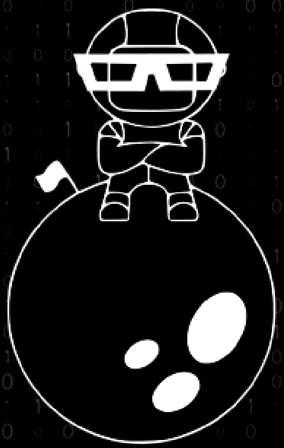


# Link Budget & Multiplexing

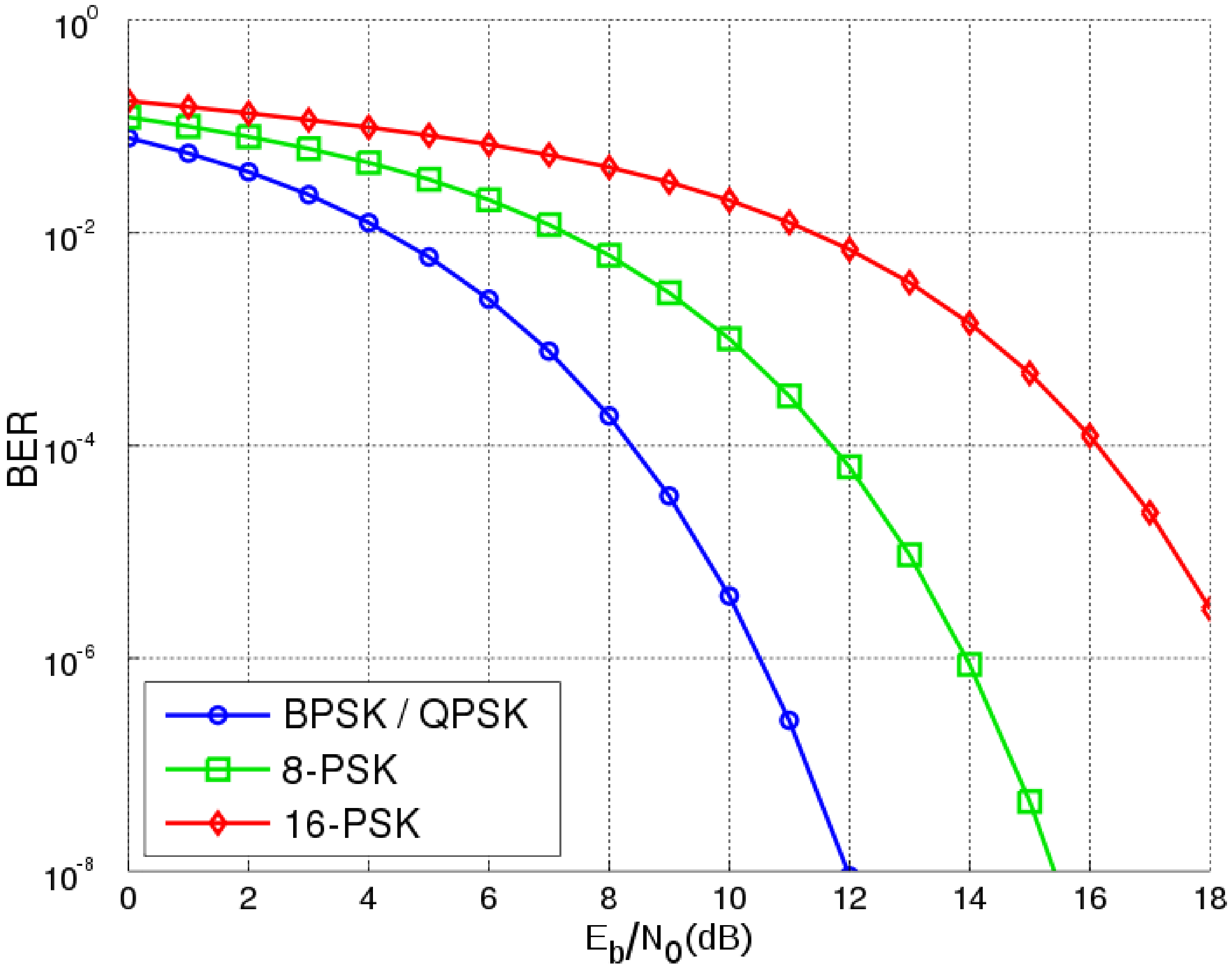
SPACE INFORMATICS

SIC Saarland Informatics Campus

# Digital Modulation Techniques

**BER vs Signal to Noise Ratio**

How small should a BER be? **(?)**




$$\frac{C}{N} = \frac{E_b}{N_0} \cdot \frac{f_b}{B}$$

Where

$C$= carrier power
$N$= noise power
$E_b$= energy per bit
$N_0$ = noise density/Hz
$f_b$= bit frequency
$B$= bandwidth

# Digital Modulation Techniques

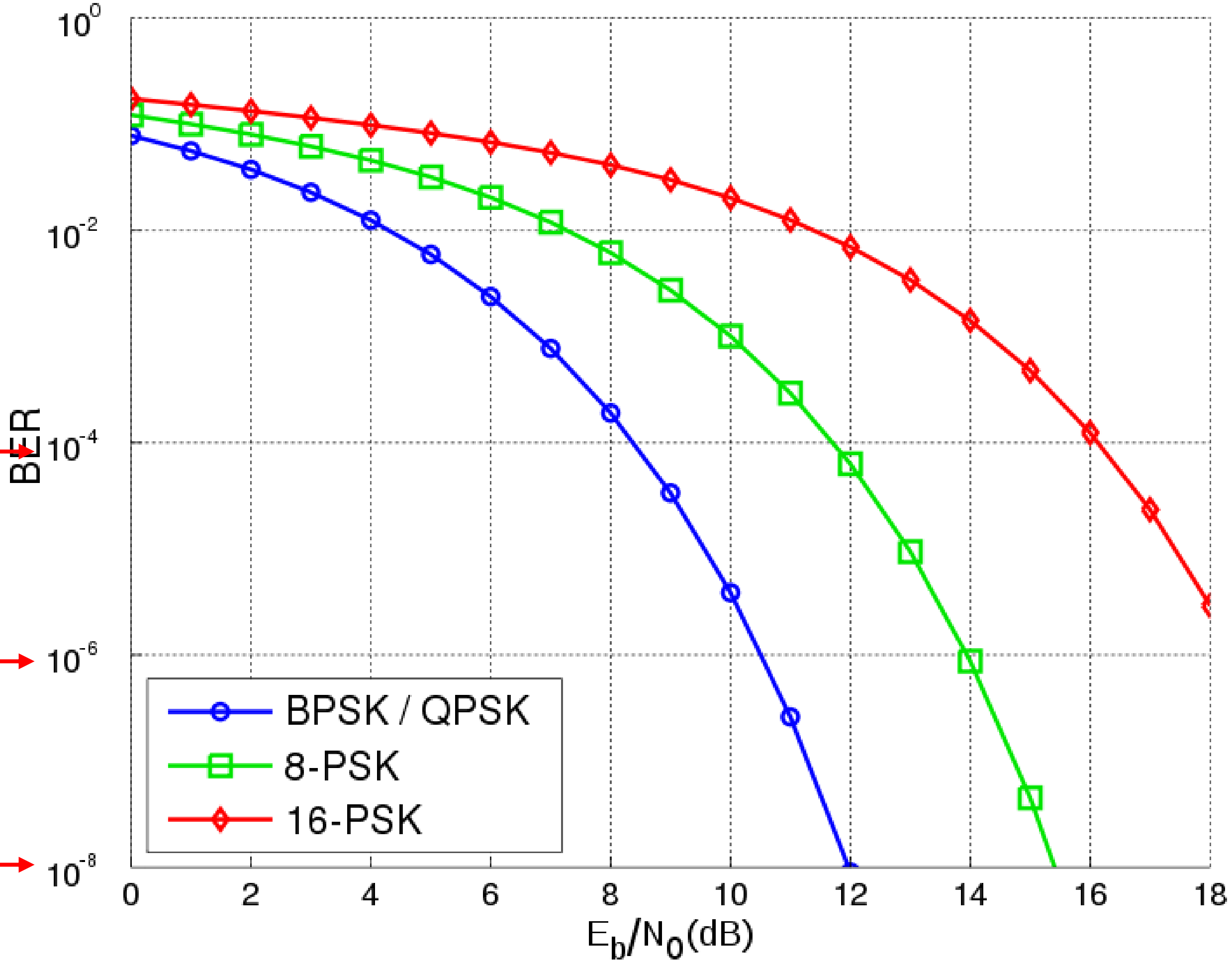
**BER vs Signal to Noise Ratio**

How small should a BER be? **(?)**

Acceptable if upper layers support error correction/recovery

Acceptable

Excellent




$$\frac{C}{N} = \frac{E_b}{N_0} \cdot \frac{f_b}{B}$$

Where

$C$ = carrier power

$N$ = noise power

$E_b$ = energy per bit

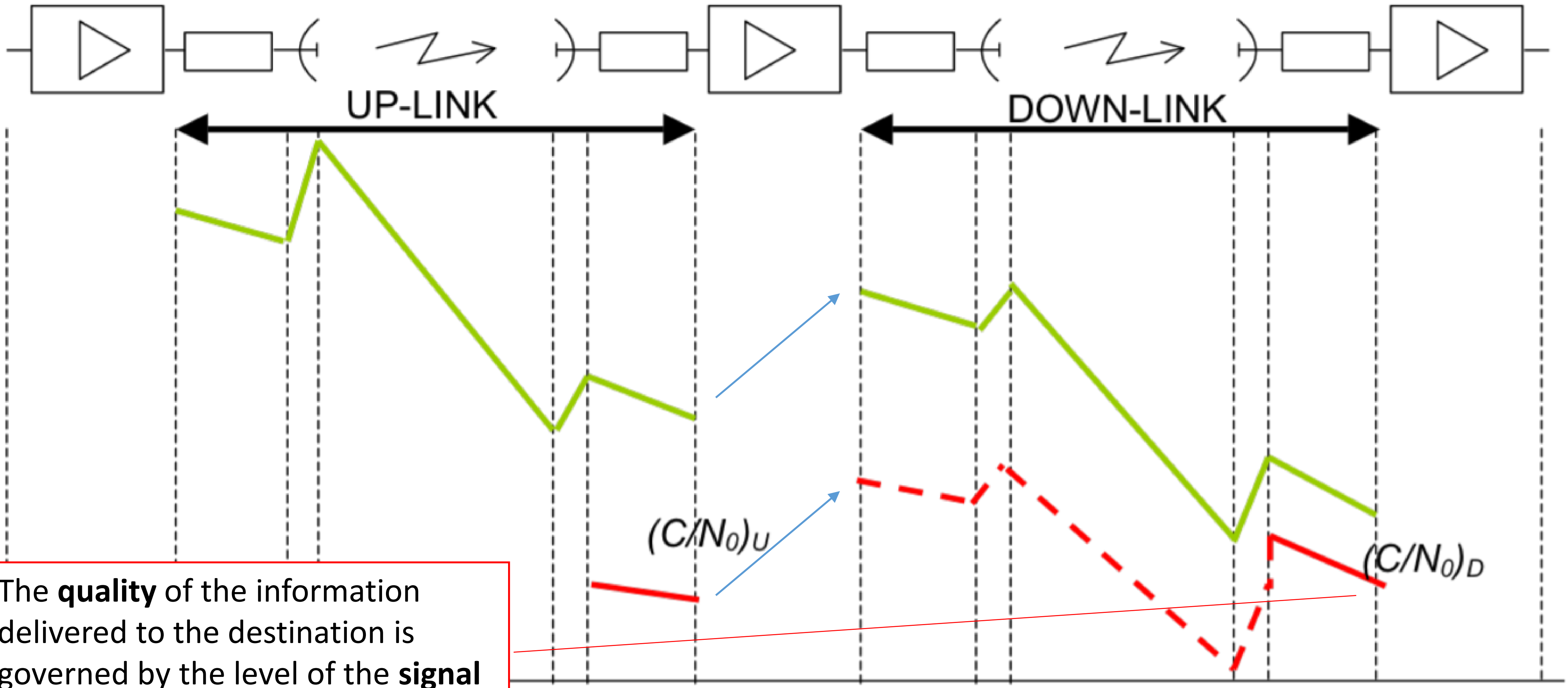
$N_0$ = noise density/Hz

$f_b$ = bit frequency

$B$ = bandwidth

# Link Budget

**Radio Link Chain (Repeater case)**




The **quality** of the information delivered to the destination is governed by the level of the **signal and noise power received**

# Link Budget

## Introduction

- The designer must therefore attempt to **optimize the overall link**, giving due attention to each element of the link and the factors associated with its performance
  - **Transmitter** (baseband, modulator, **power amplifier** and antenna)
  - **Channel** (transmission loss, atmospheric losses, noise from external sources)
  - **Receiver** (antenna, **received power**, **received and added noise**, **sensitivity**, low-noise amplifier, demodulator)
  - Uplink and downlink chains!

# Transmission Equation

## Power Flux Density

- If a transmitter radiates a power $P_T$ watts with an antenna having a gain $G_T$ (respect the isotropic radiation level), the power flux density ($P_{RD}$ in $\mathrm{W/m^2}$) due to the radiated power in the direction of the **antenna bore-sight** at a distance $d$ in meters is given by

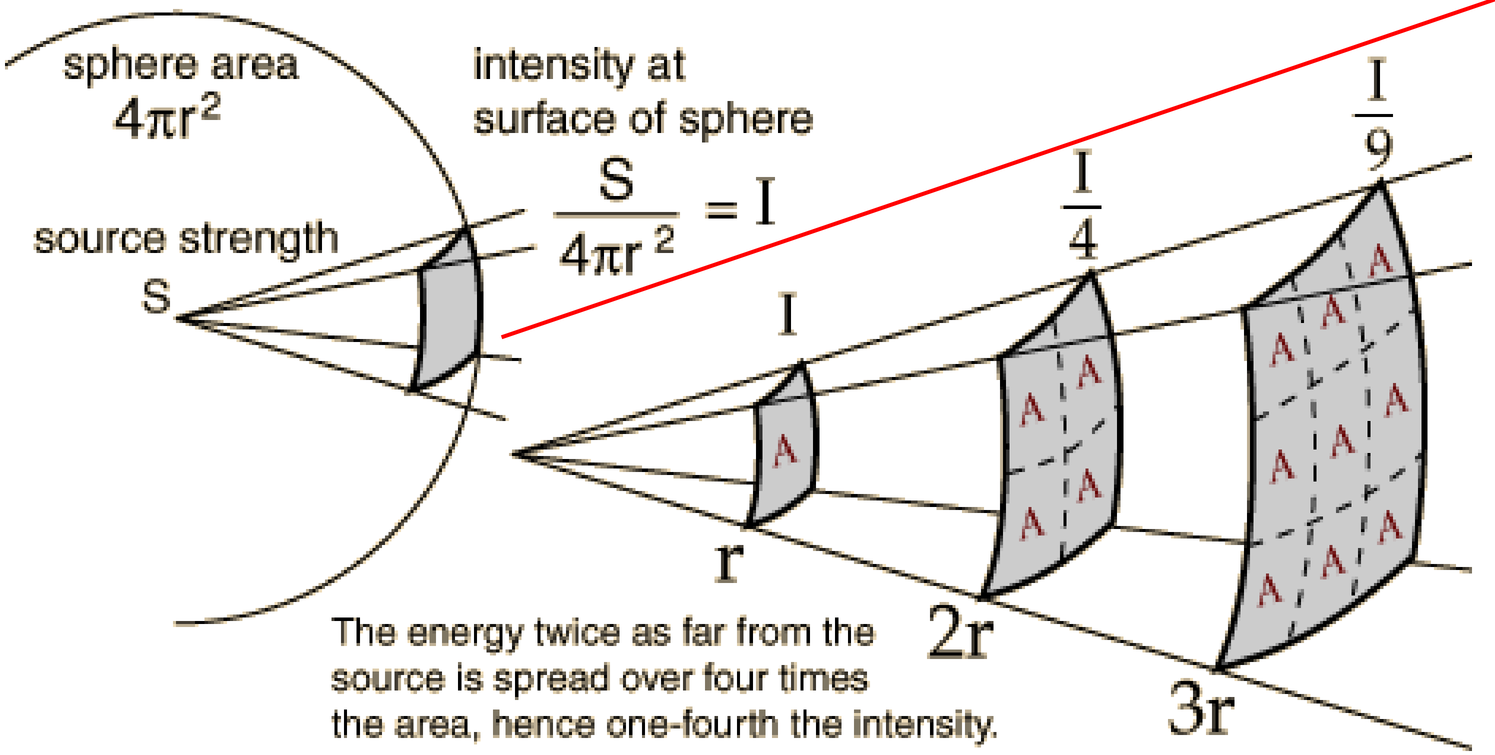
$$P_{RD}[\frac{W}{\mathrm{m}^2}] = \frac{P_T G_T}{4\pi d^2} = \frac{EIRP\ [W]}{4\pi d^2\ [\mathrm{m}^2]}$$

- The product $P_T G_T$ is the **Effective Isotropic Radiated Power** (EIRP)

# Transmission Equation

**Power Flux Density**

- The **inverse square law** comes from strictly geometrical considerations




**Antenna aperture**, effective area, or cross section

# Transmission Equation

## Received Power and Free Space Loss

- If $A_R$ is the **aperture of the receiving antenna**, then the received power $P_R$ at the receiver is

$$P_R = P_{RD}\, A_R = \left(\frac{P_T G_T}{4\pi d^2}\right) A_R$$

- The **antenna gain** is related to the **aperture** as follows

$G_R = 4\pi A_R \,/\, \lambda^2$ and also $c = \lambda \cdot f$, thus…

# Transmission Equation

## Received Power and Free Space Loss

- The resulting **transmission equation** (a.k.a. Friis equation) is

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi d)^2}$$

$$= \frac{P_T G_T G_R}{(4\pi d\,/\,\lambda)^2} = \frac{P_T G_T G_R}{(4\pi d\, f/c)^2}$$

Where $(4\pi d\,/\,\lambda)^2 = (4\pi d\, f/c)^2$ is known as **free space loss**

This is becoming quite messy already: lets see its expression in decibels…

# Decibels

## Dealing with Large Numbers

- **Decibel** units are typically used in most link budget calculations
  - Logarithmic scale
  - Conveniently transforms **multiplications** into **additions**
  - Facilitates working with **large ranges** ($\mathrm{W}$ down to $\mathrm{mW}$ or $\mu\mathrm{W}$)
- When working with power units:

$$L_P[\mathrm{dB}] = 10 \cdot \log_{10}\left(\frac{P}{P_0}\right)$$

  - If $P = P_0$ then $L_P = 0$
  - If $P > P_0$ then $L_P > 0$
  - If $P < P_0$ then $L_P < 0$
  - What is the value of $L_P$ if $P$ doubles $P_0 \rightarrow L_P = 3\mathrm{dB}$
  - What is the value of $L_P$ if $P$ halves $P_0 \rightarrow L_P = -3\mathrm{dB}$

# Decibels

## Dealing with Large Numbers

- When working with power units, a decibel can be referred to the **milliwatt (mW) unit** $P_0 = 1\ \mathrm{mW}$ in which case it is labeled $\mathrm{dBm}$:

$$L_P[\mathrm{dBm}] = 10 \cdot \log_{10}\left(\frac{P}{1\ \mathrm{mW}}\right)$$

Where $P$ is expressed in $\mathrm{mW}$

- $10\ \mathrm{W} \rightarrow 40\ \mathrm{dBm}$
- $1\ \mathrm{W} \rightarrow 30\ \mathrm{dBm}$, maximum transmission power for a GSM phone
- $500\ \mathrm{mW} \rightarrow 27\ \mathrm{dBm}$, average cellular phone transmission power
- $200\ \mathrm{mW} \rightarrow 23\ \mathrm{dBm}$, maximum transmission power for IEEE 802.11n
- $100\ \mathrm{mW} \rightarrow 20\ \mathrm{dBm}$, maximum transmission power for IEEE 802.11b/g
- $100\ \mu\mathrm{W} \rightarrow -10\ \mathrm{dBm}$, minimal reception power for IEEE 802.11 variants

# Transmission Equation

**In Decibels**

Free-space loss $L_p$

- The received power $P_R$ expressed in decibels (dB) is thus

$$10\log(P_R) = 10\log(P_T) + 10\log(G_T) + 10\log(G_R) - 20\log(4\pi d\,/\,\lambda)$$

$$P_R(\text{in dBW}) = EIRP(\text{in dBW}) + G_R(\text{in dB}) - L_P(\text{in dB})$$

- Other losses could also be considered in the equation

$$P_R = EIRP + G_R - L_P - L_{OTHER}$$

# Transmission Equation

## Power Flux Density

- Use Communications in STK to create:
  - A new (default) satellite and facility
  - Add a pointing sensor (2° cone) in the facility
  - Add a complex transmitter in the satellite (5W, 2GHz, 1Mbps, 30° beam-width) and a complex receiver in the ground station (1m diameter)
  - Compute access between transmitter and receiver
  - Study values for the pass (access, link budget report)
    - (?) **EIRP** varies, why?
    - (?) **Frequency** varies slightly, why?
    - (?) How does **free-space loss** and **received power** vary with frequency?
  - → show in STK (Stk_Communications.vdf)

# Transmission Equation

**Example**

- A GEO satellite (default at 35788 km height), with a 10 W transponder and a 20 dB transmitting antenna

$$20\ \mathrm{dB} \rightarrow 100\ times$$

$$P_{RD} = \frac{P_T G_T}{4\pi d^2} = \frac{10\ \mathrm{W} \times 100}{4\pi(35788\ \mathrm{km})^2} = 6.213 \times 10^{-14}\,\frac{\mathrm{W}}{\mathrm{m}^2},\ P_{RD} = -102.1\,\frac{\mathrm{dBm}}{\mathrm{m}^2}$$

- If the receiving antenna has an effective aperture of $10\ \mathrm{m}^2$

$$P_R = P_{RD}\,A_R = 6.213 \times 10^{-14}\,\frac{\mathrm{W}}{\mathrm{m}^2} \times 10\ \mathrm{m}^2 = 0.6213\ \mathrm{pW} \approx -92.1\ \mathrm{dBm}$$

# Satellite Link Parameters

**Choices and Considerations**

- Choice of **Operating Frequency**
  - **Coexistence** with other services (ITU)
  - **Interference-related** Problems
  - **Technology** state-of-the art
  - **Economical** constraints
  - **Propagation** Considerations
    - Atmospheric effects become an issue beyond 10 GHz

# Frequency Considerations

**C band** was very popular due to low atmosphere attenuation. Now is overcrowded

**X band, Ku and Ka** are newer bands gaining popularity for satellite systems (more bandwidth)

| Band | Frequency (GHz) |
|---|---|
| L band | 1–2 |
| S band | 2–4 |
| C band | 4–8 |
| X band | 8–12 |
| Ku band | 12–18 |
| K band | 18–27 |
| Ka band | 27–40 |
| V band | 40–75 |
| W band | 75–110 |

Frequencies are regulated by ITU which organizes assignations into **services** (UL/DL)

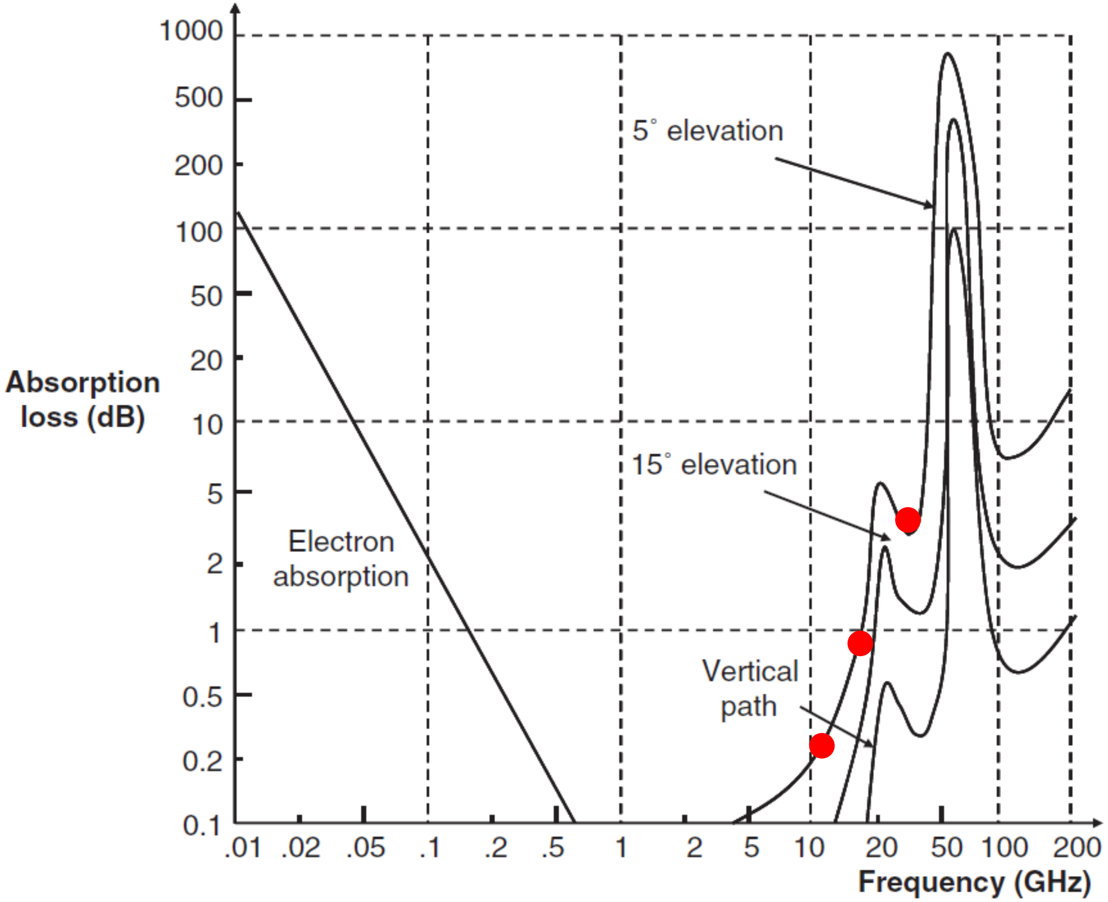
- FSS (fixed)
- ISL (inter-sat)
- MSS (mobile)
- BSS (broadcast)

and **regions**

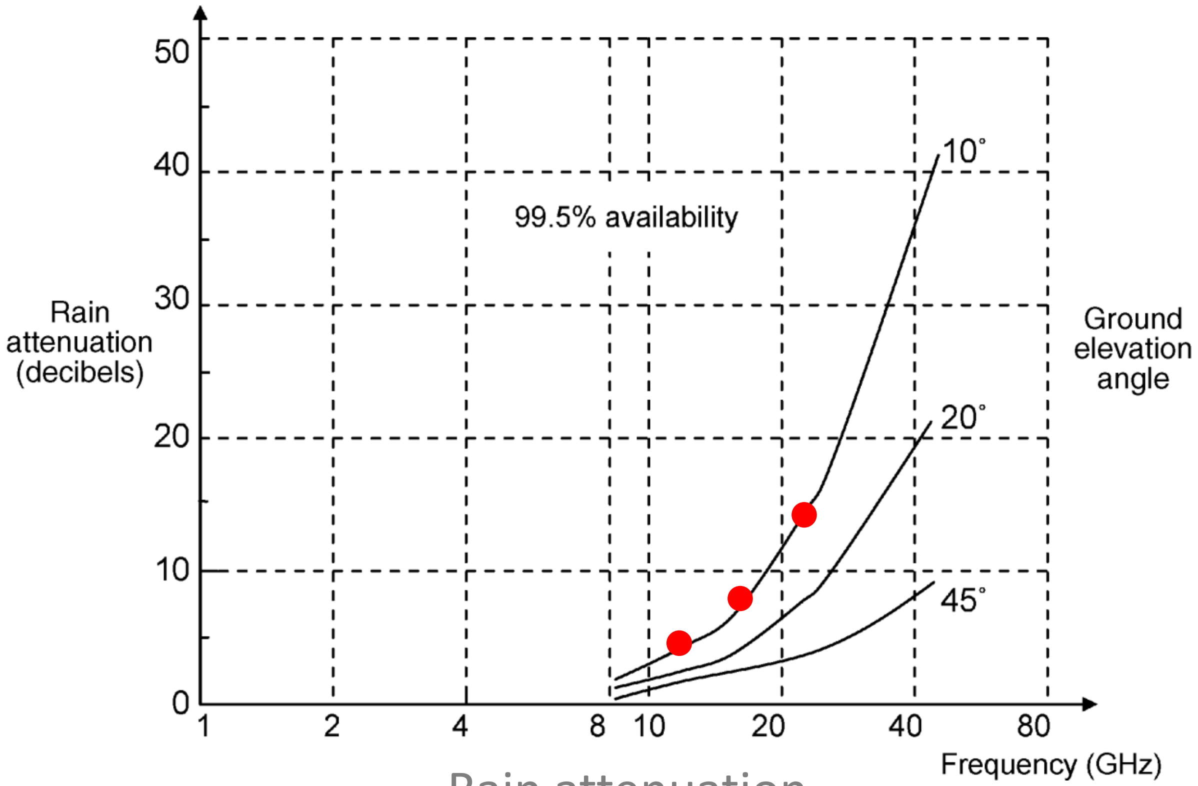
1. Europe, Africa
2. America, Greenland
3. Asia and Australia

# Propagation Considerations

## Gaseous Absorption and Rain Attenuation




Gaseous absorption




Rain attenuation

(see Recommendation ITU-R P.531 for a dozen of atmospheric effects)

# Propagation Considerations

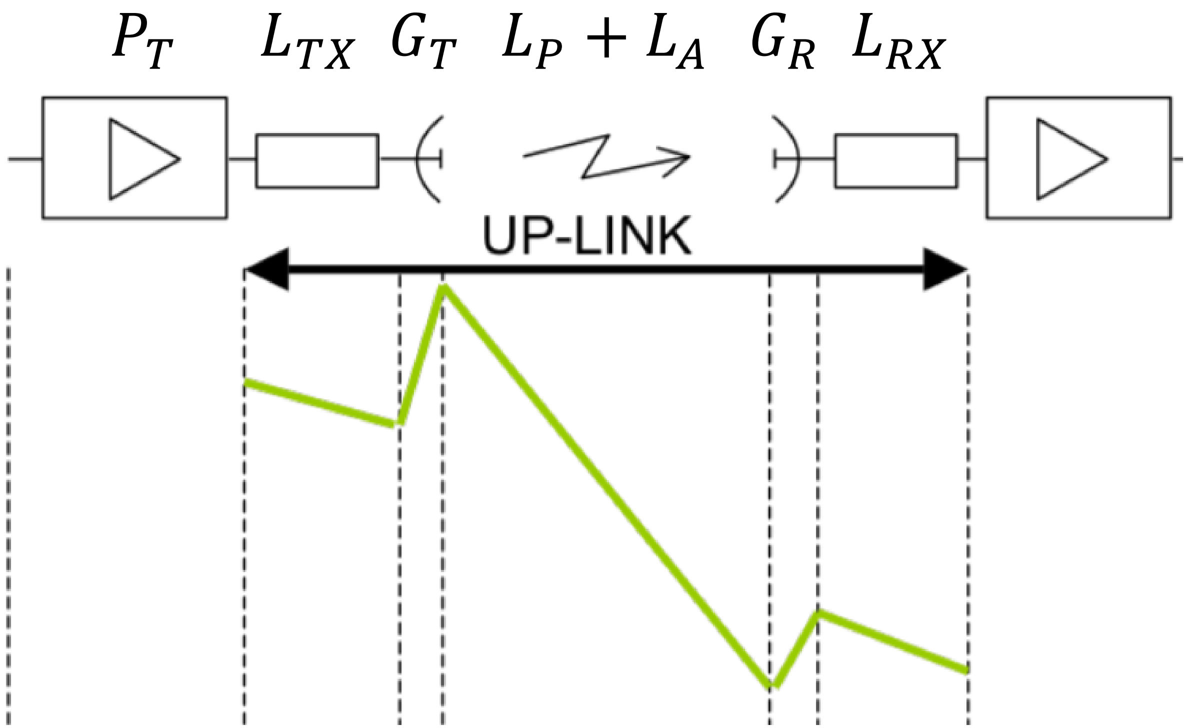
## Gaseous Absorption and Rain Attenuation and Other Losses

- Other losses in the channel:
  - Absorption in **atmospheric gases**; **absorption**, **scattering** and **depolarization** by water especially important at frequencies **above about 10 GHz**
  - Loss of signal due to **beam-divergence** of the earth-station antenna, due to the normal **refraction in the atmosphere**
  - Decrease in effective antenna gain, due to **phase decorrelation** across the antenna aperture and other **cabling losses**
  - For example, considering an atmospheric attenuation $L_A$, transmitting antenna $L_{TX}$, receiving antenna $L_{RX}$:

$$P_R = EIRP + G_R - L_P - L_A - L_{TX} - L_{RX}$$

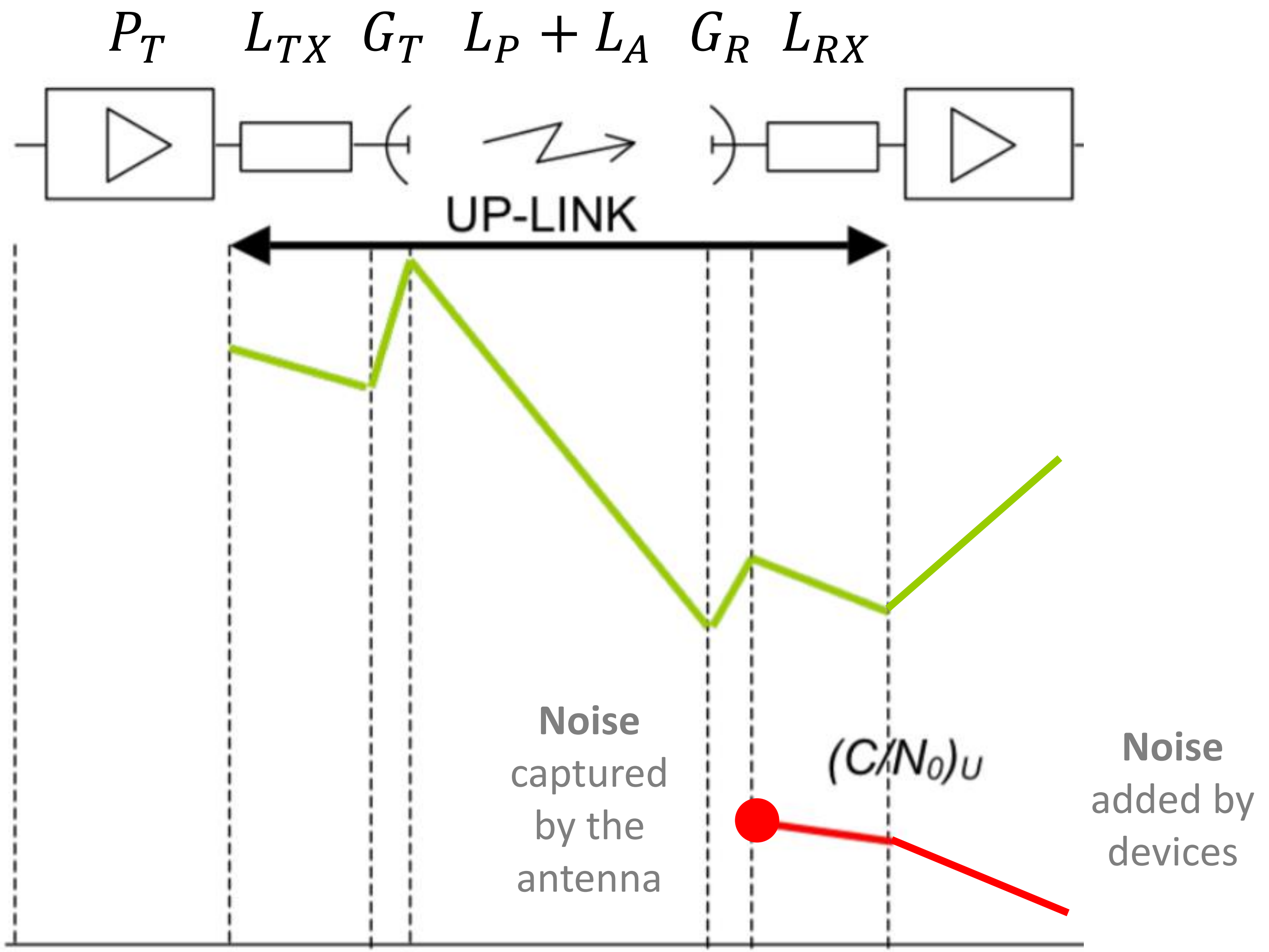
# Link Budget

**Radio Link Chain**



# Link Budget

**Radio Link Chain**




Higher than demodulator sensitivity

Good enough to provide the desired BER

# Noise Considerations



- **Thermal White Noise**
  - Noise is generated in any **resistive component** due to random motion of molecules, atoms and electrons and **captured form other sources**
  - Called *thermal* as it depends on the statistical motion of these particles
  - Called *white* since it evenly spread over the entire frequency spectrum ($N_0$)
  - Commonly modeled as **Additive white Gaussian Noise (AWGN)**

$$N_n = N_0 B = kTB$$

where

- $T$ = absolute temperature (in K)
- $B$ = bandwidth of interest (in Hz)
- $k$ = Boltzmann's constant $= 1.38 \times 10^{-23}$ J/K
- $N_n$ = noise power output of a resistor (in W)

# Noise Considerations

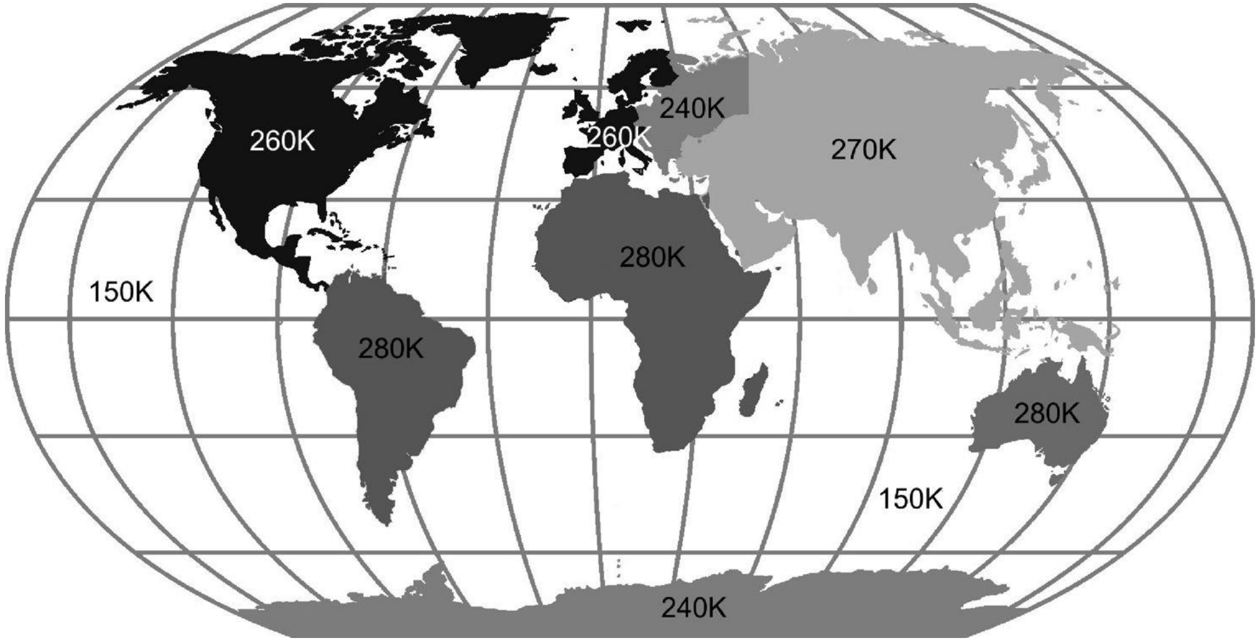
## Antenna Noise Temperature

- **Antenna Noise Temperature**
  - The antenna picks up noise radiated by sources within its directional pattern
    - **Man-made**
      - Electrical machinery,
      - Electrical and electronic equipment,
      - Power transmission lines,
      - Internal combustion engine ignition
    - **Natural**:
      - Solar radiation,
      - Emissions from atmospheric gases and hydrometeors
      - Radiation from lightning discharges
      - Background noise (celestial radio sources)
  - The noise performance of an antenna can be expressed in terms of a noise temperature called the **antenna noise temperature**

# Noise Considerations

### Antenna Noise Temperature

- **Uplink** (satellite antenna as a receiver)
  - The main sources of noise are Earth and outer space

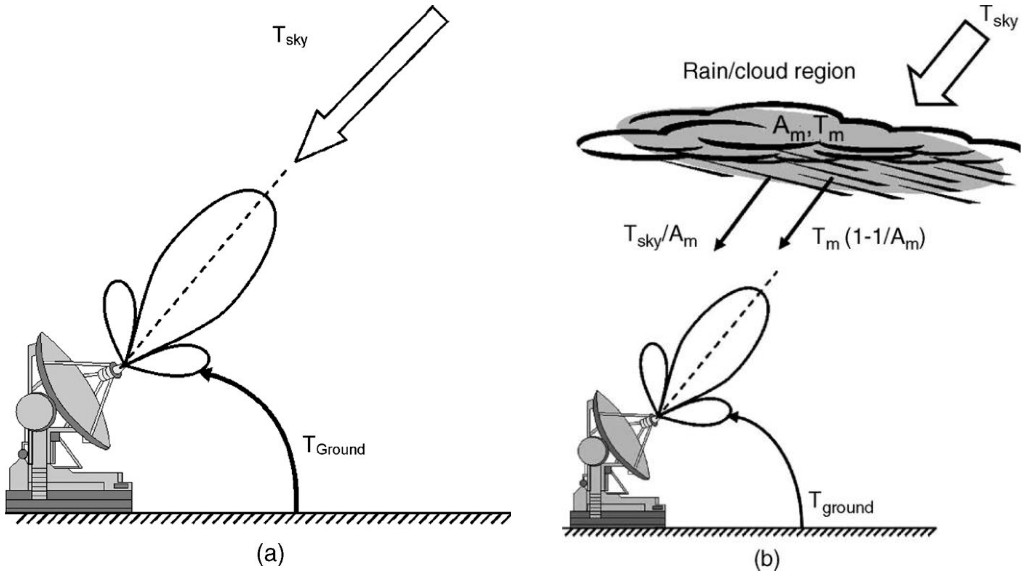



Temperatures of the Earth from space

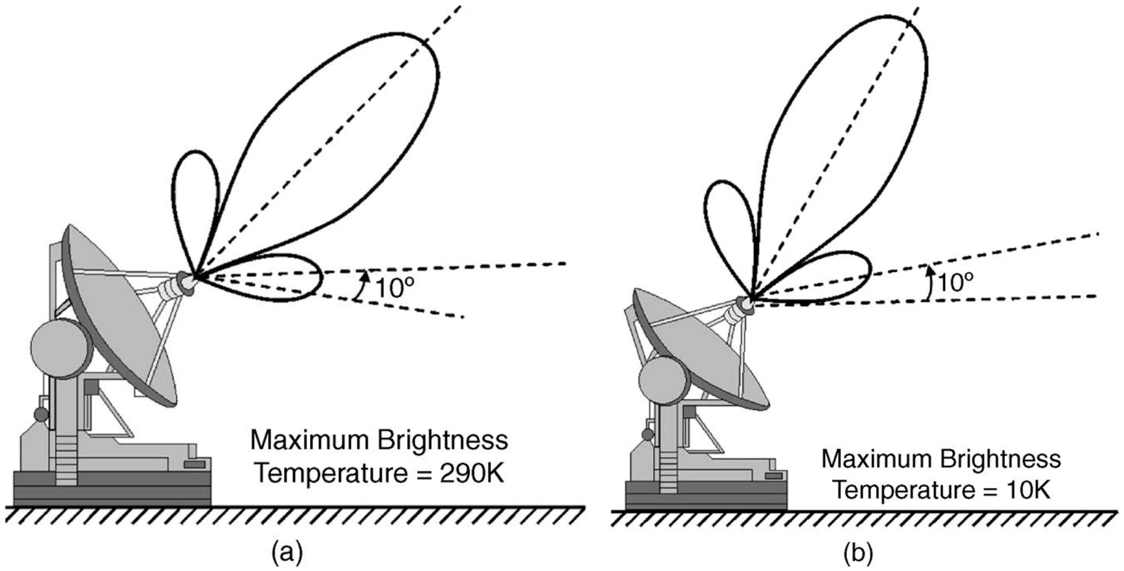
# Noise Considerations

### Antenna Noise Temperature

- **Downlink** (ground station antenna as a receiver)
  - The main sources of noise are **sky noise** (radiation from the sun and the moon and the absorption by oxygen and water vapor in the atmosphere accompanied by re-emission) and **ground noise**




Sky noise




Ground noise

# Noise Considerations

## Noise Figure

- The **noise figure** $F$ of a **device** can be defined as the ratio of the input signal-to-noise power and the output signal-to-noise power

$$F = \frac{S_i/N_i}{S_o/N_o} = \left(\frac{N_o}{N_i}\right)\left(\frac{1}{G}\right) \text{[dB]}$$

Where

- $S_i$ = available signal power at the input
- $N_i$ = available noise power at the input
- $S_o$ = available signal power at the output
- $N_o$ = available noise power at the output (in a noiseless device)
- $G$ = power gain over the specified bandwidth = $S_o/S_i$

# Link Budget Design

## Wrap-Up

- The link budget determines the antenna size to deploy, power requirements, link availability, bit error rate, etc.
- A link budget is a **tabular method** for evaluating the **power received** and the **noise ratio** in a radio link
- The link budget must be calculated for an individual transponder, and must be recalculated for each of the individual links
- Link budgets are calculated for a **worst-case scenario**, the one in which the link will have the lowest $C/N$ ratio
  - What **distance** and **elevation angle** do we consider in an elliptical orbit **(?)**

# Link Budget Design

**Wrap-Up**

- Example link budget for a C-Band GEO

Input parameters

Free space loss

Received power

Noise power and ratio

| | |
|---|---|
| C – band satellite parameters | |
| Transponder saturated output power | 20 W |
| Antenna gain on axis | 20 dB |
| Transponder bandwidth | 36 MHz |
| Downlink frequency band | 3.7 – 4.2 GHz |
| Signal FM – TV analogue signal | |
| FM – TV signal bandwidth | 30 MHz |
| Minimum permitted overall C/N in receiver | 9.5 dB |
| Receiving C – band earth station | |
| Downlink frequency | 4 GHz |
| Antenna gain on axis at 4GHz | 49.7 dB |
| Receiver IF bandwidth | 27 MHz |
| Receiving system noise temperature | 75 K |
| Downlink power budget | |
| Pt – satellite transponder output power, 20 W | 13 dB |
| Bo – transponder output backoff | -2dB |
| Gt – satellite antenna gain, on axis | 20 dB |
| Gr – earth station antenna gain | 49.7 dB |
| LP – free space path loss at 4GHz | -196.5 dB |
| Lant = edge of beam loss for satellite antenna | -3 dB |
| La = clear air atmospheric | -0.2 dB |
| Lm = other losses | -0.5dB |
| Pr = *received power at earth station* | *-119.5 dBW* |
| Downlink noise power budget in clear air | |
| k = Boltzmann's constant | -228.6 dBW/K/Hz |
| TS = system noise temperature, 75 K | 18.8 dBK |
| Bn = noise bandwidth 27 MHz | 74.3 dBHz |
| *N = receiver noise power* | *-135.5 dBW* |
| C/N ratio in receiver in clear air | |
| C/N =Pr – N = -119.5 – (-135.5) | 16.0 dB |

# Other Ways of Surviving a Bad Link

## Compensating Propagation Effects

- **Power Control**
  - Varying the EIRP of the signal to enhance the $C/N$ ratio.
  - In **open-loop** mode, the fade level on the downlink signal is used to predict one in the uplink signal and vice versa.
  - In the **closed-loop** mode, the signal power is detected at the satellite, and it sends a control signal to adjust the transmitted power
- **Signal Processing**
  - Forward Error Correction (FEC) codes
- **Diversity**
  - Time diversity: enable packet recovery algorithms (go-back-n)
  - Frequency diversity: switch to a less-attenuated frequency
  - Site diversity: other sites where weather conditions are better

## Interference

- No matter how well your link budget is calculated
- If another signal reaches the receiver at the same frequency range, **interference can hinder the possibility of successfully decoding a signal**
- There is nothing we can do about external sources – (ITU?), but we must not interfere **our own links**

# Multiple Communications

**Not only Point to Point**

- We’ve said that a typical satellite is composed of several subsystems: many communications simultaneously from a **same source**
  - **Multiplexing Techniques** (point to point)
- We’ve said a satellite provides data relay services to several users: many comms **from different sources to a same destination**
  - **Centralized Multiple Access** (point to multi-point)
- We’ve said we are going to LEO **mega-constellations** configurations: many comms **from different sources to different destinations**
  - **Distributed Multiple Access** (multi-point to multi-point)

# Multiplexing Techniques

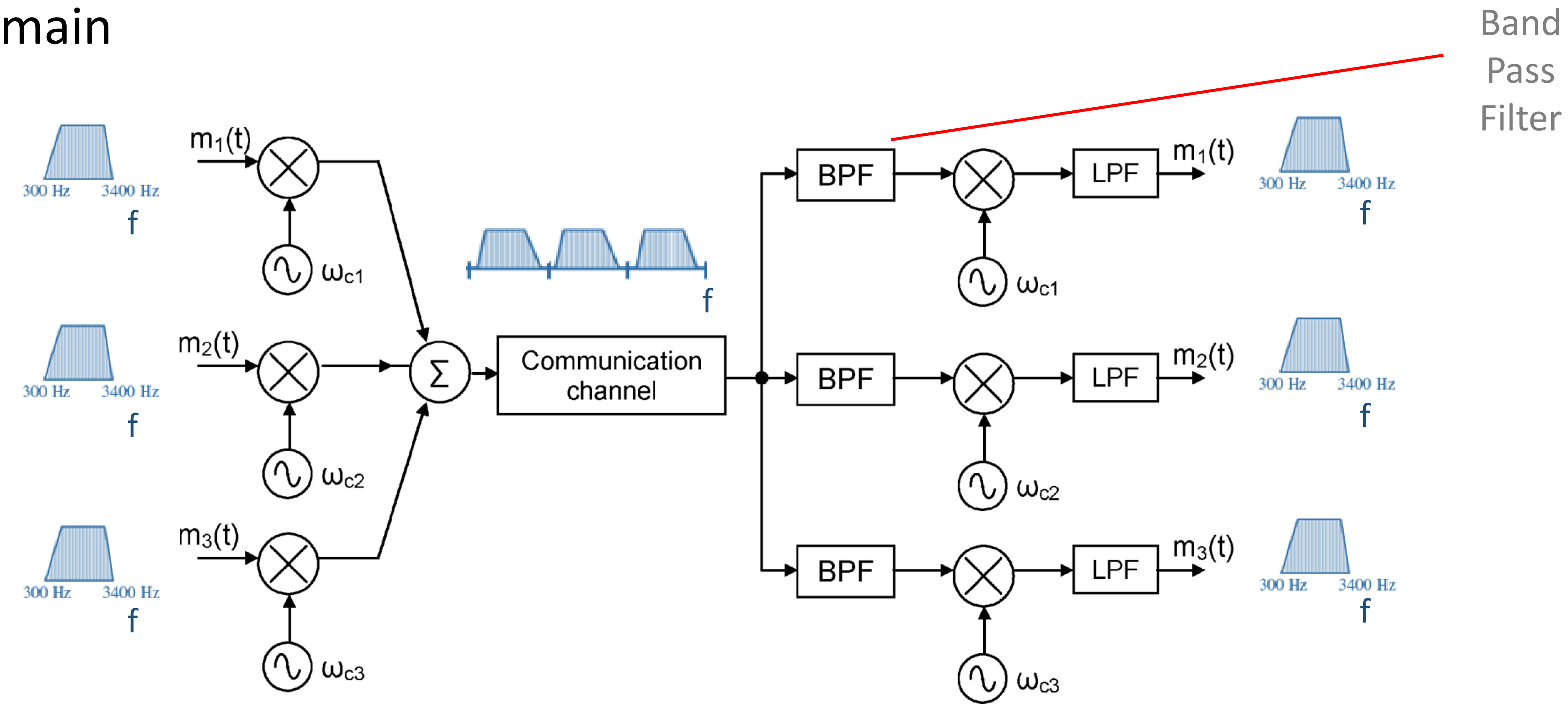
## Introduction

- Multiplexing means combining **multiple signals** into one
- Ensures that the different message signals in the composite signal do not interfere with each other and that they **can be conveniently separated out at the receiver** end
- Types
  - Frequency Division Multiplexing (**FDM**)
  - Time Division Multiplexing (**TDM**)
  - Code Division Multiplexing (**CDM**)

# Multiplexing Techniques

**Frequency Division Multiplexing (FDM)**

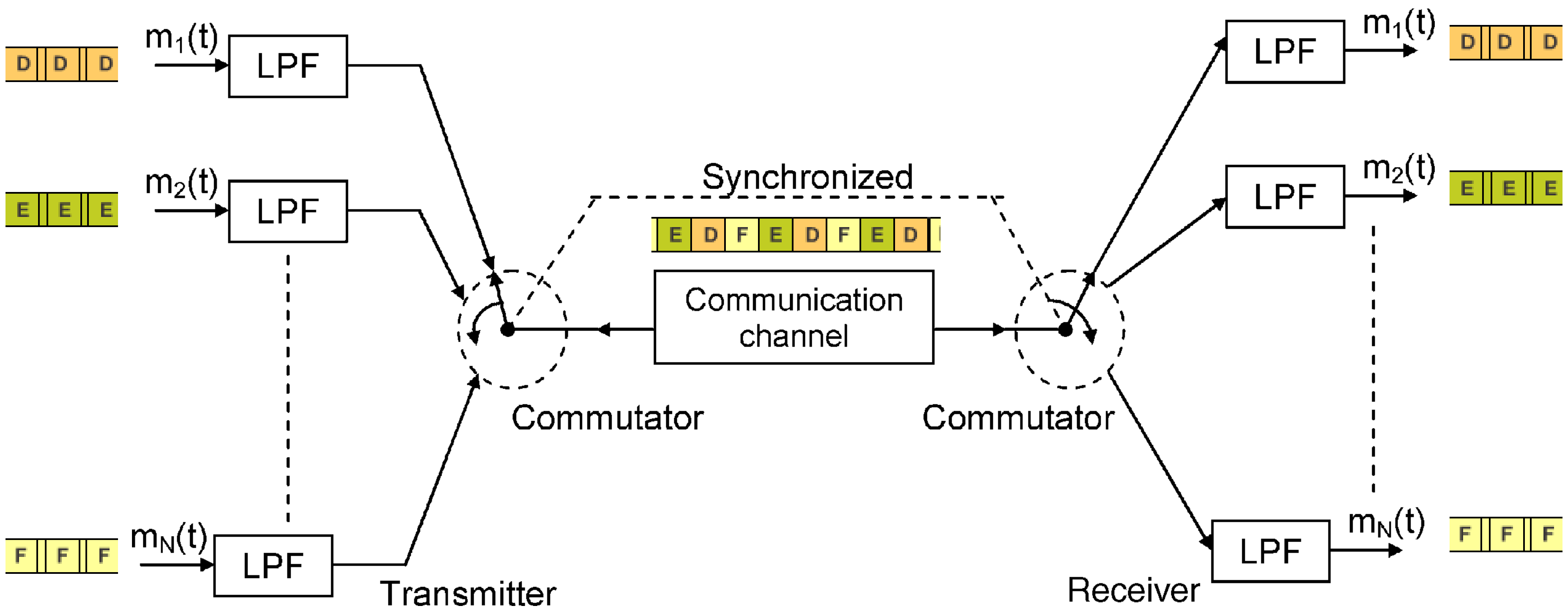
- Different message signals are separated from each other in the frequency domain



# Multiplexing Techniques

## Time Division Multiplexing (TDM)

- Multiple pulsed signals are fed to a commutator which forms a composite **time-interleaved signal**



# Multiplexing Techniques

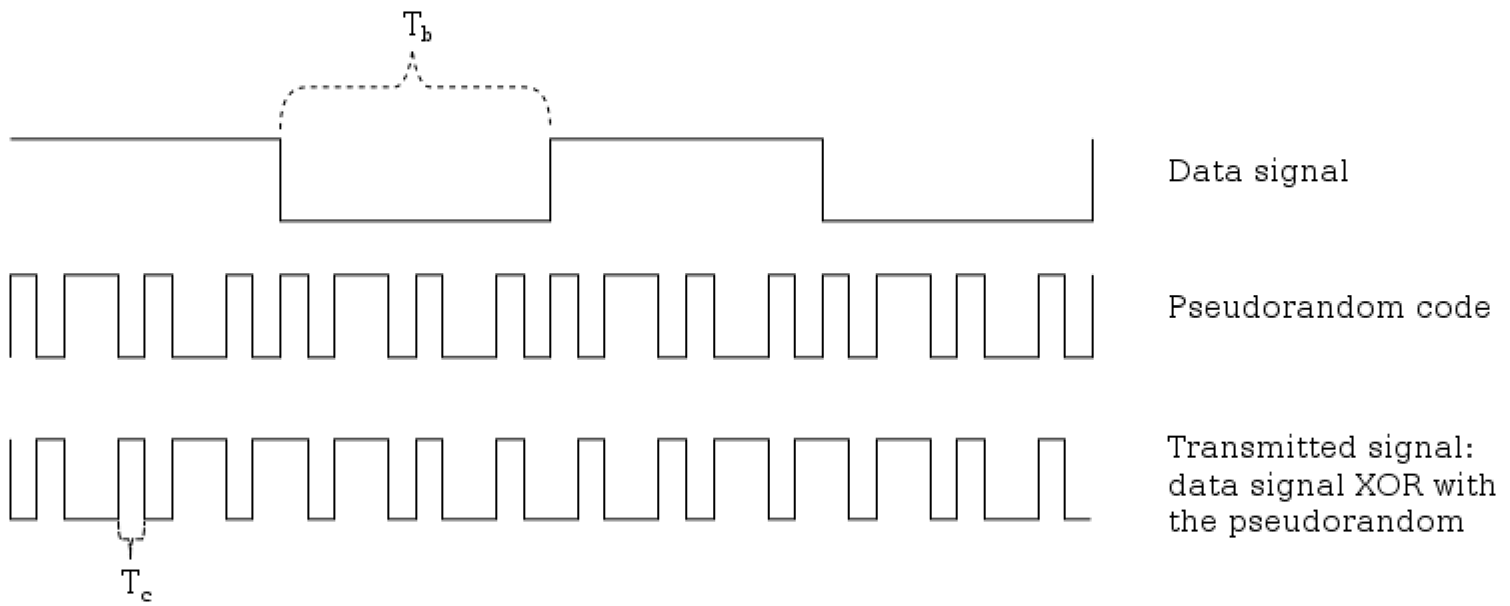
## Time Division Multiplexing (TDM)

- **Problem**: A digital telephony system comprises **24 voice channels**, each limited to **3.2 kHz** and using an **8-bit PCM**, transmits over a common communication channel using **TDM**. If the signal is sampled at **1.2 times the Nyquist** rate and a **synchronization bit** is added at the end of each frame, determine: duration of each bit and transmission rate
  - Sampling rate $(2 \times 3.2 \times 1.2)\ \mathrm{kHz} = 7.68\ \mathrm{kHz}$
  - Sampling period $1/7.68\ \mathrm{kHz} = 130\ \mu\mathrm{s}$
  - Bits per sample $24 \times 8 + 1 = 193$
  - Bit duration $130\ \mu\mathrm{s}/193 = 0.675\ \mu\mathrm{s}$
  - Transmission rate $1\ \mathrm{bit}/0.675\ \mu\mathrm{s} = 1.482\ \mathrm{Mbps}$

# Multiplexing Techniques

## Code Division Multiplexing (CDM)

- Multiple signal transmitted over a common frequency band
  - **Truly Orthogonal** or **Pseudorandom codes (PN)**
  - Spread signal over a large frequency band, larger than bandwidth of the original signal
  - At the receiver, the same orthogonal codes are used to recover the signal



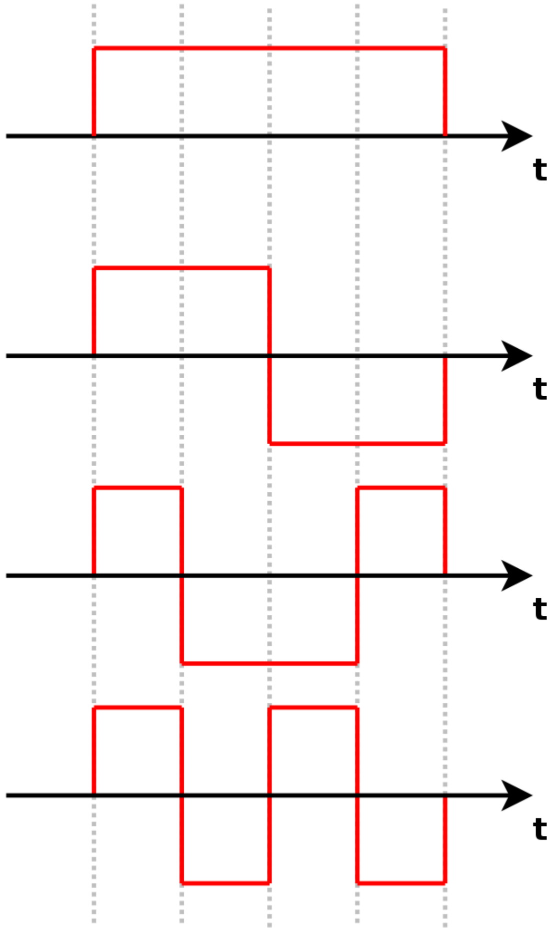
# Multiplexing Techniques

## Code Division Multiplexing (CDM) - Example

- Start with a set of orthogonal vectors $v$
- 1 is represented as positive $v$ and 0 as negative $-v$

- **Node Tx-a**: if $v = (1, -1)$, and data to transmit is $d = (1,0,1,1)$, then symbols are
  - $d = (v, -v, v, v) = (1, -1, -1, 1, 1, -1, 1, -1)$

- **Node Tx-b**: if $v = (1,1)$, and data to transmit is $d = (0,0,1,1)$, then symbols are
  - $d = (-v, -v, v, v) = (-1, -1, -1, -1, 1, 1, 1, 1)$




4 orthogonal vectors, one to each Tx entity

# Multiplexing Techniques

## Code Division Multiplexing (CDM) - Example

- Because both signals are transmitted at the same time into the air, they add to produce the raw signal

$$(1,-1,-1,1,1,-1,1,-1) + (-1,-1,-1,-1,1,1,1,1) = \mathbf{(0,-2,-2,0,2,0,2,0)}$$

- **Node Rx-a**: $v = (1,-1)$
  - $\big((0,-2),(-2,0),(2,0),(2,0)\big) \cdot (1,-1) \rightarrow ((0+2),(-2+0),(2+0),(2+0))$
  - $(2,-2,2,2) \rightarrow \color{red}{(1,0,1,1)}$

- **Node Rx-b**: $v = (1,1)$
  - $\big((0,-2),(-2,0),(2,0),(2,0)\big) \cdot (1,1) \rightarrow ((0-2),(-2+0),(2+0),(2+0))$
  - $(-2,-2,2,2) \rightarrow \color{red}{(0,0,1,1)}$

What happens in Node Rx-b if only signal $(1,-1,-1,1,1,-1,1,-1)$ is transmitted **(?)**

# Multiplexing Techniques

## Code Division Multiplexing (CDM) - Example

- If only this signal is transmitted $(1, 0, 1, 1)$ encoded to Rx-a:

$$(1, -1, -1, 1, 1, -1, 1, -1)$$

- **Node Rx-a**: $v = (1, -1)$
  - $\big((1, -1), (-1, 1), (1, -1), (1, -1)\big) \cdot (1, -1) \rightarrow (1 + 1), (-1 - 1), (1 + 1), (1 + 1)$
  - $(2, -2, 2, 2) \rightarrow$ $(1, 0, 1, 1)$

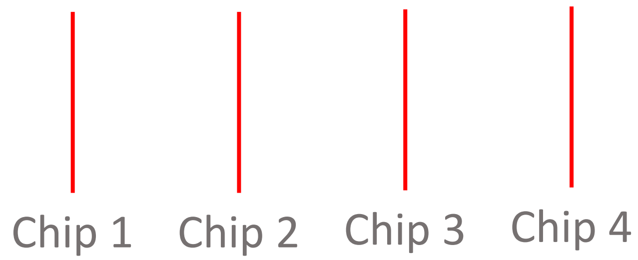
- **Node Rx-b**: $v = (1,1)$
  - $\big((1, -1), (-1, 1), (1, -1), (1, -1)\big) \cdot (1, 1) \rightarrow ((1 - 1), (-1 + 1), (1 - 1), (1 - 1))$
  - $(0, 0, 0, 0) \rightarrow$ $(0, 0, 0, 0)$ $\rightarrow$ No data!

# Multiplexing Techniques

## Code Division Multiplexing (CDM) - Example

- Transmission is composed of 4 codes words, also called “chip”

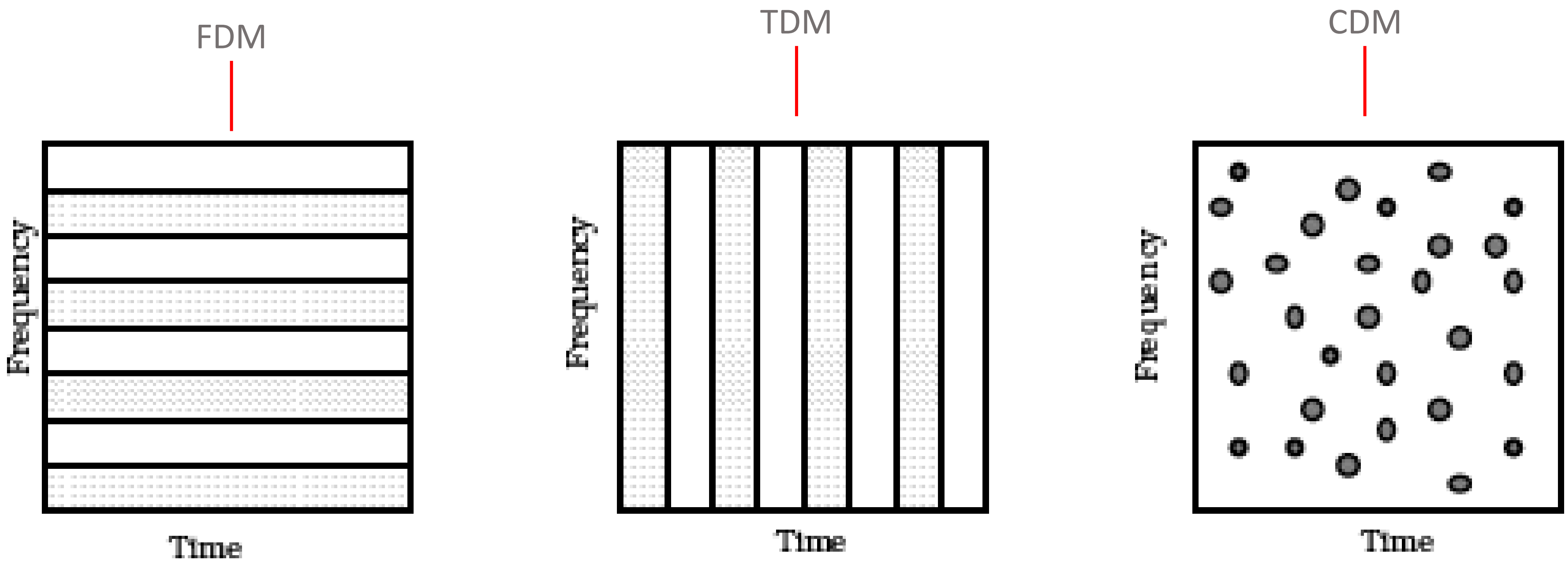
$$(1, -1, -1, 1, 1, -1, 1, -1)$$




- CDM signals are typically characterized by a **chip rate** which is equal to the **information bit rate** of the channel.
- The **real bit rate** is equal to the information bit rate times the chip size

# Multiplexing Techniques

**Wrap-Up**



**Questions?**