Sampling

Pulse Amplitude Modulation
Pulse Code Modulation
Sampling Rate: Nyquist Theorem
How Many Bits per Sample?
Bit Rate
PAM - Pulse Amplitude Modulation

a. Analog signal

b. PAM signal
Pulse amplitude modulation has some applications, but it is not used by itself in data communication.

However, it is the first step in another very popular conversion method called pulse code modulation.
PCM Pulse Code Modulation Quantized PAM signal

PCM modifies the pulses created by PAM to create a completely digital signal. PCM quantizes the PAM pulses (assigns integer values in a specific range to sampled instances.)

Amplitude

Time

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Sign Bit</th>
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<tbody>
<tr>
<td>+024</td>
<td>00011000</td>
</tr>
<tr>
<td>+038</td>
<td>00100110</td>
</tr>
<tr>
<td>+048</td>
<td>00110000</td>
</tr>
<tr>
<td>+039</td>
<td>00100111</td>
</tr>
<tr>
<td>+026</td>
<td>00011010</td>
</tr>
<tr>
<td>-015</td>
<td>10011000</td>
</tr>
<tr>
<td>-080</td>
<td>10110010</td>
</tr>
<tr>
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<td>+127</td>
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</table>
PCM

Direction of transfer

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<tr>
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<th>-015</th>
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<tr>
<td>+024</td>
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<td>+127</td>
<td>01111111</td>
<td>+077</td>
<td>01001101</td>
</tr>
</tbody>
</table>

Sign bit
+ is 0  – is 1
From analog signal to PCM digital code

- Analog data
- Sampled analog data
- PAM
- Binary encoding
- Quantified data
- Quantization
- Line coding
- Binary data
- Digital signal
According to the Nyquist theorem, the sampling rate must be at least 2 times the highest frequency.

- Highest frequency = $x$ Hz
- Sampling rate = $2x$ samples/s
- Sampling interval = $\frac{1}{2^x}$
1. What sampling rate is needed for a signal with a bandwidth of 10,000 Hz (1000 to 11,000 Hz)?

*The sampling rate must be twice the highest frequency in the signal:*

\[
\text{Sampling rate} = 2 \times (11,000) = 22,000 \text{ samples/s}
\]

2. We want to digitize the human voice. What is the bit rate, assuming 8 bits per sample?

The human voice normally contains frequencies from 0 to 4000 Hz.

\[
\text{Sampling rate} = 4000 \times 2 = 8000 \text{ samples/s}
\]

\[
\text{Bit rate} = \text{sampling rate} \times \text{number of bits per sample}
\]

\[
= 8000 \times 8 = 64,000 \text{ bps} = 64 \text{ Kbps}
\]
Note that we can always change a band-pass signal to a low-pass signal before sampling. In this case, the sampling rate is twice the bandwidth.
Transmission Mode

Parallel Transmission

Serial Transmission
Data transmission

- Parallel
- Serial
  - Synchronous
  - Asynchronous
Parallel transmission

The 8 bits are sent together

We need eight lines.
Serial transmission

The 8 bits are sent one after another.

We need only one line (wire).

Parallel/serial converter

Serial/parallel converter
In asynchronous transmission:

we send

• 1 start bit (0) at the beginning and

• 1 or more stop bits (1s) at the end of each byte.

There may be a gap between each byte.

Asynchronous here means “asynchronous at the byte level,” but the bits are still synchronized; their durations are the same.
Asynchronous transmission
In synchronous transmission, we send bits one after another without start/stop bits or gaps. It is the responsibility of the receiver to group the bits.
Analog Transmission
Modulation of Digital Data

Digital-to-Analog Conversion
Amplitude Shift Keying (ASK)
Frequency Shift Keying (FSK)
Phase Shift Keying (PSK)
Quadrature Amplitude Modulation
Bit/Baud Comparison
Figure 5.1  Digital-to-analog modulation
Types of digital-to-analog modulation

- **ASK** - Amplitude shift keying
- **FSK** - Frequency shift keying
- **PSK** - Phase shift keying
- **QAM** - Quadrature amplitude modulation
• **Bit rate is the number of bits per second.**
• **Baud rate is the number of signal units per second.**
• **Baud rate is less than or equal to the bit rate.**

\[
\text{Baud rate} = \frac{\text{Bit rate}}{\text{nr of bits per signal unit}}
\]
1. An analog signal carries 4 bits in each signal unit.

If 1000 signal units are sent per second, find the baud rate and the bit rate

\[
\text{Baud rate} = 1000 \text{ bauds per second (baud/s)} \\
\text{Bit rate} = 1000 \times 4 = 4000 \text{ bps}
\]

2. The bit rate of a signal is 3000.

If each signal unit carries 6 bits, what is the baud rate?

\[
\text{Baud rate} = \frac{3000}{6} = 500 \text{ baud/s}
\]
ASK Amplitude Shift Keying

Frequency and phase remain constant while the amplitude changes

**ASK:**
\[ s(t) = A \cos(2 \pi f_c t) \text{ binary 1} \]
\[ s(t) = B \cos(2 \pi f_c t) \text{ binary 0} \]
Relationship between baud rate and bandwidth in ASK

\[ BW = (1 + d) \times N_{\text{baud}} \]

Where:
- \( BW \) is the bandwidth;
- \( N_{\text{baud}} \) is the baud rate;
- \( f_c \) is the carrier frequency;
- \( d \) is a factor related to the modulation process.
Example

Find the minimum bandwidth for an ASK signal transmitting at 2000 bps. The transmission mode is half-duplex.

Solution

In ASK the *baud rate and bit rate* are the same. The baud rate is therefore 2000. An ASK signal requires a minimum bandwidth equal to its baud rate. Therefore, the minimum bandwidth is 2000 Hz.
Given a bandwidth of 5000 Hz for an ASK signal, what are the baud rate and bit rate?

In ASK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But because the baud rate and the bit rate are also the same for ASK, the bit rate is 5000 bps.
**Example**

Given a bandwidth of 10,000 Hz (1000 to 11,000 Hz), draw the full-duplex ASK diagram of the system. Find the carriers and the bandwidths in each direction. Assume there is no gap between the bands in the two directions.

For full-duplex ASK, the bandwidth for each direction is

\[ BW = \frac{10000}{2} = 5000 \text{ Hz} \]

The carrier frequencies can be chosen at the middle of each band

\[ f_c \text{ (forward)} = 1000 + \frac{5000}{2} = 3500 \text{ Hz} \]

\[ f_c \text{ (backward)} = 11000 - \frac{5000}{2} = 8500 \text{ Hz} \]
In FSK the frequency of the carrier signal is varied to represent binary 1 or 0.

Both peak amplitude and phase remain constant.

FSK:

\[ s(t) = A \cos(2\pi f_c t) \text{ binary 1} \]
\[ s(t) = A \cos(2\pi f_c t) \text{ binary 0} \]
The bandwidth for FSK is equal to the baud rate $N_{\text{baud}}$ of the signal plus the frequency shift (difference between the two carrier frequencies)

$$BW = f_{c1} - f_{c0} + N_{\text{baud}}$$
Example

Find the minimum bandwidth for an FSK signal transmitting at 2000 bps. Transmission is in half-duplex mode, and the carriers are separated by 3000 Hz.

Solution

For FSK

\[ BW = \text{baud rate} + f_{c1} - f_{c0} \]

\[ BW = \text{bit rate} + f_{c1} - f_{c0} = 2000 + 3000 = 5000 \text{ Hz} \]
**Example**

Find the maximum bit rates for an FSK signal if the bandwidth of the medium is 12,000 Hz and the difference between the two carriers is 2000 Hz. Transmission is in full-duplex mode.

**Solution**

Because the transmission is full duplex, only 6000 Hz is allocated for each direction.

\[
BW = \text{baud rate} + f_{c1} - f_{c0}
\]

Baud rate = \(BW - (f_{c1} - f_{c0}) = 6000 - 2000 = 4000\)

But because the baud rate is the same as the bit rate, the bit rate is 4000 bps.
PSK – Phase Shift Keying

In PSK the phase of the carrier signal is varied to represent binary 1 or 0. Both peak amplitude and frequency remain constant.

ASK:

\[ s(t) = A \cos(2\pi f_c t) = A \cos(2\pi f_c t) \quad \text{binary 1} \]
\[ s(t) = A \cos(2\pi f_c t + \pi) = -A \cos(2\pi f_c t) \quad \text{binary 0} \]

\[ S_d(t) = A d(t) \cos(2\pi f_c t) \]

\[ d(t) = +1 \text{ for bits "1"} \]
\[ d(t) = -1 \text{ for bits "0"} \]

<table>
<thead>
<tr>
<th>Bit</th>
<th>Phase</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>1</td>
<td>180</td>
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</table>

Constellation diagram

Amplitude

Bit rate: 5  Baud rate: 5

1 baud 1 baud 1 baud 1 baud 1 baud

1 bit 1 bit 1 bit 1 bit 1 bit

0 1 1 0 1

1 s
The 4-PSK characteristics

\[ S(t) = A \cos(2 \pi f_c t) \]
\[ S(t) = A \cos(2 \pi f_c t + \pi/2) \]
\[ S(t) = A \cos(2 \pi f_c t + \pi) \]
\[ S(t) = A \cos(2 \pi f_c t + 3\pi/2) \]

<table>
<thead>
<tr>
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<th>Phase</th>
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<tbody>
<tr>
<td>00</td>
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<td>10</td>
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<td>11</td>
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The 8-PSK characteristics

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<tr>
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<tr>
<td>111</td>
<td>315</td>
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</table>

Tribits (3 bits)

Constellation diagram
Relationship between baud rate and bandwidth in PSK

Amplitude

Frequency

Minimum bandwidth = \( N_{\text{baud}} \)

\( f_c - N_{\text{baud}}/2 \)

\( f_c - N_{\text{baud}}/2 \)
Example

Find the bandwidth for a 4-PSK signal transmitting at 2000 bps. Transmission is half-duplex mode.

Solution

For 4-PSK the baud rate is one-half of the bit rate. The baud rate is therefore 1000. A PSK require a bandwidth equal to its baud rate. Therefore, the bandwidth is 1000 Hz.
Example

Given a bandwidth of 5000 Hz for an 8-PSK signal, what are the baud rate and bit rate?

Solution

For PSK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But in 8-PSK the bit rate is 3 times the baud rate, So the bit rate is 15,000 bps.
Quadrature amplitude modulation is a combination of ASK and PSK so that a maximum contrast between each signal unit (bit, dabit, tribit, and so on) is achieved.
Quadrature Amplitude Modulation

- QAM used on asymmetric digital subscriber line (ADSL) and some wireless
- Combination of ASK and PSK
- Logical extension of QPSK
- Send two different signals simultaneously on same carrier frequency
  - Use two copies of carrier, one shifted 90°
  - Each carrier is ASK modulated
  - Two independent signals over same medium
  - Demodulate and combine for original binary output
QAM Modulator

- Binary input $d(t)$ R bps
- d(t) serial-to-parallel converter
- $d_1(t)$ R/2 bps
- Carrier oscillator
- Phase shift $\phi_p/2$
- $d_2(t)$ R/2 bps
- $\cos 2pf_ct$
- $\sin 2pf_ct$
- QAM signal output $s(t)$
QAM Demodulator
Time domain for an 8-QAM signal

Bit rate: 24

Baud rate: 8

Amplitude

3 bits 3 bits 3 bits 3 bits 3 bits 3 bits 3 bits 3 bits

101 100 001 000 010 011 110 111

1 baud 1 baud 1 baud 1 baud 1 baud 1 baud 1 baud 1 baud

1 s
16-QAM constellations

3 amplitudes, 12 phases

4 amplitudes, 8 phases

2 amplitudes, 8 phases
<table>
<thead>
<tr>
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<th>Baud rate = $N$</th>
<th>Bit rate = $N$</th>
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<tbody>
<tr>
<td></td>
<td>0 0 1 0 1 0 0 0</td>
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<table>
<thead>
<tr>
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<table>
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<table>
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<tr>
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### Bit and baud rate comparison

<table>
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<th>Units</th>
<th>Bits/Baud</th>
<th>Baud rate</th>
<th>Bit Rate</th>
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<td>N</td>
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<td>4-PSK, 4-QAM</td>
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<td>2N</td>
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<td>3N</td>
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<td>Quadbit</td>
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<td>4N</td>
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<td>Hexabit</td>
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<td>N</td>
<td>6N</td>
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<td>128-QAM</td>
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<tr>
<td>256-QAM</td>
<td>Octabit</td>
<td>8</td>
<td>N</td>
<td>8N</td>
</tr>
</tbody>
</table>
**Example**

A constellation diagram consists of eight equally spaced points on a circle. If the bit rate is 4800 bps, what is the baud rate?

**Solution**

The constellation indicates 8-PSK with the points 45 degrees apart.

Since $2^3 = 8$,
3 bits are transmitted with each signal unit.

Therefore, the baud rate is:

$$\frac{4800}{3} = 1600 \text{ baud}$$
Example

Compute the bit rate for a 1000-baud 16-QAM signal.

Solution

A 16-QAM signal has 4 bits per signal unit since
\[ \log_2 16 = 4. \]
Thus,
\[ (1000) \times (4) = 4000 \text{ bps} \]
Example 12

Compute the baud rate for a 72,000-bps 64-QAM signal.

Solution

A 64-QAM signal has 6 bits per signal unit since
\[ \log_2 64 = 6. \]

Thus,

\[ 72000 / 6 = 12,000 \text{ baud} \]
Modem Standards
A telephone line has a bandwidth of almost 2400 Hz for data transmission.
Modem stands for modulator/demodulator.
The V.32 constellation and bandwidth

FDX 2400 baud
9600 bps 2-wire
The V.32bis constellation and bandwidth

FDX, 2400 baud
14,400 bps 4-wire
Traditional modems

Sampling and noise here limits communication from A to B

- PCM
  - Telco
  - Modem: 01101
  - A

- Telephone network
  - A to B
    - Quantization noise happens in the telco office near A

- Inverse PCM
  - Modem: 01101
  - B

Sampling and noise here limits communication from B to A

- Telephone network
  - B to A
    - Quantization noise happens in the telco office near B

- PCM
  - Telco
  - Modem: 01101
  - A

- B