Chapter 5

Analog Transmission
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
Figure 5.2  Types of digital-to-analog modulation

- ASK
- FSK
- PSK
- QAM
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.
**Example 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.

**Solution**

Baud rate = 1000 bauds per second (baud/s)

Bit rate = 1000 x 4 = 4000 bps
Example 2

The bit rate of a signal is 3000. If each signal unit carries 6 bits, what is the baud rate?

Solution

Baud rate = 3000 / 6 = 500 baud/s
Figure 5.4  Relationship between baud rate and bandwidth in ASK

Minimum bandwidth = $N_{\text{baud}}$

$f_c - N_{\text{baud}}/2$

$f_c + N_{\text{baud}}/2$
Example 3

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.
Example 4

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

Solution

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 5

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.

Solution

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 (see Fig. 5.5).

$$fc \ (\text{forward}) = 1000 + \frac{5000}{2} = 3500 \text{ Hz}$$
$$fc \ (\text{backward}) = 11000 - \frac{5000}{2} = 8500 \text{ Hz}$$
Figure 5.5  Solution to Example 5

Amplitude

\[ f_C(\text{backward}) \]

\[ f_C(\text{forward}) \]

Frequency

1000  3500  6000  8500  11,000
Figure 5.6  FSK

Amplitude

Bit rate: 5  Baud rate: 5

1 bit  1 bit  1 bit  1 bit  1 bit
0     1     1     0     1

1 baud  1 baud  1 baud  1 baud  1 baud

1 s
Figure 5.7  Relationship between baud rate and bandwidth in FSK

\[ BW = f_{c1} - f_{c0} + N_{baud} \]
Example 6

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

\[
BW = \text{baud rate} + f_{c1} - f_{c0} \\
BW = \text{bit rate} + fc1 - fc0 = 2000 + 3000 = 5000 \text{ Hz}
\]
Example 7

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.

\[BW = \text{baud rate} + fc1 - fc0\]

\[
\text{Baud rate} = BW - (fc1 - fc0) = 6000 - 2000 = 4000
\]

But because the baud rate is the same as the bit rate, the bit rate is 4000 bps.
Figure 5.8  PSK

Amplitude

Bit rate: 5

1 bit  1 bit  1 bit  1 bit  1 bit
0     1     1     0     1

Baud rate: 5

1 baud 1 baud 1 baud 1 baud 1 baud

1 s
Figure 5.9  PSK constellation

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

Constellation diagram
Figure 5.10  The 4-PSK method

Amplitude

<table>
<thead>
<tr>
<th>Bit rate: 10</th>
<th>Baud rate: 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 bits</td>
<td>2 bits</td>
</tr>
<tr>
<td>01</td>
<td>10</td>
</tr>
<tr>
<td>2 bits</td>
<td>2 bits</td>
</tr>
<tr>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>2 bits</td>
<td>2 bits</td>
</tr>
<tr>
<td>00</td>
<td>1 baud</td>
</tr>
<tr>
<td>1 baud</td>
<td>1 baud</td>
</tr>
<tr>
<td>1 baud</td>
<td>1 baud</td>
</tr>
<tr>
<td>1 baud</td>
<td>1 baud</td>
</tr>
</tbody>
</table>

Time

1 s
Figure 5.11 *The 4-PSK characteristics*

<table>
<thead>
<tr>
<th>Dibit</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>0</td>
</tr>
<tr>
<td>01</td>
<td>90</td>
</tr>
<tr>
<td>10</td>
<td>180</td>
</tr>
<tr>
<td>11</td>
<td>270</td>
</tr>
</tbody>
</table>

**Constellation diagram**

- 00
- 01
- 10
- 11

**Dibit (2 bits)**
Figure 5.12 The 8-PSK characteristics

<table>
<thead>
<tr>
<th>Tribit</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>0</td>
</tr>
<tr>
<td>001</td>
<td>45</td>
</tr>
<tr>
<td>010</td>
<td>90</td>
</tr>
<tr>
<td>011</td>
<td>135</td>
</tr>
<tr>
<td>100</td>
<td>180</td>
</tr>
<tr>
<td>101</td>
<td>225</td>
</tr>
<tr>
<td>110</td>
<td>270</td>
</tr>
<tr>
<td>111</td>
<td>315</td>
</tr>
</tbody>
</table>

Constellation diagram
Figure 5.13  Relationship between baud rate and bandwidth in PSK

Amplitude

Minimum bandwidth = $N_{\text{baud}}$

Frequency

$f_c - N_{\text{baud}}/2$

$f_c - N_{\text{baud}}/2$
Example 8

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

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.
Example 9

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, dibit, tribit, and so on) is achieved.
Figure 5.14  The 4-QAM and 8-QAM constellations

4-QAM
1 amplitude, 4 phases

8-QAM
2 amplitudes, 4 phases
Figure 5.15  *Time domain for an 8-QAM signal*

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Bit rate: 24</th>
<th>Baud rate: 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 bits</td>
<td>101</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>100</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>001</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>000</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>010</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>011</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>110</td>
<td>3 bits</td>
</tr>
<tr>
<td>3 bits</td>
<td>111</td>
<td>3 bits</td>
</tr>
</tbody>
</table>

1 baud  | 1 baud | 1 baud | 1 baud | 1 baud | 1 baud | 1 baud | 1 baud | 1 baud | 1 s

---

Figure 5.16  **16-QAM constellations**

3 amplitudes, 12 phases

4 amplitudes, 8 phases

2 amplitudes, 8 phases
Figure 5.17  Bit and baud

**Bit**

<table>
<thead>
<tr>
<th>Baud rate = $N$</th>
<th>Bit rate = $N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 1 0 1 0 0 0 1 0 1 0 1 0 1 0</td>
<td></td>
</tr>
</tbody>
</table>

**Dibit**

<table>
<thead>
<tr>
<th>Baud rate = $N$</th>
<th>Bit rate = $2N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 1 0 1 0 0 0 1 0 1 0 1 1 1 0</td>
<td></td>
</tr>
</tbody>
</table>

**Tribit**

<table>
<thead>
<tr>
<th>Baud rate = $N$</th>
<th>Bit rate = $3N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 1 0 1 0 0 0 1 0 1 0 1 1 1 0</td>
<td></td>
</tr>
</tbody>
</table>

**Quadbit**

<table>
<thead>
<tr>
<th>Baud rate = $N$</th>
<th>Bit rate = $4N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 1 0 1 0 0 0 1 0 1 0 1 1 1 0</td>
<td></td>
</tr>
<tr>
<td>Modulation</td>
<td>Units</td>
</tr>
<tr>
<td>------------------</td>
<td>-------</td>
</tr>
<tr>
<td>ASK, FSK, 2-PSK</td>
<td>Bit</td>
</tr>
<tr>
<td>4-PSK, 4-QAM</td>
<td>Dibit</td>
</tr>
<tr>
<td>8-PSK, 8-QAM</td>
<td>Tribit</td>
</tr>
<tr>
<td>16-QAM</td>
<td>Quadbit</td>
</tr>
<tr>
<td>32-QAM</td>
<td>Pentabit</td>
</tr>
<tr>
<td>64-QAM</td>
<td>Hexabit</td>
</tr>
<tr>
<td>128-QAM</td>
<td>Septabit</td>
</tr>
<tr>
<td>256-QAM</td>
<td>Octabit</td>
</tr>
</tbody>
</table>
Example 10

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

\[
4800 / 3 = 1600 \text{ baud}
\]
Example 11

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,
\[ (1000)(4) = 4000 \text{ bps} \]
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,

\[ 72000 \div 6 = 12,000 \text{ baud} \]
5.2 Telephone Modems

Modem Standards
A telephone line has a bandwidth of almost 2400 Hz for data transmission.
Figure 5.18  Telephone line bandwidth

- Used for voice
- Used for data

- 3000 Hz for voice
- 2400 Hz for data
Note:

Modem stands for modulator/demodulator.
Figure 5.19  Modulation/demodulation
Figure 5.20  The V.32 constellation and bandwidth

FDX 2400 baud
9600 bps 2-wire
Figure 5.21  The V.32bis constellation and bandwidth

FDX, 2400 baud
14,400 bps 4-wire
Figure 5.22  Traditional modems

Sampling and noise here limits communication from A to B

A to B
Quantization noise happens in the telco office near A

B to A
Quantization noise happens in the telco office near B

Sampling and noise here limits communication from B to A
Figure 5.23  56K modems
5.3 Modulation of Analog Signals

Amplitude Modulation (AM)

Frequency Modulation (FM)

Phase Modulation (PM)
Figure 5.24  Analog-to-analog modulation
The total bandwidth required for AM can be determined from the bandwidth of the audio signal:

\[ BW_t = 2 \times BW_m. \]
Figure 5.26  *Amplitude modulation*
Figure 5.27  *AM bandwidth*

\[
\text{BW}_m = \text{bandwidth of the modulating signal (audio)}
\]

\[
\text{BW}_t = \text{total bandwidth (radio)}
\]

\[
f_c = \text{frequency of the carrier}
\]

Amplitude

\[
\text{BW}_t = 2 \times \text{BW}_m
\]

Frequency

\[
\text{BW}_m \quad \text{BW}_m
\]
Figure 5.28  AM band allocation

\[ f_c = \text{carrier frequency of the station} \]
Example 13

We have an audio signal with a bandwidth of 4 KHz. What is the bandwidth needed if we modulate the signal using AM? Ignore FCC regulations.

Solution

An AM signal requires twice the bandwidth of the original signal:

\[ BW = 2 \times 4 \text{ KHz} = 8 \text{ KHz} \]
The total bandwidth required for FM can be determined from the bandwidth of the audio signal:

\[ BW_t = 10 \times BW_m. \]
Figure 5.29  Frequency modulation

Amplitude

Modulating signal (audio)

Time

Amplitude

Carrier frequency

Time

Amplitude

FM signal

Time
Figure 5.30  **FM bandwidth**

- $BW_m = $ bandwidth of the modulating signal (audio)
- $BW_t = $ total bandwidth (radio)
- $f_c = $ frequency of the carrier

Amplitude vs. Frequency diagram with labels:

- $5BW_m$ to $f_c$ to $5BW_m$
- $BW_t = 10 \times BW_m$
The bandwidth of a stereo audio signal is usually 15 KHz. Therefore, an FM station needs at least a bandwidth of 150 KHz. The FCC requires the minimum bandwidth to be at least 200 KHz (0.2 MHz).
Figure 5.31  FM band allocation

\[ f_c = \text{carrier frequency of the station} \]

\[ f_c \quad f_c \quad f_c \quad f_c \quad f_c \quad f_c \]

No station here  No station here  \[ \cdots \]  No station here

88 MHz  \[ \text{200 kHz} \]  108 MHz
Example 14

We have an audio signal with a bandwidth of 4 MHz. What is the bandwidth needed if we modulate the signal using FM? Ignore FCC regulations.

Solution

An FM signal requires 10 times the bandwidth of the original signal:

\[ BW = 10 \times 4 \text{ MHz} = 40 \text{ MHz} \]