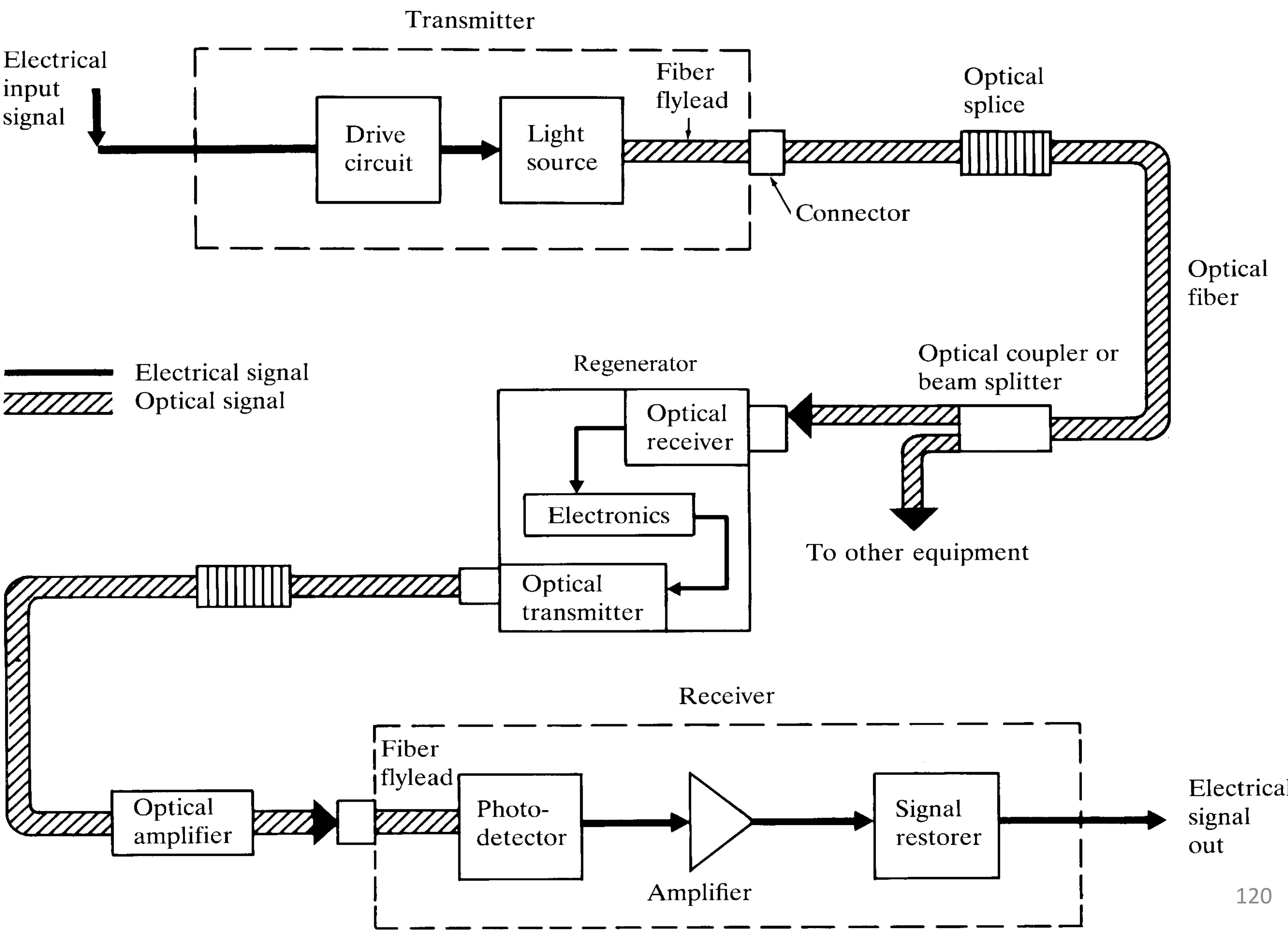
Dramatic Increase in Capacity !!

Multi Standard Fiber-Wireless

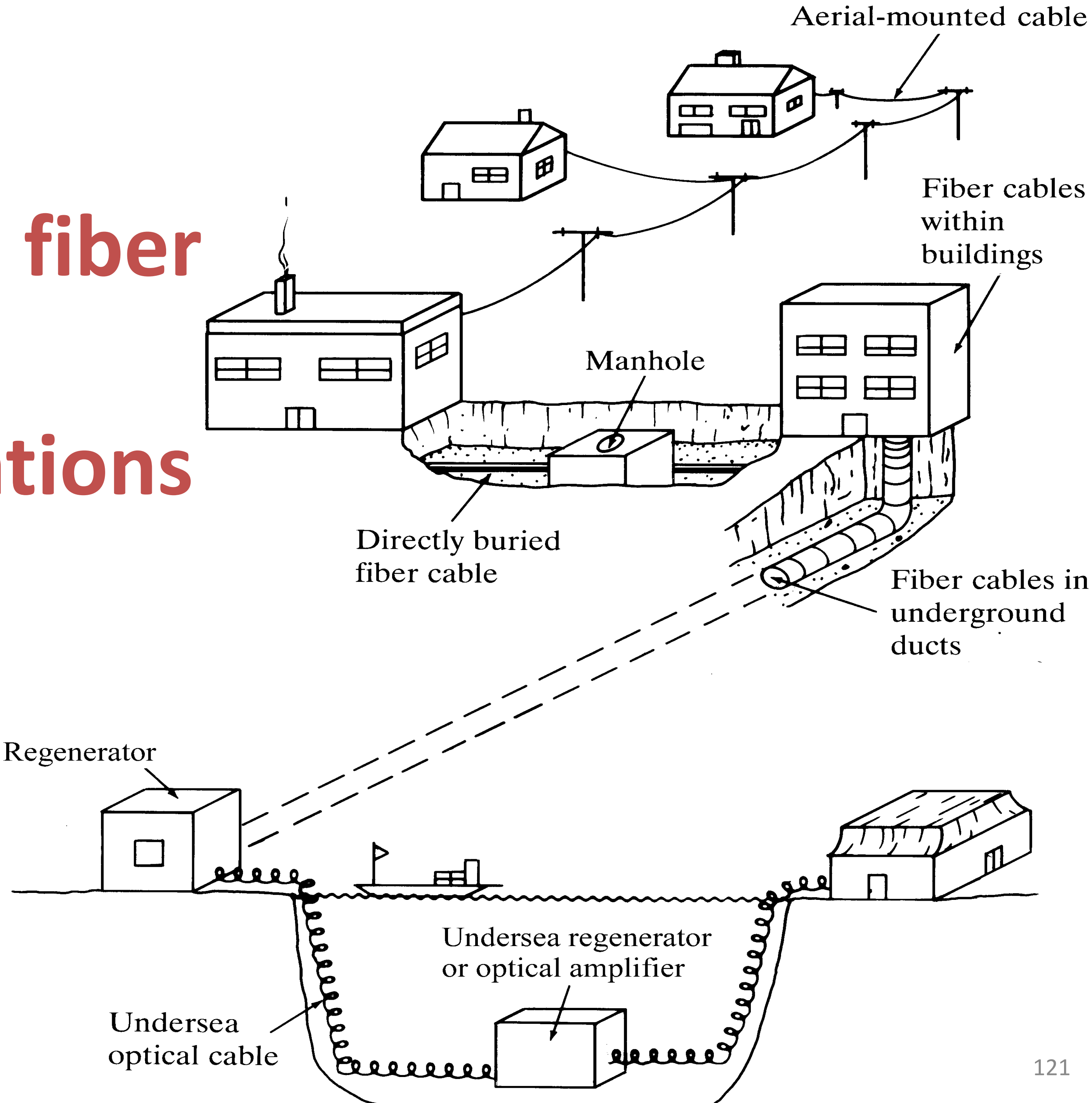


Single ROF link can support voice and data simultaneously

Major elements of an optical fiber link



Optical fiber cable installations



Telecom / Data Networks

Telecom networks

- Have been around for more than a century
- Rich in service features for voice communications, but high in cost
- Switching is used to eliminate the need for direct connections between all nodes in the network
- Basic unit is the 64-kb/s voice circuit
  - 64-kb/s circuits are multiplexed into higher-bit-rate formats (SONET/SDH)

Data networks

- Have evolved since the early 1960's from time-sharing systems to the Internet
- Bare-bones service at very low cost
- Basic unit is the packet or frame, not a fixed amount of bandwidth
- Routing is used to eliminate the need for direct connections between all
- nodes in the network

‘Good Old Days’ of Telecom Systems

Analog voice circuits between customers and central office

- Maximum frequency transmitted: 4 kHz
- Carried on a single twisted copper-wire pair

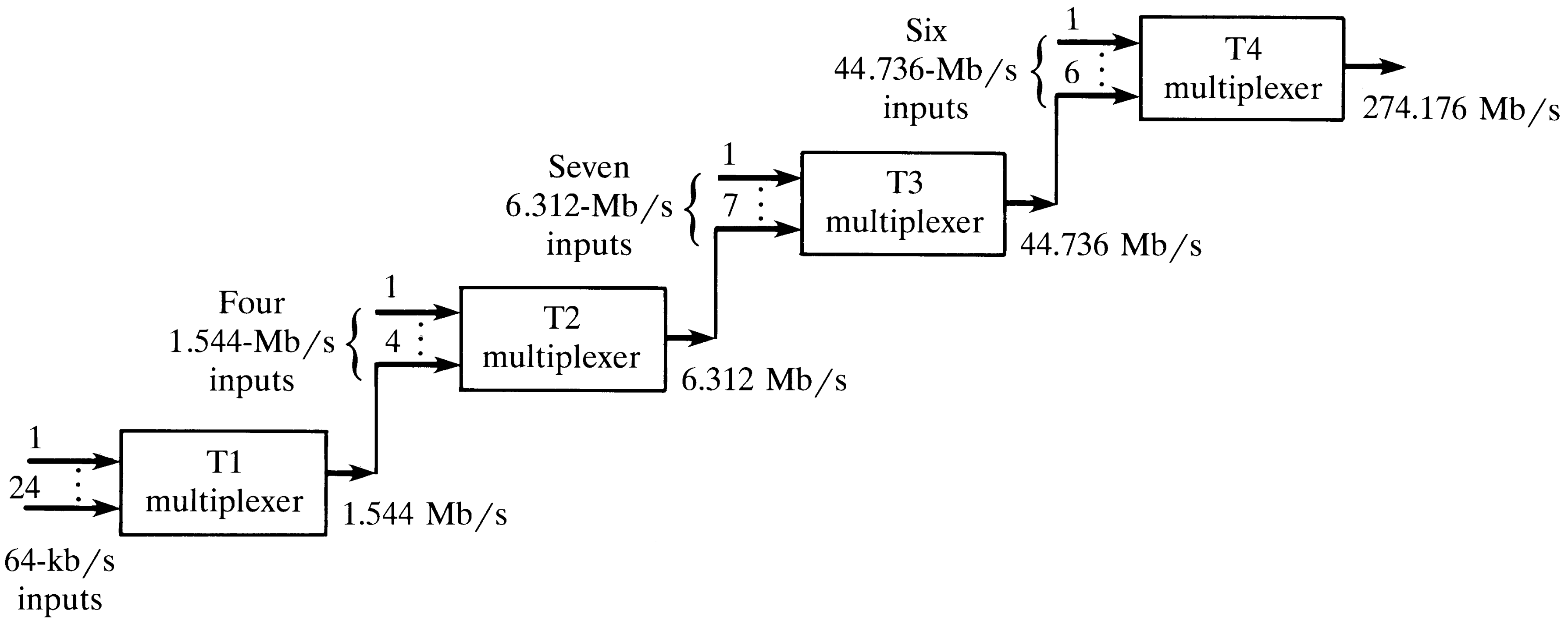
Analog inter-central-office trunks:

- Required repeaters every 2 km
- Duct diameter (10 cm) limited the number of circuits

Bell Labs solution (1962): Digital interoffice trunks using DS-1 (D*igital* S*ignal Type* 1) signals

- A voice signal digitized at a sampling rate of 8 kHz is DS-0 (64 kbits/s)
- T-1 carrier systems used since 1962: DS-1 carried on twisted pair wires,
- with repeaters every 2 km to remove electromagnetic crosstalk and to
- compensate for attenuation

Digital Transmission Hierarchy



Called Telephony or T-Networks

Uses Copper

First Generation Fiber Optic Systems

Purpose:

- Eliminate repeaters in T-1 systems used in inter-office trunk lines

Technology:

- 0.8 μm GaAs semiconductor lasers
- Multimode silica fibers

Limitations:

- **Fiber attenuation**
- Intermodal dispersion

Deployed since 1974

Second Generation Systems

Opportunity:

- Development of low-attenuation fiber (removal of H2O and other impurities)
- Eliminate repeaters in long-distance lines

Technology:

- 1.3 μm multi-mode semiconductor lasers
- Single-mode, low-attenuation silica fibers
- DS-3 signal: 28 multiplexed DS-1 signals carried at 44.736 Mbits/s

Limitation:

- **Fiber attenuation** (repeater spacing ≈ 6 km)

Deployed since 1978

Third Generation Systems

Opportunity:

- Deregulation of long-distance market

Technology:

- 1.55 μm single-mode semiconductor lasers
- Single-mode, low-attenuation silica fibers
- OC-48 signal: 810 multiplexed 64-kb/s voice channels carried at 2.488 Gbits/s

Limitations:

- **Fiber attenuation** (repeater spacing ≈ 40 km)
- **Fiber dispersion**

Deployed since 1982

Fourth Generation Systems

Opportunity:

- Development of erbium-doped fiber amplifiers (EDFA)

Technology (deployment began in 1994):

- 1.55 μm single-mode, narrow-band semiconductor lasers
- Single-mode, low-attenuation, dispersion-shifted silica fibers
- Wavelength-division multiplexing of 2.5 Gb/s or 10 Gb/s signals

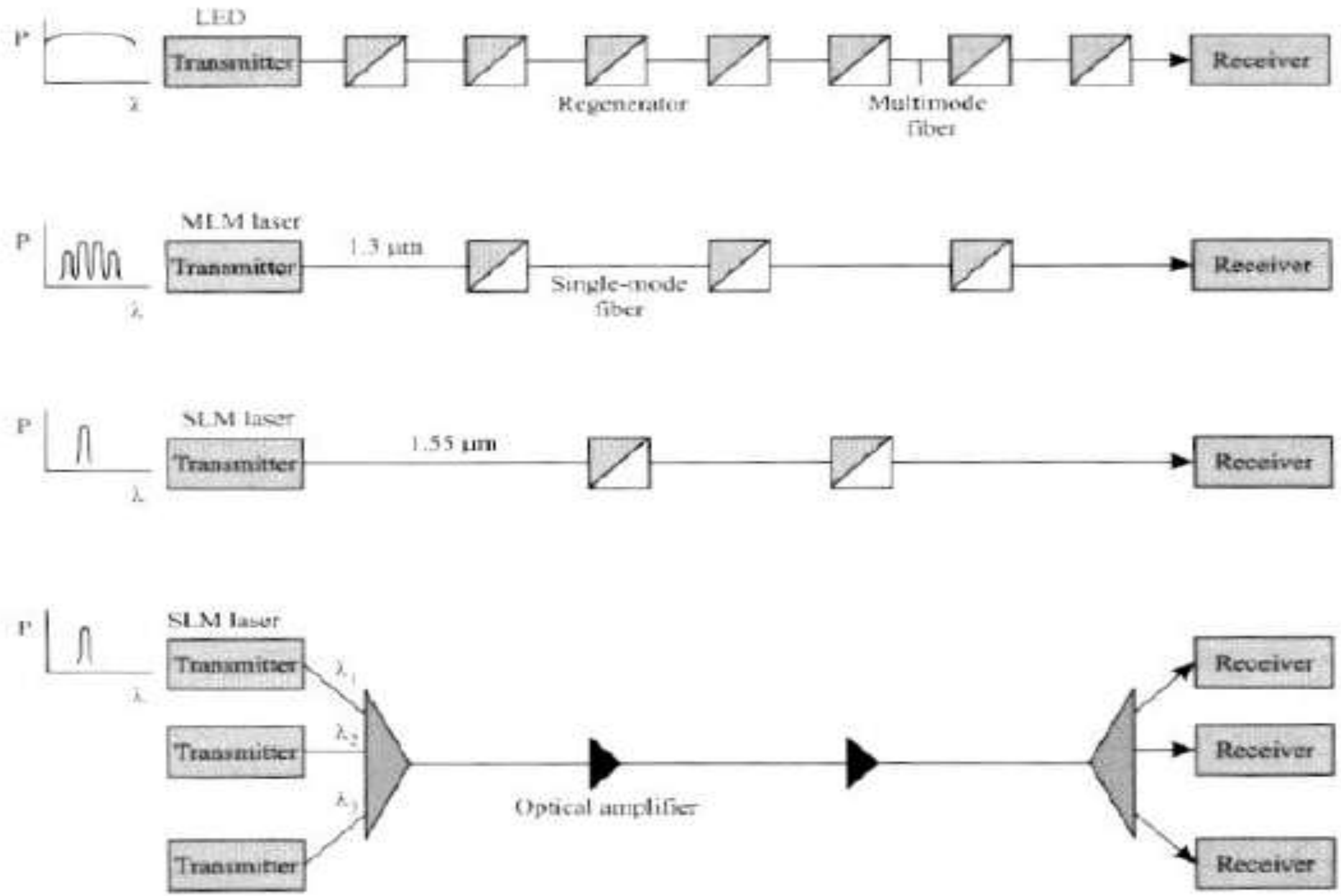
Nonlinear effects limit the following system parameters:

- Signal launch power
- Propagation distance without regeneration/re-clocking
- WDM channel separation
- Maximum number of WDM channels per fiber

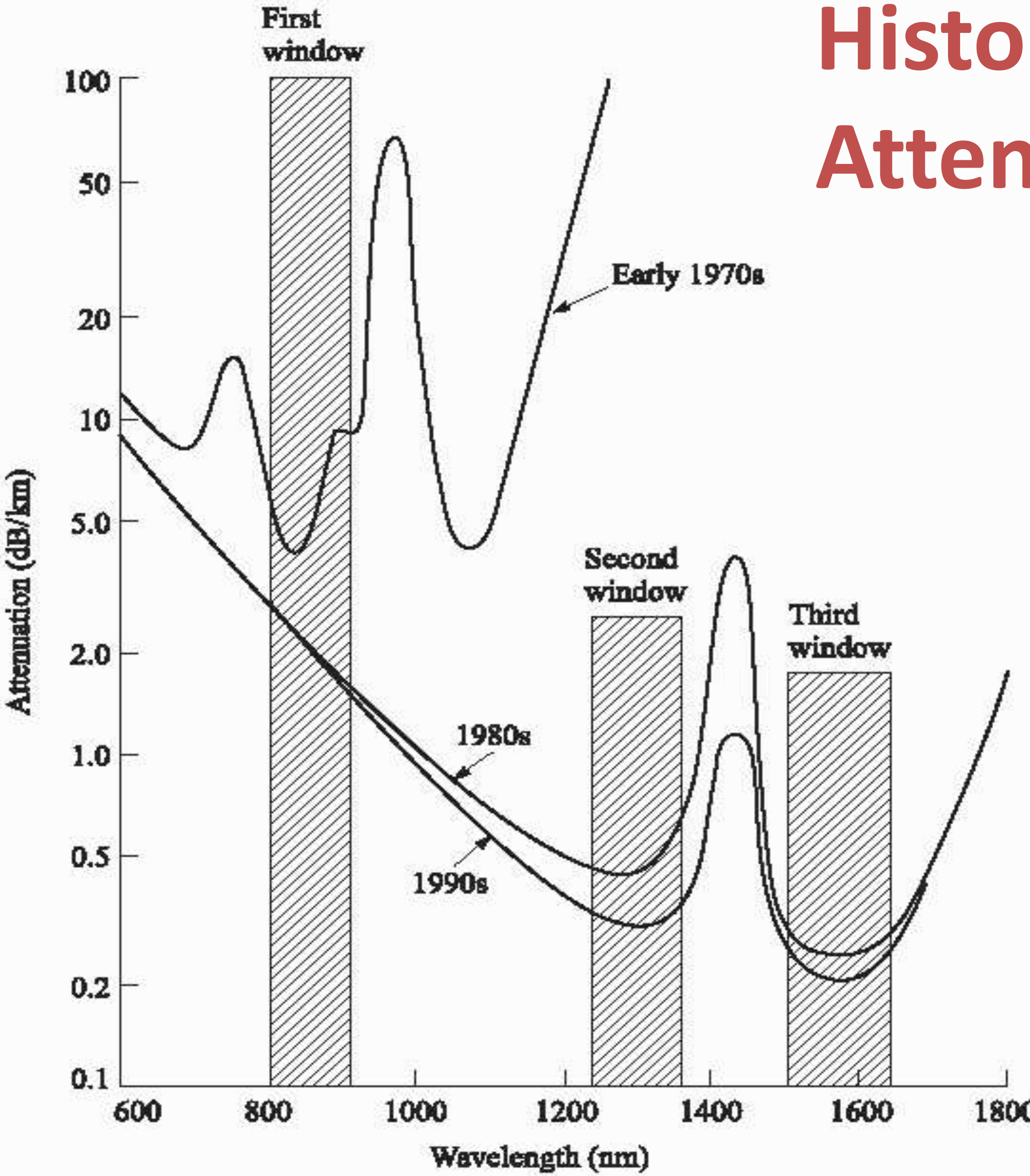
Polarization-mode dispersion limits the following parameters:

- Propagation distance without regeneration/re-clocking

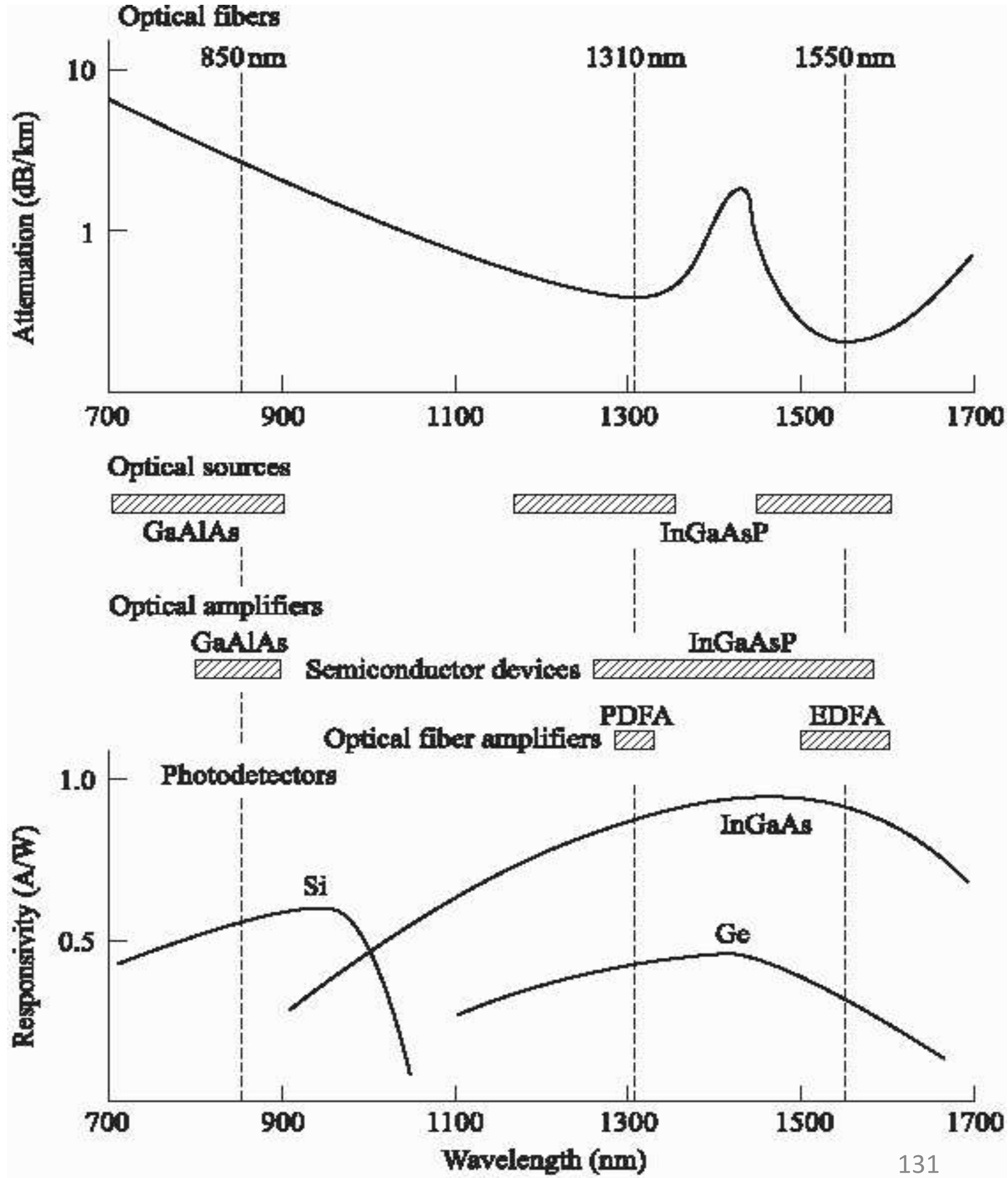
Evolution of Optical Networks



History of Attenuation

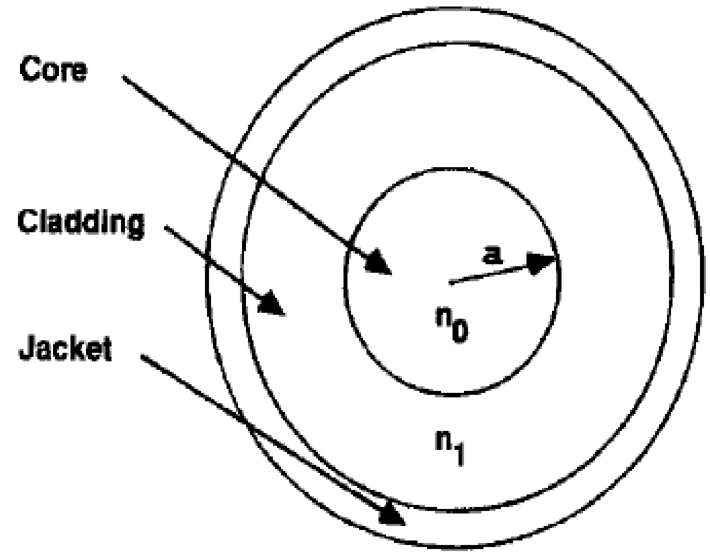


Three Windows based on Wavelength



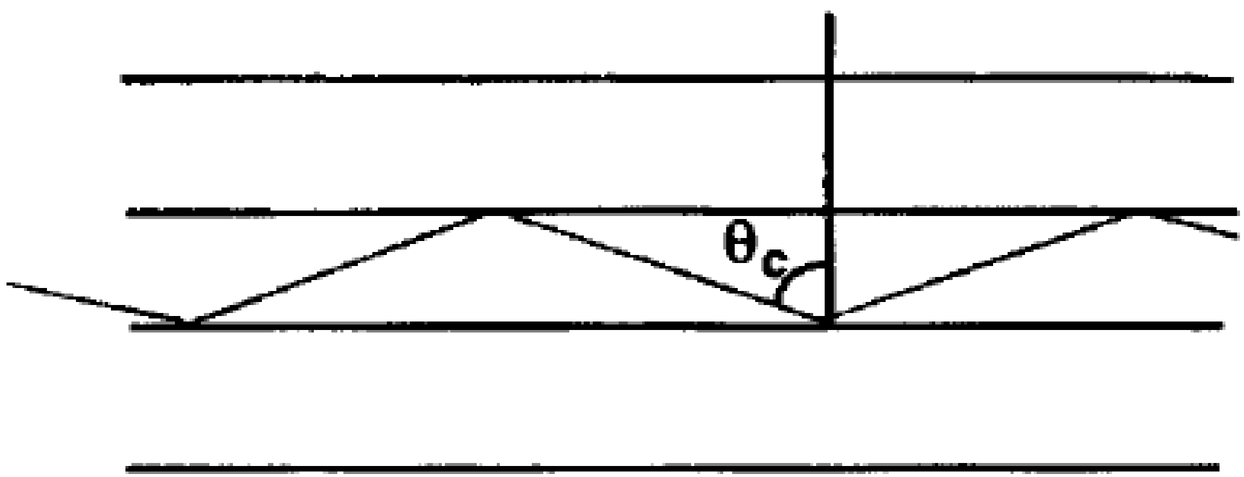
Basics of optical fiber transmission I

- What is an optical fiber?
  - A glass or plastic fiber that has the ability to guide light along its axis.
- A fiber cable consists of three layers:
  - core,
  - cladding,
  - jacket.



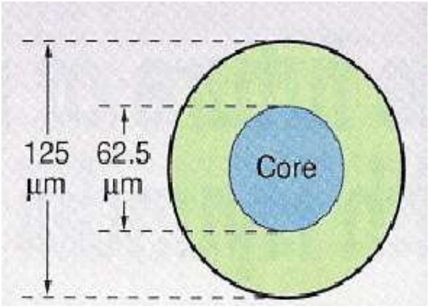
Basics of optical fiber transmission II

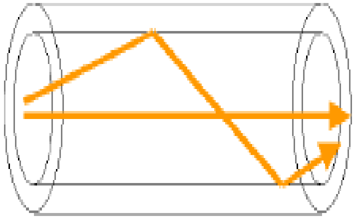
- Total Internal Reflection: when $\theta_c \geq \sin^{-1}(n_1/n_0)$ then the light is totally reflected in the core, where n_0, n_1 refractive index of the core and cladding respectively.



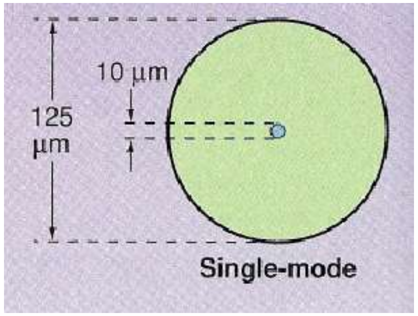
Fiber Types

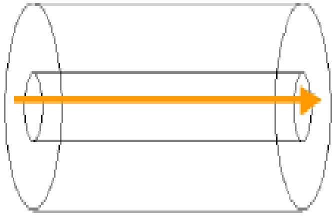
- Multi-Mode: supports hundreds paths for light.





- Single-Mode: supports a single path for light



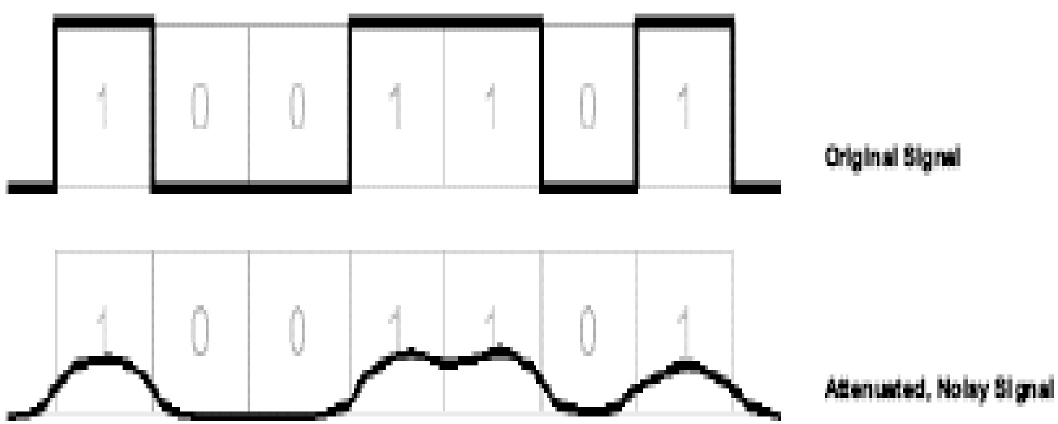


Multi-Mode vs Single-Mode

	Multi-Mode	**Single-Mode**
Modes of light	Many	One
Distance	Short	Long
Bandwidth	Low	High
Typical Application	Access	Metro, Core

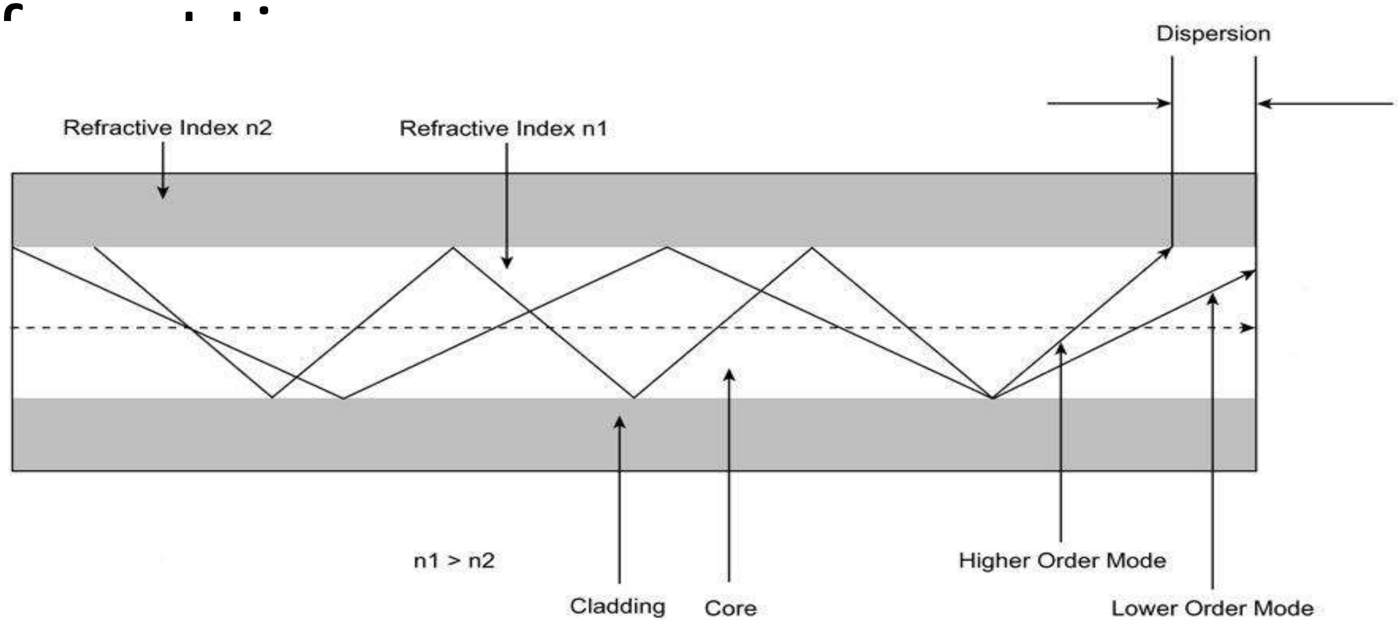
Attenuation

- It is the reduction of light power over the length of the fiber.
  - It's mainly caused by scattering.
  - It depends on the transmission frequency.
  - It's measured in dB/km. ($dB = 10\log_{10}(P_{out}/P_{in})$)



Multimode Dispersion

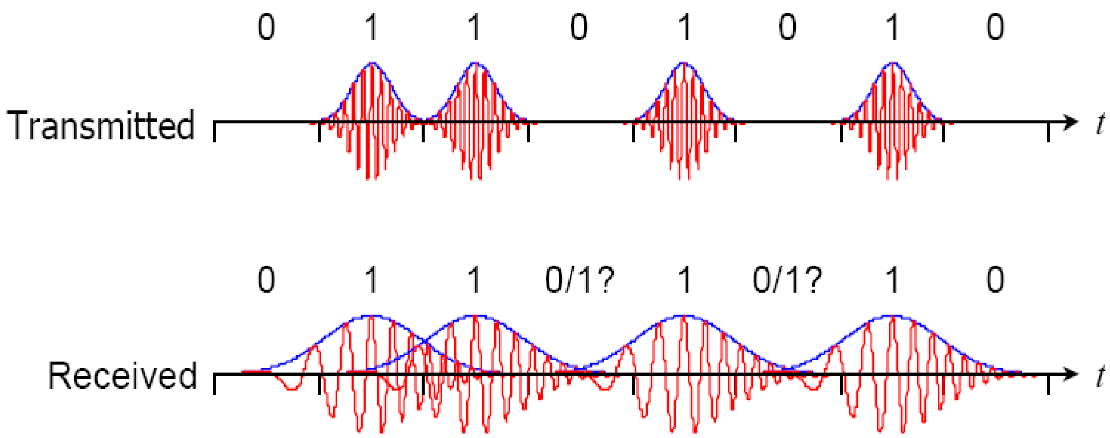
- Light rays are transmitted from the source at a variety of angles and arrive at the receiver at



Source www.cisco.com

Chromatic Dispersion (CD)

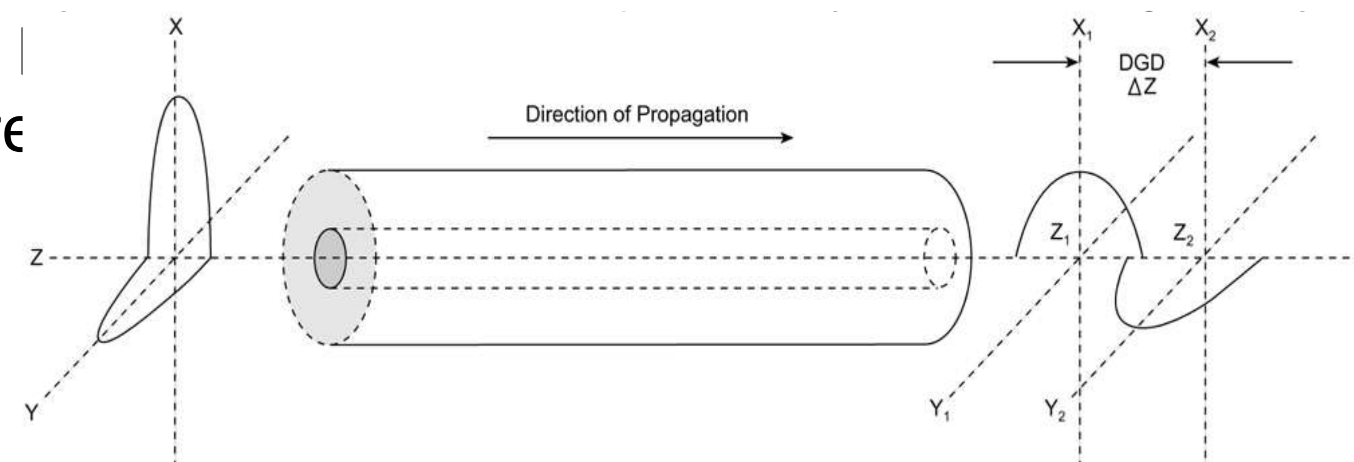
- Light from lasers consists of a range of wavelengths, each of which travels at a slightly different speed. This results to light pulse spreading over time.
  - It's measured in psec/nm/km.
- The chromatic dispersion effects increase for high rates.



Source www.teraxion.com

Polarization Mode Dispersion (PMD)

- Single-mode fibers support two orthogonal polarizations of the transmitted signal. Polarization modes travel with different speeds resulting in dispersion.
  - It's measured in $ps/\sqrt{km}$
- This … s or more



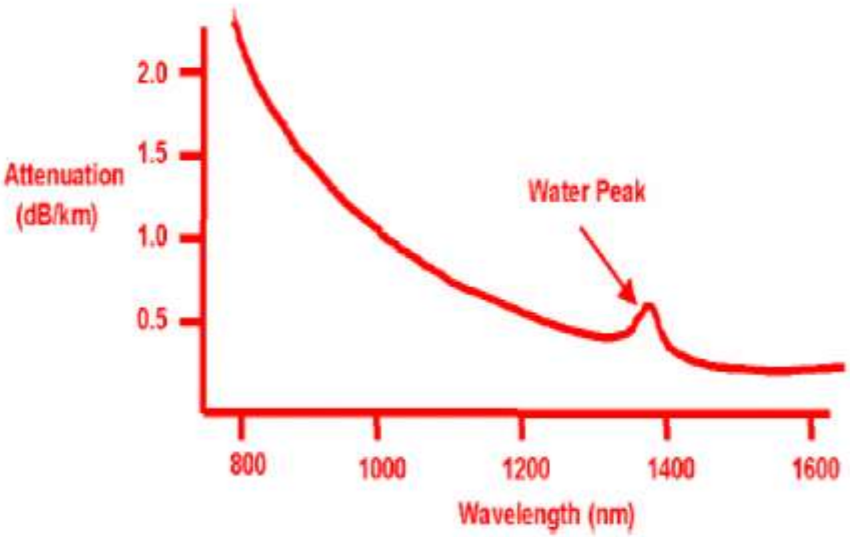
Transmission Bands

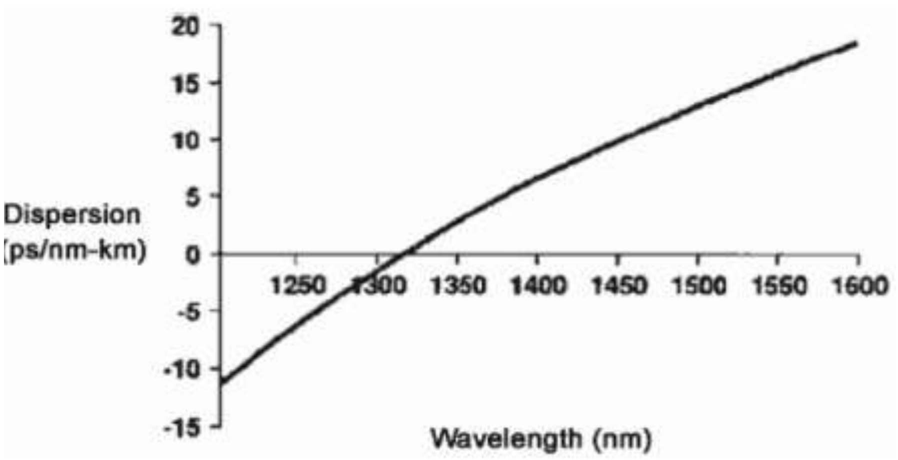
- Optical transmission is conducted in wavelength regions, called "bands".
- Commercial DWDM systems typically transmit at the C-band
  - Mainly because of the Erbium-Doped Fiber Amplifiers (EDFA).
- Commercial CWDM systems typically transmit at the S, C and L bands.
- ITU-T has defined the wavelength grid for xWDM transmission
  - G.694.1 recommendation for DWDM transmission, covering S, C and L bands.
  - G.694.2 recommendation for CWDM transmission, covering O, E, S, C and L bands.

Band	*Wavelength (nm)*
O	1260 – 1360
E	1360 – 1460
S	1460 – 1530
C	1530 – 1565
L	1565 – 1625
U	1625 – 1675

Single Mode Fiber Standards I

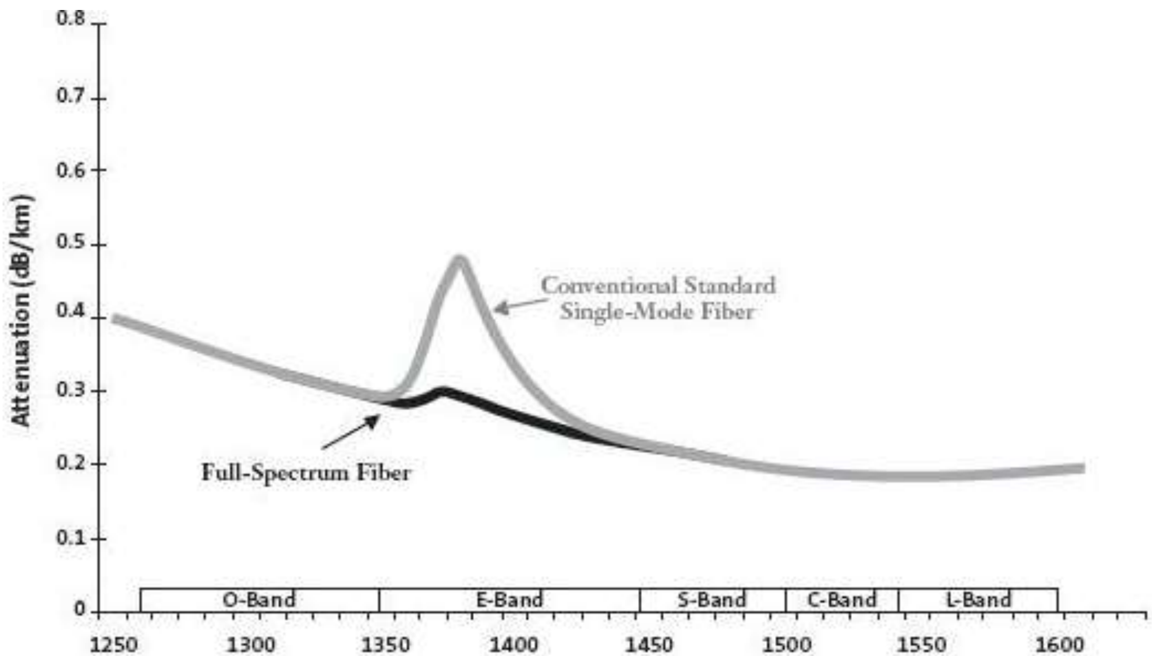
- ITU-T G.652 – standard Single Mode Fiber (SMF) or Non Dispersion Shifted Fiber (NDSF).
  - The most commonly deployed fiber (95% of worldwide deployments).
- "Water Peak Region": it is the wavelength region of approximately 80 nanometers (nm) centered on 1383 nm with high attenuation.





Single Mode Fiber Standards II

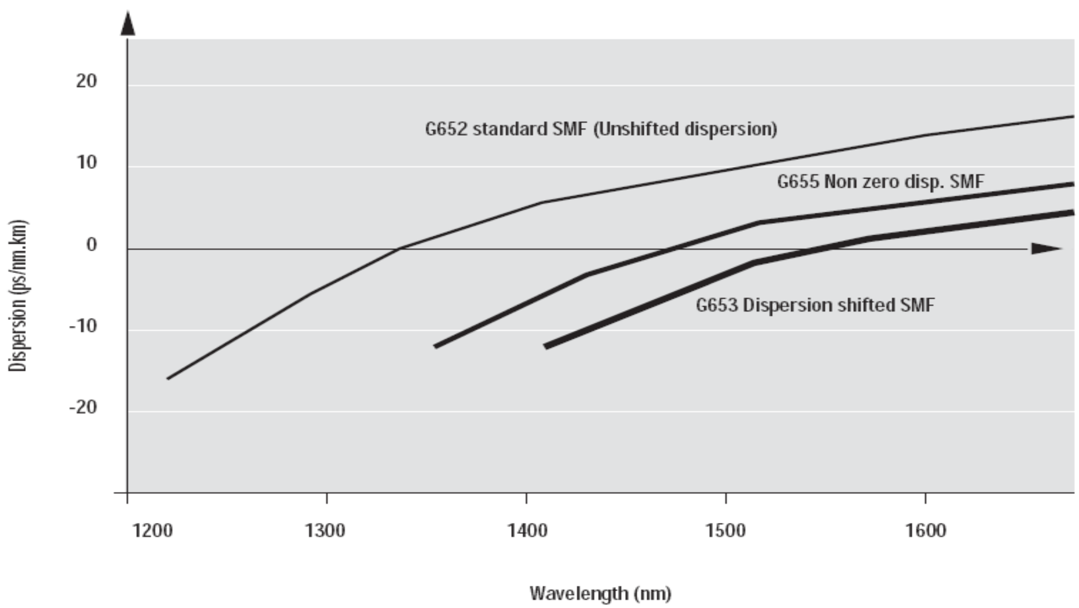
- ITU-T G.652c - Low Water Peak Non Dispersion Shifted Fiber.



Source www.corning.com

Single Mode Fiber Standards III

- ITU-T G.653 – Dispersion Shifted Fiber (DSF)
  - It shifts the zero dispersion value within the C-band.
  - Channels allocated at the C-band are seriously affected by noise due to nonlinear effects (Four Wave Mixing).



Single Mode Fiber Standards IV

- ITU-T G.655 – Non Zero Dispersion Shifted Fiber (NZDSF)
  - Small amount of chromatic dispersion at C-band: minimization of nonlinear effects
- Optimized for DWDM transmission (C and L bands)

Single Mode Fiber Standards V

ITU-T Standard	Name	Typical Attenuation value (C-band)	Typical CD value (C-band)	Applicability
G.652	standard Single Mode Fiber	0.25dB/km	17 ps/nm-km	OK for xWDM
G.652c	Low Water Peak SMF	0.25dB/km	17 ps/nm-km	Good for CWDM
G.653	Dispersion-Shifted Fiber (DSF)	0.25dB/km	0 ps/nm-km	Bad for xWDM
G.655	Non-Zero Dispersion-Shifted Fiber (NZDSF)	0.25dB/km	4.5 ps/nm-km	Good for DWDM

Fiber optic transmission advantages

- Really broadband medium.
- The fiber is immune to virtually all kinds of interference.
- A fiber optic cable is much smaller and lighter in weight than a wire or coaxial cable with similar information carrying capacity.
- Fiber optic cable is ideal for secure communications.
- Low production cost (~euro/km)

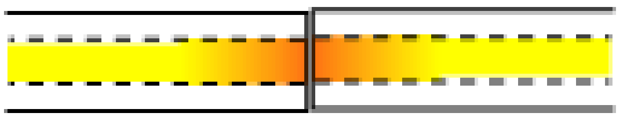
- **Fiber Cable Termination**

Fiber Cable Termination

- We terminate fiber optic cable two ways - with connectors that can mate two fibers to create a temporary joint and/or connect the fiber to a piece of network gear or with splices which create a permanent joint between the two fibers.
- These terminations must be of the right style, installed in a manner that makes them have little light loss and protected against dirt or damage in use.
- Each new design was meant to offer better performance (less light loss and back reflection), easier and/or termination and lower cost.
- Loss is minimized when the two fiber cores are identical and perfectly aligned, the connectors or splices are properly finished and no dirt is present.

Connector and Splice Loss Mechanisms

- Only the light that is coupled into the receiving fiber's core will propagate, so all the rest of the light becomes the connector or splice loss.
- End gaps cause two problems, insertion loss and return loss. The emerging cone of light from the connector will spill over the core of the receiving fiber and be lost.
- The air gap between the fibers causes a reflection when the light encounters the change n refractive index from the glass fiber to the air in the g
- back reflection or optical returr



Back Reflection (Return Loss)

Fiber Optic Connectors

- Connectors use a number of polishing techniques to insure physical contact of the fiber ends to minimize back reflection.
- The end finish of the fiber must be properly polished to minimize loss. A rough surface will scatter light and dirt can scatter and absorb light.
- Since the optical fiber is so small, typical airborne dirt can be a major source of loss.
- Whenever connectors are not terminated, they should be covered to protect the end of the ferrule from dirt.
- One should never touch the end of the ferrule, since the oils on one's skin causes the fiber to attract dirt.
- Before connection and testing, it is advisable to clean connectors with lint-free wipes moistened with isopropyl alcohol.

Fiber Optic Connectors

- SC is a snap-in connector that is widely used in single mode systems for it's excellent performance. It's a snap-in connector that latches with a simple push-pull motion.
- FC/PC has been one of the most popular single mode connectors for many years.
- It screws on firmly, but make sure you have the key aligned in the slot properly before tightening.
- It's being replaced by SCs and LCs.

Fiber Optic Connectors

- LC is a new connector that uses a 1.25 mm ferrule, half the size of the ST. Otherwise, it's a standard ceramic ferrule connector, easily terminated with any adhesive. Good performance, highly favored for singlemode.
- ST (an AT&T Trademark) is the most popular connector for multimode networks, like most buildings and campuses. It has a bayonet mount and a long cylindrical ferrule to hold the fiber.

Connector Ferrule Shapes & Polishes

- Ferrule: A tube which holds a fiber for alignment, usually part of a connector
- Fiber optic connectors can have several different ferrule shapes or finishes, usually referred to as polishes.
- Early connectors, because they did not have keyed ferrules and could rotate in mating adapters, always had an air gap between the connectors to prevent them rotating and grinding scratches into the ends of the fibers.
- Beginning with the ST and FC which had keyed ferrules, the connectors were designed to contact tightly, what we now call physical contact (PC) connectors.

Connector Ferrule Shapes & Polishes

- Reducing the air gap reduced the loss and back reflection (very important to laser-based singlemode systems), since light has a loss of about 5% (~0.25 dB) at each air gap and light is reflected back up the fiber.
- While air gap connectors usually had losses of 0.5 dB or more and return loss of 20 dB, PC connectors had typical losses of 0.3 dB and a return loss of 30 to 40 dB.

Zero Tolerance for Dirt

- Airborne particles are about the size of the core of SM fiber- they absorb lots of light and may scratch connectors if not removed
- Dirt on connectors is the biggest cause of scratches on polished connectors and high loss measurements
- 1. Try to work in a clean area. Avoid working around heating outlets, as they blow dust all over you
- 2. Always keep dust caps on connectors, bulkhead splices, patch panels or anything else that is going to have a connection made with it.
- 3. Use lint free pads and isopropyl alcohol to clean the connectors.
- 4. Ferrules on the connectors/cables used for testing will get dirty by scraping off the material of the alignment sleeve in the splice bushing - creating a 1-2 dB attenuator.

Terms for installation and termination

- Stripper: A cutter for removing the heavy outside jacket of cables
- Fiber Stripper: A precise stripper used to remove the buffer coating of the fiber itself for termination.
- Cleaver: A tool that precisely "breaks" the fiber to produce a flat end for polishing or splicing.
- Scribe: A hard, sharp tool that scratches the fiber to allow cleaving.
- Polishing Puck: for connectors that require polishing, the puck holds the connector in proper alignment to the polishing film.
- Polishing Film: Fine grit film used to polish the end of the connector ferrule.
- Crimper: A tool that crimps the connector to the aramid fibers in the cable to add mechanical strength.

Termination

- Most connectors use epoxies to hold the fiber in the connector.
- Use only the specified epoxy, as the fiber to ferrule bond is critical for low loss and long term reliability.
- Epoxy/Polish: Most connectors are the simple "epoxy/polish" type where the fiber is glued into the connector with epoxy and the end polished with special polishing film.
- These provide the most reliable connection, lowest losses (less than 0.5 dB) and lowest costs, especially if you are doing a lot of connectors.
- The epoxy can be allowed to set overnight or cured in an inexpensive oven. A "heat gun" should never be used to try to cure the epoxy faster as the uneven heat may not cure all the epoxy or may overheat some of it which will prevent it ever curing!

Fiber Optic Connectors & Splices

- Connectors
  - Demountable terminations for fiber
  - Connect to transmitters and receivers
- Splices
  - Permanent termination of two fibers

Fiber Optic Splices

- Permanent terminations for fiber
- Specifications
  - Loss
  - Repeatability
  - Environment
  - Reliability
  - Back reflection
  - Ease of termination
  - Cost

Cable, Connector & Splice Testing

- Continuity testing with visual tracer/fault locator
- Insertion loss with source and meter
- OTDR testing