Satellite Communications

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Example of an analog communication system

Major components:

1. signal
2. transmitting channel (cable, radio)
3. electronics (amplifiers, filters, modems, etc)

and a lot of engineering!
Outline

1 **Signal processing elements**
   - Signal ≡ information!
   - Source coding (dealing with the information content)
   - Modulation
   - Multiplexing

2 **Propagation and radio communications**
   - Introduction to radio communications
   - Radiowave propagation
   - Examples of antennas

3 **Engineering**
   - Noise
   - Link budget

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Satellite Communications
Signal ≡ information!
Source coding (dealing with the information content)
Modulation
Multiplexing
Main types of satellite → different types of information

- **Astronomical satellites**: used for observation of distant planets, galaxies, and other outer space objects.

- **Navigational satellites** [GPS, Galileo]: they use radio time signals transmitted to enable mobile receivers on the ground to determine their exact location (positioning).

- **Earth observation satellites**: used for environmental monitoring, meteorology, map making.

- **Miniaturized satellites**: satellites of unusually low masses and small sizes.

- **Communications satellites**: stationed in space for the purpose of telecommunications. Modern communications satellites typically use geosynchronous orbits, or Low Earth orbits (LEO).

### Types of data streams

<table>
<thead>
<tr>
<th>Types of data</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control data</td>
<td>Must be very reliable</td>
</tr>
<tr>
<td>Measurements</td>
<td>Accurate signals with constant monitoring</td>
</tr>
<tr>
<td>Remote sensing data</td>
<td>High volume of downstream data</td>
</tr>
<tr>
<td>Localization data</td>
<td>Accurate time reference (synchronization)</td>
</tr>
<tr>
<td>Broadcasting</td>
<td>Television channels</td>
</tr>
<tr>
<td>Payload</td>
<td>Unicast communication for mobile ground station</td>
</tr>
</tbody>
</table>

Because the purposes of data sent are different, the mechanism to transmit the data is designed according to the constraints.

**Simplified typography of data streams:**

- **control data**
- **payload** (+ some unavoidable overhead)
Main concerns related to signals

- **Signal source handling** (preparation of the signal, at the source, in the transmitter):
  - filtering (remove what is useless for communications)
  - analog ↔ digital (digitization)
  - remove the redundancy in the signal: compression

- **Signal over the channel**:
  - signal shaping to make it suitable for transmission (*coding*, *modulation*, *multiplexing*, etc)
  - signal power versus the noise signal (protect the signal against noise effects)

---

**Digitization**

*Digitization* = from analog to digital

<table>
<thead>
<tr>
<th>analog</th>
<th>digital</th>
</tr>
</thead>
<tbody>
<tr>
<td>g(t)</td>
<td>g[iT], with i = 0, 1, 2, ... and T, a time period</td>
</tr>
<tr>
<td>signal over time</td>
<td>sampling</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Analog and digital signals: don’t confuse *information* and its *representation*!

![Analog information signal](image1.png) ![Digital information signal](image2.png)

**Characterization of signals over the channel**

<table>
<thead>
<tr>
<th>Analog signal</th>
<th>Digital signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>bandwidth [Hz]</td>
<td>bit rate [bit/s]</td>
</tr>
<tr>
<td>Signal to Noise Ratio (S/N or SNR)</td>
<td>Bit Error Rate (BER)</td>
</tr>
<tr>
<td>bandwidth of the underlying channel [Hz]</td>
<td></td>
</tr>
</tbody>
</table>

Going digital because:
- possibility to regenerate a digital signal
- better bandwidth usage

**Example**

[better bandwidth usage]: from analog television to digital television

- analog PAL television channel: bandwidth of 8 [MHz]
- digital television, PAL quality $\sim 5$ [Mb/s]
  - With a 64-QAM modulation, whose spectral efficiency is $6b/s$ per Hz. A bandwidth of 8 [MHz] allows for 48 [Mb/s].
  - Conclusion: thanks to digitization, there is room for 10 digital television channels instead of 1 analog television channel.
Software organization of a transmitter/receiver: the OSI reference model

Consequence: encapsulation $\Rightarrow$ overhead

OSI reference model vs Internet model (+ some corresponding Internet protocols)
Elements of a communication system

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   - Examples of antennas

3. Engineering
   - Noise
   - Link budget
Information theory and channel capacity: there is *maximum* bit rate!

**Theorem**

[Shannon-Hartley] *The channel capacity* $C$ (*conditions for the error rate* $BER \to 0$) *is given by*

$$C \left[ \frac{b}{s} \right] = W \log_2 \left( 1 + \frac{S}{N} \right) \quad (1)$$

where

- $W$ is the channel bandwidth in Hz
- $\frac{S}{N}$ the signal-to-noise ratio (in watts/watts, not in dB).

**Consequences of the capacity theorem**

Let $R_b$ be the bit rate $[b/s]$ and $E_b$ the energy per bit $[\text{Joule/b}]$, we have $S = E_b R_b$ [Watt], and $N = N_0 W$ (where $N_0$ is the noise spectral power density; $N_0 = k_B T$ as shown later). Therefore:

$$C = W \log_2 \left( 1 + \frac{E_b}{N_0} \frac{R_b}{W} \right) \quad (2)$$

The ratio $\frac{R_b}{W}$ is the *spectral efficiency* expressed in $[b/s]$ per $[\text{Hz}]$.

**Consequences:**

- the capacity is **bounded** (there is a maximal limit), related to
  - the $\frac{E_b}{N_0}$ ratio. We only have control over $E_b$.
  - the spectral efficiency
- for a fixed $\frac{E_b}{N_0}$ ratio and spectral efficiency, $C$ can only be increased by increasing the bandwidth. But the bandwidth is a *scarce resource*. 
Assume a packet of size $N$ and let $P_e$ be the probability error on one bit. The probability for the packet to be correct is

$$ (1 - P_e)^N $$

(3)

Therefore the **packet error rate** is

$$ P_P = 1 - (1 - P_e)^N. $$

(4)

For large packets and small $P_e$, this becomes

$$ P_P \approx 1 - (1 - NP_e) = N \times P_e. $$

(5)

**Example**

With $N = 10^5$ bits and a bit error rate of $P_e = 10^{-7}$, $P_P \approx 10^{-2}$. We thus need to lower $P_e \Rightarrow$ error detection/correction mechanisms

**Forward Error Coding**

A simplistic example of **Forward Error Coding (FEC)** is to transmit each data bit 3 times, known as a (3,1) repetition code.

<table>
<thead>
<tr>
<th>Received bits</th>
<th>Interpreted as</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>0 (error free)</td>
</tr>
<tr>
<td>001</td>
<td>0</td>
</tr>
<tr>
<td>010</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>111</td>
<td>1 (error free)</td>
</tr>
<tr>
<td>110</td>
<td>1</td>
</tr>
<tr>
<td>101</td>
<td>1</td>
</tr>
<tr>
<td>011</td>
<td>1</td>
</tr>
</tbody>
</table>

Comparison of BPSK modulation and repetition codes with different repetition factors.
Other forward error codes

- Hamming code
- Reed–Solomon code
- Turbo code, ...

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Modulation: principles

Principle: modulation is all about using of a carrier frequency $f_c$ for transmitting information

$$s(t) = A(t) \cos(2\pi f_c(t) + \phi(t))$$

Amplitude modulation [AM]  Phase modulation [PM]

Consequences of modulation

- frequency band is shifted towards the carrier frequency ($\Rightarrow f_c$)
- bandwidth modification

Example

Effects of Amplitude modulation on the spectrum ($s(t) = A_c m(t) \cos(2\pi f_c t)$)

\[\frac{\Delta f}{2} \delta(f + f_c)\]

\[\frac{\Delta f}{2} \delta(f - f_c)\]
Modulated signal: \( s(t) = m(t) \cos(2\pi f_c t) \). Recover \( m(t) \).

Principles of a synchronous demodulation. At the receiver:
1. acquire a local, synchronous, copy of the carrier \( f_c \) ⇒ build a local \( \cos(2\pi f_c t) \)
2. multiply \( s(t) \) by \( \cos(2\pi f_c t) \):
   \[
   \cos a \cos b = \frac{1}{2} \cos(a - b) + \frac{1}{2} \cos(a + b)
   \]
   \[
   s(t) \cos(2\pi f_c t) = m(t) \cos^2(2\pi f_c t) = m(t) \left[ \frac{1}{2} + \frac{1}{2} \cos(2\pi(2f_c) t) \right]
   \]
   \[
   = \frac{1}{2} m(t) + \frac{1}{2} m(t) \cos(2\pi(2f_c) t)
   \]
3. filter out the \( 2f_c \) components \( \rightarrow \frac{1}{2} m(t) \)
Basic digital modulation (coding) techniques

Quadrature modulation

It is possible to use both a cosine and a sine:

\[ s(t) = m_1(t) \cos(2\pi f_c t) - m_2(t) \sin(2\pi f_c t) \]  \hspace{1cm} (9)
Quadrature demodulation: principles

\[ s(t) = m_1(t)\cos(2\pi f_c t) + m_2(t)\sin(2\pi f_c t) \] is the modulated signal.

We want to recover \( m_1(t) \) and \( m_2(t) \):

- **Step 1**: multiply by \( \cos(2\pi f_c t) \)
  \[
  s(t) \times \cos(2\pi f_c t) = m_1(t)\cos^2(2\pi f_c t) + m_2(t)\sin(2\pi f_c t)\cos(2\pi f_c t) 
  = \frac{1}{2}m_1(t) + \frac{1}{2}m_1(t)\cos(2\pi(2f_c)t) + \frac{1}{2}m_2(t)\sin(2\pi(2f_c)t)
  
  \]

- **Step 2**: filter to keep the baseband signal
  \[
  \frac{1}{2}m_1(t)
  
  \]

- **Steps 3 and 4**: multiply by \( \sin(2\pi f_c t) \) and low-pass filter to get \( m_2(t) \)

**Purposes of the quadrature modulation**

There are two possible uses or advantages for the quadrature modulation:

1. **[Bandwidth savings by a factor of 2]** Send two signals in the same bandwidth
   \[
   s(t) = m_1(t)\cos(2\pi f_c t) + m_2(t)\sin(2\pi f_c t) \tag{10}
   
   \]
   Both \( m_1(t)\cos(2\pi f_c t) \) and \( m_2(t)\sin(2\pi f_c t) \) have exactly the same bandwidth, that is \([f_c - W, f_c + W] \) where \( W \) denotes the original bandwidth of \( m_1(t) \) and \( m_2(t) \).

2. **[Easier demodulation]**
   A coherent demodulation of \( m(t)\cos(2\pi f_c t + \phi_c) \) requires the perfect knowledge of \( f_c \) and \( \phi_c \) at the receiver. However, it is sometimes difficult to synchronize the receiver. Therefore,
   \[
   s(t) = m(t)\cos(2\pi f_c t + \phi_c) + m(t)\sin(2\pi f_c t + \phi_c) \tag{11}
   
   \]
is sometimes used.
   At the receiver, \( m(t) \), the signal of interest can be obtained by
   \[
   \sqrt{m^2(t)\cos^2(.) + m^2(t)\sin^2(.)} = |m(t)|.
   \]
Multiplexing: combining several sources

Mechanisms to share resources between users:
- **Frequency Division Multiplexing (FDM)**
- **Time Division Multiplexing (TDM)**
- **Code Division Multiplexing (CDM)**
- Space Division Multiplexing
- + combinations!
Frequency Division Multiplexing (FDM)

Demultiplexing
Time Division Multiplexing (TDM)

Spread spectrum for Code Division Multiplexing

Principle of spread spectrum: multiply a digital signal with a faster pseudo-random sequence (spreading step)

At the receiver, the same, synchronized, pseudo-random sequence is generated and used to despread the signal (despreading step)
Each user is given its own code (multiple codes can be used simultaneously)
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Satellite link definition

CHANNEL – one way link from A → B or B → A
CIRCUIT – full duplex link – A ↔ B
HALF CIRCUIT – two way link – A ↔ S or S ↔ B
TRANSPONDER – ▶️ basic satellite repeater electronics, usually one channel
Frequency bands

But it is also common to designate the **carrier frequency** and **bandwidth** directly.

Regulatory bodies

- **International Telecommunications Union (ITU):**
  Radiocommunications Sector (ITU-R)
  - service regions
  - organizes WARC (World Administrative Radio Conference) - worldwide allocation of frequencies
- Regional body: European Conference of Postal and Telecommunications Administrations (CEPT)
## Frequency allocations [2]

<table>
<thead>
<tr>
<th>Radio communications service</th>
<th>Typical uplink/downlink</th>
<th>Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed satellite service (FSS)</td>
<td>6/4 [GHz]</td>
<td>C band</td>
</tr>
<tr>
<td></td>
<td>8/7 [GHz]</td>
<td>X band</td>
</tr>
<tr>
<td></td>
<td>14/12.1 [GHz]</td>
<td>Ku band</td>
</tr>
<tr>
<td>Mobile satellite service (MSS)</td>
<td>30/20 [GHz]</td>
<td>Ka band</td>
</tr>
<tr>
<td></td>
<td>50/40 [GHz]</td>
<td>V band</td>
</tr>
<tr>
<td>Broadcasting satellite service (BSS)</td>
<td>2/2.2 [GHz]</td>
<td>S band</td>
</tr>
<tr>
<td></td>
<td>12 [GHz]</td>
<td>Ku band</td>
</tr>
<tr>
<td></td>
<td>2.6/2.5 [GHz]</td>
<td>S band</td>
</tr>
</tbody>
</table>

- Note that frequencies for downlinks are usually lower than for uplinks: this is because attenuation increases with the frequency.
- The use of higher frequencies allows larger bandwidths, better tracking capability and minimizes ionospheric effects. But it also requires greater pointing accuracy.
Engineering considerations:

- **distance** between user and satellite.
  - delay (increases with the distance)
  - attenuation of the signal (increases with the distance)
- relative position of the user/satellite pair

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Important issues:
- channel characteristics
- attenuation (distance)
- atmospheric effects
  - wave polarization
  - rain mitigation
- antenna design
- power budget (related to the Signal to Noise ratio)

Inverse square law of radiation

The power flux density (or power density) $S$, over the surface of a sphere of radius $r_a$ from the point $P$, is given by (Poynting vector)

$$S_a = \frac{P_t}{4\pi r_a^2} \left[ \frac{W}{m^2} \right]$$

(12)
Effective Isotropic Radiated Power [EIRP]

**Definition**

The **Effective Isotropic Radiated Power** (EIRP) of a transmitter is the power that the transmitter appears to have if the transmitter were an isotropic radiator (if the antenna radiated equally in all directions).

From the receiver’s point of view,

\[ P_t = P_T G_T \]  

(13)

where:

- \( P_t \) is the power of a imaginary isotropic antenna.
- \( P_T \) is the transmitter power and \( G_T \) is its gain (in that direction).

If the cable losses can be neglected, then EIRP = \( P_T G_T \).

**Effective area**

**Definition**

The effective area of an antenna is the ratio of the available power to the power flux density (Poynting vector):

\[ A_{\text{eff},R} = \frac{P_R}{S_{\text{eff}}} \]  

(14)

**Theorem**

*The effective area of an antenna is related to its gain by the following formula*

\[ A_{\text{eff},R} = G_R \frac{\lambda^2}{4\pi} \]  

(15)
Friis relationship

We have

\[ P_R = S_{\text{eff},R} A_{\text{eff},R} \]

\[ = \left( \frac{P_T G_T}{4\pi d^2} \right) A_{\text{eff},R} = \left( \frac{P_T G_T}{4\pi d^2} \right) \left( \frac{\lambda^2}{4\pi} \right) G_R = P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2 \]

<table>
<thead>
<tr>
<th>Free space path loss</th>
<th>Friis’s relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{FS} = \left( \frac{\lambda}{4\pi d} \right)^2 )</td>
<td>( \varepsilon = \frac{P_T}{P_R} = \left( \frac{4\pi d}{\lambda} \right)^2 \frac{1}{G_T G_R} )</td>
</tr>
</tbody>
</table>

Decibel as a common power unit

\[ x \leftrightarrow 10 \log_{10}(x) \text{[dB]} \]  \hspace{1cm} (16)

\[ P \text{[dBm]} = 10 \log_{10} \frac{P \text{[mW]}}{1 \text{[mW]}} \]  \hspace{1cm} (17)

<table>
<thead>
<tr>
<th>( x \text{[W]} )</th>
<th>( 10 \log_{10}(x) \text{[dBW]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 \text{[W]}</td>
<td>0\text{[dBW]}</td>
</tr>
<tr>
<td>2 \text{[W]}</td>
<td>3\text{[dBW]}</td>
</tr>
<tr>
<td>0.5 \text{[W]}</td>
<td>-3\text{[dBW]}</td>
</tr>
<tr>
<td>5 \text{[W]}</td>
<td>7\text{[dBW]}</td>
</tr>
<tr>
<td>( 10^n \text{[W]} )</td>
<td>( 10 \times n \text{[dBW]} )</td>
</tr>
</tbody>
</table>

Orders of magnitude:

- Transmitter power: \( 100 \text{[W]} \equiv 20 \text{[dB]} \)
- Received power: \( 100 \text{[pW]} = 100 \times 10^{-12} \text{[W]} \equiv -100 \text{[dB]} \)
Free space losses

In [dB], Friis’s relationship becomes

$$\varepsilon = 32.5 + 20 \log f_{[MHz]} + 20 \log d_{[km]} - G_T [dB] - G_R [dB]$$

The attenuation (loss) increases with $f$. So ?!

Remember that

$$A_{eff} = G \frac{\lambda^2}{4\pi}$$ (18)

So,

$$\varepsilon = \left( \frac{4\pi d}{\lambda} \right)^2 \frac{1}{G_T G_R} = \left( \frac{4\pi d}{\lambda} \right)^2 \frac{\lambda^2}{4\pi A_T} \frac{\lambda^2}{4\pi A_R}$$ (19)

$$= \frac{\lambda^2 d^2}{A_T A_R} = \frac{c^2 d^2}{f^2 A_T A_R}$$ (20)

It all depends on the antenna gains!
Are high frequencies less adequate?

In [dB], Friis’s relationship becomes

\[ \varepsilon = 32.5 + 20 \log f_{[MHz]} + 20 \log d_{[km]} - G_T [dB] - G_R [dB] \]

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So,

\[
\varepsilon = \left( \frac{4\pi d}{\lambda} \right)^2 \frac{1}{G_T G_R} = \left( \frac{4\pi d}{\lambda} \right)^2 \frac{\lambda^2}{4\pi A_T} \frac{\lambda^2}{4\pi A_R} \quad (19)
\]

\[
= \frac{\lambda^2 d^2}{A_T A_R} = \frac{c^2 d^2}{f^2 A_T A_R} \quad (20)
\]

It all depends on the antenna gains!

Practical case: VSAT in the Ku-band [1]

Antenna gains: 48.93 [dB]

The free space path loss is, in [dB],

\[ L_{FS} = 32.5 + 20 \log f_{[MHz]} + 20 \log d_{[km]} = 205.1 [dB] \]

The received power is, in [dB],

\[ P_R = P_T + G_T + G_R - L_{FS} \]

\[ = 10 + 48.93 + 48.93 - 205.1 = -97.24 [dB] \]

In [W], the received power is

\[ P_R = 10^{-\frac{97.24}{10}} = 1.89 \times 10^{-10} [W] = 189 [pW] \]
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Terrestrial antennas
Beamwidth and aperture

- Antenna pattern
- G, antenna gain (at boresight)
- \( \theta \) for 1/2 power beamwidth (power 3 dB down from boresight)
- Sidelobes

Ground station antenna
Parabolic (dish) antenna

Radiation pattern

Deployable antenna

Monitor camera for the sending antenna

Monitor camera for the receiving antenna

View of the monitor camera for the receiving antenna
Horn antenna and waveguide feed

Yagi antenna

(a) Yagi Antenna Model  
(b) Yagi Antenna 3D Radiation Pattern

(c) Yagi Antenna Azimuth Plane Pattern  
(d) Yagi Antenna Elevation Plane Pattern
Patch array antenna

(a) 4x4 Patch Array Antenna
(b) 4x4 Patch Array 3D Radiation Pattern
(c) 4x4 Patch Array Azimuth Plane Pattern
(d) 4x4 Patch Array Elevation Plane Pattern

Phased array antenna

(c) ESA - 2004 - PACER
Radio wave propagation mechanisms

+ Doppler effect

Earth atmosphere absorption

Expressed in terms of the wavelength: \[ \lambda [m] = \frac{c}{f} = \frac{3 \times 10^8 [m/s]}{f [Hz]} \]
Attenuation due to atmospheric gases

Zenith attenuation due to atmospheric gases (source: ITU-R P.676-6)

\[ O_2 \text{ and } H_2O \text{ are the main contributors} \]

Rain attenuation

Total path rain attenuation as a function of frequency and elevation angle.

Location: Washington, DC, Link Availability: 99%
Cloud attenuation as a function of frequency, for elevation angles from 5 to 30°

The ITU recommends that all tropospheric contributions to signal attenuation are combined as follows:

\[ A_T(p) = A_G + \sqrt{(A_R(p) + A_c(p))^2 + A_s(p)} \]  \hspace{1cm} (24)

where:

- \( A_T(p) \) is the total attenuation for a given probability
- \( A_G(p) \) is the attenuation due to water vapor and oxygen
- \( A_R(p) \) is the attenuation due to rain
- \( A_c(p) \) is the attenuation due to clouds
- \( A_s(p) \) is the attenuation due to scintillation (rapid fluctuations attributed to irregularities in the tropospheric refractive index)
Customers ask for a guaranteed level of quality: this leads to a Service Level Agreement with the satellite operator. In engineering terms: introduction of power margins!
The available power from a thermal source in a bandwidth of $W$ is

$$P_N = k_B T W$$

(25)

where

- $k_B = 1.38 \times 10^{-23} [J/K]$ is the constant of Boltzmann ($-198 [dBm/K/Hz] = -228.6 [dBw/K/Hz]$).
- $T$ is the equivalent noise temperature of the noise source
- $W$ is the bandwidth of the system

Thermal noise is one the main sources of noise in a satellite → put electronics in the cold zone of a satellite.

**Definitions**

**Noise Factor** ($F$): [provided by the manufacturer]

$$F = \frac{(S/N)_{in}}{(S/N)_{out}} > 1$$

(26)

**Noise Figure** ($NF$):

$$NF = 10 \log_{10} F$$

(27)

**Effective noise temperature** $T_e$ ($T_0 = 290 [K]$):

$$T_e = T_0 (F - 1)$$

(28)
Noise factor of a two-port cascade

\[
(F_{01} - 1) \gamma_{aN_1}(f) 
\]
\[
\gamma_{aN_1}(f) 
\]
\[
F_{01} 
\]
\[
G_1 
\]
\[
(F_{02} - 1) \gamma_{aN_1}(f) 
\]
\[
G_1 F_{01} \gamma_{aN_1}(f) 
\]
\[
G_2 
\]
\[
(F_{01} - 1) \gamma_{aN_1}(f) (F_{02} - 1) \gamma_{aN_1}(f) G_1 F_{01} \gamma_{aN_1}(f) G_2 
\]

Figure: Cascading two-port elements.

For a two-port network with \( n \) stages,

\[
F_0 = F_{01} + \frac{F_{02} - 1}{G_1} + \frac{F_{03} - 1}{G_1 G_2} + \cdots = F_{01} + \sum_{i=2}^{n} \frac{F_{0i} - 1}{\prod_{j=1}^{i-1} G_j} 
\]  

(29)

Likewise,

\[
T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots = T_{e1} + \sum_{i=2}^{n} \frac{T_{ei}}{\prod_{j=1}^{i-1} G_j} 
\]  

(30)

Receiver front end

Rule of thumb: highest gain \( (G_1) \) and best noise figure \( (F_{01}) \) first. Then

\[
F_0 = F_{01} + \frac{F_{02} - 1}{G_1} + \frac{F_{03} - 1}{G_1 G_2} + \cdots \approx F_{01} + \frac{F_{02} - 1}{G_1} 
\]  

(31)

\[
T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \approx T_{e1} + \frac{T_{e2}}{G_1} 
\]  

(32)
Example of the calculation of a noise budget [1]

Low Noise Amplifier: \( T_{LA} = 290 \times (10^{4/10} - 1) = 438 \) [K]

Line. For a passive two-part, the noise factor is the attenuation \( F_0 = A \).

- \( T_{Line} = 290 \times (10^{3/10} - 1) = 289 \) [K],
- \( G_{Line} = \frac{1}{2} \)

The effective noise temperature, including the antenna noise, is

\[
T_e = t_A + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \tag{33}
\]

\[
= 60 + \frac{438}{498} + \frac{289}{1000} + \frac{2610}{1000 \times \frac{1}{2}} + \cdots = 509.3 \) [K] \tag{34}

Typical values for the increase in antenna temperature due to rain [1]

<table>
<thead>
<tr>
<th>Rain Fade Level (dB)</th>
<th>1</th>
<th>3</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise Temperature (°K)</td>
<td>56</td>
<td>135</td>
<td>243</td>
<td>267</td>
<td>270</td>
</tr>
</tbody>
</table>

Typical values for the increase in antenna temperature due to rain [1]
## Signal processing elements
- Signal ≡ information!
- Source coding (dealing with the information content)
- Modulation
- Multiplexing

## Propagation and radio communications
- Introduction to radio communications
- Radiowave propagation
- Examples of antennas

## Engineering
- Noise
- Link budget

### Example of parameter values for a communication satellite [1]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>uplink</th>
<th>downlink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>14.1 [GHz]</td>
<td>12.1 [GHz]</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>30 [MHz]</td>
<td>30 [MHz]</td>
</tr>
<tr>
<td>Transmitter power</td>
<td>100 – 1000 [W]</td>
<td>20 – 200 [W]</td>
</tr>
<tr>
<td>Transmitter antenna gain</td>
<td>54 [dBi]</td>
<td>36.9 [dBi]</td>
</tr>
<tr>
<td>Receiver antenna gain</td>
<td>37.9 [dBi]</td>
<td>52.6 [dBi]</td>
</tr>
<tr>
<td>Receiver noise figure</td>
<td>8 [dB]</td>
<td>3 [dB]</td>
</tr>
<tr>
<td>Receiver antenna temperature</td>
<td>290 [K]</td>
<td>50 [K]</td>
</tr>
<tr>
<td>Free space path loss (30° elevation)</td>
<td>207.2 [dB]</td>
<td>205.8 [dB]</td>
</tr>
</tbody>
</table>
For further reading


- **Wikipedia.**
  [http://wikipedia.org](http://wikipedia.org)