Digital Communications
Introduction

1) Definitions
2) Propagation channel
3) Elements of the communication channel
4) Performance criteria

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Transmit a given bit rate $R_b$ = Number of bits to be transmitted per second.

**DVB example:**

$BER < 10^{-10}$, (QEF transmission)

$R_b \sim 30 \text{ à } 40 \text{ Mbps}$

Obtain a given Bit Error Rate:

$$BER = \frac{\text{Number of erroneous bits}}{\text{Number of transmitted bits}}$$

Example:

Transmit: 0110010110

Received: 0101011111

$BER = 4/10$
Basic digital *transmission* channel

Analog signal: sound, image ...

Digitization

Binary information to transmit: 0 1 1 0 0 1 0 1 1 0

Transmitter

Analog signal

Transmission channel

Corrupted analog signal

Receiver

Received Binary information: 0 1 0 1 0 1 1 ...
- **Wired transmissions:** xDSL, optical fiber, cable TV, power Line communications...
  ⇒ Propagation on copper, coaxial cables or optical fibers via electrical or optical signals.

- **Wireless transmissions:** WiFi, Terrestrial TV, Satellite transmissions, GSM, 3G, 4G ...
  => Propagation in free space via radio (or Hertzian): frequencies < 3000 GHz

- Examples:
Radio waves, ETSI standards (European Telecommunications Standards Institute)
Transmission in bands
L : 1.4-1.6 GHz, C : 4-6GHz, Ku : 10.7-12.45 GHz and Ka : 20-30 GHz

Radio waves, IEEE standards (Institute of Electrical and Electronics Engineers)
Transmission in ISM (around 2.4 GHz) and UNII (around 5 GHz) bands

Electrical waves, IEEE standards (International Telecommunication Union)
Transmission between 1.5 and 30 MHz

Radio waves, ETSI standards
VHF and UHF (470-862 MHz) frequency bands

Electrical waves, ITU recommendations
Baseband transmissions

Optical waves, ITU recommendations

Baseband transmission

Propagation channel
Telecommunication Standards / Recommendations
Propagation channel: **distorsions/constraints**

- **Attenuation of the transmitted signal**
  Absorption, scattering due to atmospheric gases, to clouds, to rain, skin effect for cooper (Increases with increasing frequency),

- **Baseband or carrier modulated transmission**

- **Shared communication channel**
  → Multiplexing methods, regulation agencies.

- **Noise**
  → External noise = other signals received in addition to the useful communication signal.
  → Internal Noise = due to electronic devices/components inside the receiver.

- **One or several paths between the transmitter and the receiver**
  => flat fading or frequency selective channel

- **Limited allocated bandwidth**

- **Fixed or Mobile transmission**
  => stationnary or non stationnary channel
Attenuation effect on a DVB-S transmission (absorption, scattering due to atmospheric gases, clouds and rain)
Example of a fixed satellite DVB-S transmission DVB-S:

Propagation in bands
L : 1.4-1.6 GHz, C : 4-6 GHz, Ku : 10.7-12.45 GHz and Ka : 20-30 GHz
- **Shared propagation channel:** frequencies regulation

- **Depending on the countries: regulatory agencies or a ministries**
  
  Examples:
  
  → In France: ARCEP (Autorité de Régulation des Communications Electroniques), ANRT (Agence Nationale de Régulation des Fréquences), CSA (Conseil Supérieur de l’Audiovisuel)
  
  → In the United States of America: FCC (Federal Communications Commission)
  
  → In Japan: MIC (Ministry of Internal Affairs and Communications)

- **Collaborations between states:**
  
  Examples:
  
  → ORECE: Organe des Régulateurs Européens des Communications Electroniques in Europ,
  
  → NARUC: National Association of Regulatory Utility Commissioners (regulators of individual states) in the United States,
  
  → ARTAC: Association des Régulateurs de Télécommunications de l’Afrique Centrale, in Africa,

- **International Telecommunication Union (ITU)**
  
  → Responsible for the telecommunications regulation in the world
  
  → 193 member states and 700 associated members (from Information and Communication Technology sector).
  
  → Forum in which the states and the private sector coordinate together.

- **Unlicensed bandwidth**
  
  → industrial, scientific and medical (ISM): (902-928 MHz, 2.400-2.4835 GHz)
  
  → Unlicensed National Information Infrastructure (UNII): 5.15-5.25 GHz, 5.25-5.35 GHz
  
  → UNII-3/ISM: 5.725-5.850 GHz
Shared propagation channel: **Multiplexing methods**

→ Examples of multiplexing methods

**FDM**
(Frequency Division Multiplexing)

**TDM**
(Time Division Multiplexing)

**CDM**
(Code Division Multiplexing)

**MF-TDM**
(Multi Frequency - Time Division Multiplexing)
Propagation channel: **Additive noise**

Transmitted signal $x(t)$ → $h_c(t)$ → Received signal $y(t)$

Some noise is added to the transmitted signal by the propagation channel

- **Noise characteristics:**

  → White noise, with PSD = $N_0/2$ whatever is the frequency, with $N_0 = k(T_e + T_i)$
    - $k =$ Bolzmann constant
    - $T_e =$ external noise temperature
    - $T_i =$ internal noise temperature

  → Gaussian Noise, with power $\sigma^2$

  → Added at the receiver input, assuming then that its components are ideal,

  → A dégradation measurement: the Signal to Noise Ratio or SNR

$$\text{SNR}_{\text{dB}} = 10 \log \left( \frac{P_{\text{useful signal}}}{P_{\text{noise}}} \right)$$
→ Additive noise:
  → Other signals received in addition to the useful communication signal.
  → Coming from natural sources: atmosphere (storm, lightning, thunder), earth, sky (sun, milky way)
  → Coming from artificial sources: human activity.
  → Electronic devices in the receiver: amplifiers, antenna, etc.

→ Examples of introduced distortions

Examples:

- NRZ-type transmitted signal
- Noisy signal, $\text{SNR}_{\text{dB}} = 10 \text{ dB}$
- Noisy signal, $\text{SNR}_{\text{dB}} = 0 \text{ dB}$
Propagation channel

One or several paths between the transmitter and the receiver

- Only one path: the line of sight (LOS) between the transmitter and the receiver

\[ y(t) = \alpha x(t-\tau) + n(t) \]

- Several paths between the transmitter and the receiver (« multi-paths » channel)

\[ y(t) = \sum_{k=0}^{N-1} \alpha_k x(t-\tau_k) + n(t) \]
- Only the line of sight between the transmitter and the receiver

\[ y(t) = \alpha x(t - \tau) + n(t) = \alpha \delta(t - \tau) * x(t) + n(t) \]

- Several paths between the transmitter and the receiver (« multi-paths » channel)

\[ y(t) = \sum_{k=0}^{N-1} \alpha_k x(t - \tau_k) + n(t) = \sum_{k=0}^{N-1} \alpha_k \delta(t - \tau_k) * x(t) + n(t) \]

- Propagation channel model

The transmitted signal is filtered by the propagation channel
Propagation channel
One or several paths between the transmitter and the receiver

- Propagation channel model

\[ x(t) \xrightarrow{h_c(t)} y(t) \]

\[ n(t) \]

The transmitted signal is filtered by the propagation channel

- AWGN (Additive White Gaussian Noise) channel

\[ |H_c(f)| \]

\[ \text{Arg}(H_c(f)) \]

\[ f \]
Propagation channel
One or several paths between the transmitter and the receiver

- Propagation channel model

![Diagram showing the transmitted signal being filtered by the propagation channel.]

\[ x(t) \xrightarrow{h_c(t)} y(t) \]

- Limited bandwidth AWGN channel

**Baseband transmission:**

**Carrier modulated transmission:**

![Graphs showing the magnitude and phase of the channel transfer function for baseband and carrier modulated transmission.]

\[ |H_c(f)| \]
Propagation channel
Example of a band limited AWGN channel: DVB-S fixed satellite transmission

In bands L(1.4-1.6 GHz), C(4-6 GHz), Ku(10.70-12.75 GHz) ou Ka(20-30 GHz).

Several services

36 MHz (a transponder)

BW1 BW2 BW3
Propagation channel
One or several paths between the transmitter and the receiver

- Propagation channel model

The transmitted signal is filtered by the propagation channel

\[ x(t) \rightarrow h_c(t) \rightarrow y(t) \]

\[ n(t) \]

- Frequency selective channel

→ « Channel coherence bandwidth »: widest frequency band for which the channel can be considered as « flat »
Example of distorsions introduced by a frequency selective channel

Propagation channel
Example of a frequency selective channel: DTV (DVB-T) transmission

- PSD of the transmitted signal: Fréquences normalisées
- PSD of the received signal: Fréquences normalisées

Transmitted image:

Received image:
Propagation channel

**Fixed or mobile transmission**

- **Fixed transmission**

\[
y(t) = \sum_{k=0}^{N-1} \alpha_k x(t - \tau_k) + n(t)
\]

- **Mobile transmission**

\[
y(t) = \sum_{k=0}^{N-1} \alpha_k(t)x(t - \tau_k(t)) + n(t)
\]

→ « Channel coherence time » : duration for which the channel impulse response can be considered as invariant (stationnary channel)
Basic digital transmission channel

Analog signal: sound, image ...

Digitization

Binary information to transmit: 0 1 1 0 0 1 0 1 1 0

Transmitter

Analog signal

Transmission channel

Corrupted analog signal

Receiver

Received Binary information: 0 1 1 0 0 1 0 1 1 0
Basic digital transmission channel

Example:

Analog signal:

\[ V - t \]

Corrupted analog signal:

\[ V - t \]

\[ V - t \]

\[ V - t \]

SNR = 10 dB:

\[ V - t \]

\[ V - t \]

BER = 2.38 \times 10^{-6}

SNR = 0 dB:

\[ V - t \]

\[ V - t \]

BER = 0.0784

Analog signal:

\[ V - t \]

Transmission channel

Corrupted analog signal

Receiver

Received binary information: 0 1 0 1 1 1 1 1

Transmitter

Binary information to transmit: 0 1 1 0 0 1 0 1 1 0

Digitization

Analog signal: sound, image ...
Basic digital transmission channel

Analog signal: sound, image ...

Digitization

Binary information to transmit: 0 1 1 0 0 1 0 1 1 0

Transmitter

Analog signal

Transmission channel

Corrupted analog signal

Receiver

Transmission quality is improved:
Quality criterion is the Bit Error Rate (BER) which can be very low even with corrupted received analog signals. Of course BER is a function of SNR.

Received Binary information: 0 1 1 0 0 1 0 1 1 0
Basic digital transmission channel

- **Analog signal**: sound, image ...
  - Digitization
  - Binary information to transmit: 0 1 1 0 0 1 0 1 1 0
  - **Transmitter**
  - **Analog signal**
  - **Transmission channel**
  - **Corrupted analog signal**
  - **Receiver**

- **Received Binary information**: 0 1 1 0 0 1 0 1 1 0

**Transmission quality is improved**: Quality criterion is the Bit Error Rate (BER) which can be very low even with corrupted received analog signals. Of course BER is a function of SNR.

**Price to pay**: occupied bandwidth is larger for digital transmissions.

Example: fixed phone digitization

- \( B_{\text{analog}} = 3.1 \text{ kHz} \)
- \( B_{\text{digital}} \approx 64 \text{ kHz} \) (\( Fe=8\text{kHz} \), \( nb=8 \text{ bits} \))

But source coding will help on this point!
Basic digital transmission channel: source coding

Binary information to transmit: 0 1 1 0 0 1 0 ...

Source coding

Physical layer

Analog signal

Transmission channel

Disturbed analog signal

Physical layer

Source decoding

Received Binary information: 0 1 0 1 0 1 1 ...
Message to transmit: EMMENE MOI A LA MER

Natural binary coding:
9 different characters = > 4 bits per character ($2^4=16$)

<table>
<thead>
<tr>
<th>E</th>
<th>M</th>
<th>Espace</th>
<th>A</th>
<th>N</th>
<th>I</th>
<th>O</th>
<th>R</th>
<th>L</th>
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<td>4/19</td>
<td>4/19</td>
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<td>0100</td>
<td>0101</td>
<td>0110</td>
<td>0111</td>
<td>1000</td>
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</tbody>
</table>

$$19 \times 4 = 76 \text{ bits to be sent, example with 2G transmission (9,6 kbps) : 0,79 ms}$$

Smarter code (Huffman) :

<table>
<thead>
<tr>
<th>E</th>
<th>M</th>
<th>Espace</th>
<th>A</th>
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<td>1/19</td>
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<td>1/19</td>
<td>1/19</td>
<td>1/19</td>
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<tr>
<td>01</td>
<td>10</td>
<td>11</td>
<td>0000</td>
<td>0011</td>
<td>00100</td>
<td>00101</td>
<td>00010</td>
<td>00011</td>
</tr>
</tbody>
</table>

$$12 \times 2 + 3 \times 4 + 4 \times 5 = 56 \text{ bits to be sent, example with 2G transmission (9,6 kbps) : 0,58 ms}$$

Gain : 26,32 %
Analog signal: sound, image ...

Digitization

Binary information to transmit: 0 1 1 0 0 1 0 1 1 0

Transmitter

Analog signal

Transmission channel

Corrupted analog signal

Receiver

Received Binary information: 0 1 1 0 0 1 0 1 1 0

Transmission quality is improved:
Quality criterion is the Bit Error Rate (BER) which can be very low even with corrupted received analog signals. Of course BER is a function of SNR.

Of course there is a price to pay: occupied bandwidth is larger for digital transmissions. But source coding will help on this point!
Basic digital transmission channel

Analog signal: sound, image ...

Digitization

Binary information to transmit: 0 1 1 0 0 1 0 1 1 0

Transmitter

Analog signal

Transmission channel

Corrupted analog signal

Receiver

Received Binary information: 0 1 1 0 0 1 0 1 1 0

Transmission quality is improved:
Quality criterion is the Bit Error Rate (BER) which can be very low even with corrupted received analog signals. Of course BER is a function of SNR.

New functions (digital functions) can be used in the transmission channel, like channel coding allowing to obtain the same BER with a lower transmitted power.

Of course there is a price to pay: occupied bandwidth is larger for digital transmissions. But source coding will help on this point!
Basic digital transmission channel: channel coding

Binary information to transmit: 0 1 1 0 0 1 0 ...

Source coding

Channel coding

Physical layer

Analog signal

Transmission channel

Disturbed analog signal

Channel decoding

Physical layer

Source decoding

Received Binary information: 0 1 0 1 0 1 1 ...
Example of channel coding

Binary information to transmit:
0 1 1 0

Channel coding

Coded Binary information:
0 0 0 1 1 1 1 1 1 0 0 0

Modulation

Analog signal

Transmission channel

Corrupted analog signal

Demodulation

Corrupted coded binary information:
0 0 1 1 0 0 1 1 1 1 1 1 1

Channel decoding

Decoded Binary information:
0 0 1 1

Adding redundancy
Coding rate = 1/3

Detection ability: 2 errors
Correction ability: 1 error
Basic digital transmission channel: **modulation**

- **Binary information to transmit:** 0 1 1 0 0 1 0 ...

- **Source coding**
  - **Channel coding**
    - **Modulation**
      - **Analog signal**
        - **Transmission channel**
          - **Disturbed analog signal**
            - **Demodulation**
              - **Channel decoding**
                - **Source decoding**

- **Received Binary information:** 0 1 0 1 0 1 1 ...
Example of Modulation

Binary information to transmit: 0 1 1 0

Channel coding

Coded Binary information: 0 0 1 1 1 1 1 1 0 0 0

Baseband Modulation

(Frequency Transposition)

Digital signal

Digital to Analog Convertor

Analog signal

Example: NRZ signal

Transmission channel

Retrieved binary information: 0 0 1 1

BER=2/4

Channel decoding

Corrupted coded Binary information: 0 0 1 1 0 0 1 1 1 1 1 1 1

Baseband Demodulation

(Down conversion)

Corrupted Digital signal

Analog To Digital Convertor

Corrupted Analog signal

SNR=0 dB
Basic digital transmission channel: synchronization

Binary information to transmit: 0 1 1 0 0 1 0 ...

Source coding

Channel coding

Modulation

DAC

Analog signal

Transmission channel

Corrupted analog signal

ADC

Demodulation

Channel decoding

Synchronization

Source decoding

Received Binary information: 0 1 0 1 0 1 1 ...
Synchronization on the clock (« in time ») and on the carrier (« in frequency »)

- On the clock

  Binary information to transmit:
  
<table>
<thead>
<tr>
<th>0</th>
<th>1</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
</table>

  Signal:
  
  \[ V \]
  
  \[ -V \]
  
  \[ T_s \text{ : symbol duration} \]

  Time 0

- On the carrier (for carrier-modulated transmissions)

  Carrier frequency error

  Baseband signal:
  Spectrum around frequency 0

  Carrier-modulated signal:
  Spectrum around a given carrier frequency \( f_p \)

  Down conversion before baseband demodulation
Basic digital transmission channel: performance criteria

Binary information to transmit: 0 1 1 0 0 1 0 ...

Source coding

Channel coding

Modulation

DAC

Analog signal

Transmission channel

Corrupted analog signal

ADC

Demodulation

Synchronization

Channel decoding

Source decoding

Transmitter

Received Binary information: 0 1 0 1 1 1 ...

Bit rate $R_b$

Spectral Efficiency:
needed bandwidth $B$ to transmit wanted $R_b$

Power Efficiency:
needed SNR per bit at the receiver input to achieve wanted BER

Bit Error Rate (BER)

Needed transmission bandwidth $B$

Needed SNR
Channel transmission is designed to:

- Transmit a given bit rate
  \[ R_b = \text{Number of bits to be transmitted per second.} \]

It will cost in terms of:

- Needed bandwidth \( B \) in the transmission channel

<table>
<thead>
<tr>
<th>Bit Rate ( R_{\text{u}} ) (after MUX) [Mbit/s]</th>
<th>Bit Rate ( R'_{\text{u}} ) (after RS) [Mbit/s]</th>
<th>Symbol Rate [Mbaud]</th>
<th>Convolut. Inner Code Rate</th>
<th>RS Outer Code Rate</th>
<th>C/N (33 MHz) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.754</td>
<td>25.776</td>
<td>25.776</td>
<td>1/2</td>
<td>188/204</td>
<td>4.1</td>
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<td>31.672</td>
<td>34.366</td>
<td>25.776</td>
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<td>188/204</td>
<td>5.8</td>
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<td>35.631</td>
<td>38.664</td>
<td>25.776</td>
<td>3/4</td>
<td>188/204</td>
<td>6.8</td>
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<td>39.500</td>
<td>42.960</td>
<td>25.776</td>
<td>5/6</td>
<td>188/204</td>
<td>7.8</td>
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<td>41.570</td>
<td>45.108</td>
<td>25.776</td>
<td>7/8</td>
<td>188/204</td>
<td>8.4</td>
</tr>
</tbody>
</table>

**DVB-S example: satellite broadcasting for muti-media contents**

**Quasi Error Free (QEF) transmission:**

\[ \text{BER} < 10^{-10} \]

- Achieve a given Bit Error Rate

\[ \text{BER} = \frac{\text{Number of erroneous bits}}{\text{Number of transmitted bits}} < 1 \]

- Needed SNR at the receiver input \( \Rightarrow \) needed transmitted power.
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