Sampling

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

PAM - Pulse Amplitude Modulation

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

+024	00011000	–015	10001111	+125	01111101
+038	00100110	–080	11010000	+110	01101110
+048	00110000	–050	10110010	+090	01011010
+039	00100111	+052	00110110	+088	01011000
+026	00011010	+127	01111111	+077	01001101

Sign bit
+ is 0 – is 1

PCM

+024	00011000	–015	10001111	+125	01111101
+038	00100110	–080	11010000	+110	01101110
+048	00110000	–050	10110010	+090	01011010
+039	00100111	+052	00110110	+088	01011000
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Sign bit
+ is 0 – is 1

From analog signal to PCM

Pulse Code Modulation) digital code

PAM - Pulse Amplitude Modulation

Nyquist theorem

According to the Nyquist theorem, the sampling rate must be at least 2 times the highest frequency.

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:

Sampling rate = 2 x (11,000) = 22,000 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.

Sampling rate = 4000 x 2 = 8000 samples/s

Bit rate = sampling rate x number of bits per sample
= 8000 x 8 = 64,000 bps = 64 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 transmission

Serial transmission

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

Digital-to-analog 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.***

Baud rate= Bit rate / 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

   Baud rate = 1000 bauds per second (baud/s)
   Bit rate = 1000 x 4 = 4000 bps

2. The bit rate of a signal is 3000.

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

   Baud rate = 3000 / 6 = 500 baud/s

Types of digital-to-analog modulation

$$s(t) = A \cdot \sin(2\pi ft + \phi)$$

ASK – Amplitude shift keying - A

FSK – Frequency shift keying - f

PSK – Phase shift keying - ϕ

QAM – Quadrature amplitude modulation

Bit rate, N, is the number of bits per second (bps).
Baud rate is the number of signal elements per second (bauds).

In the analog transmission of digital data, the signal or baud rate is less than or equal to the bit rate.

$$S = N/r \text{ bauds}$$

Where r is the number of data bits per signal element.

ASK Amplitude Shift Keying

Frequency and phase remain constant while the amplitude changes

ASK : $s(t)=A\cos(2\pi f_c t)$ **binary 1**

$s(t)=B\cos(2\pi f_c t)$ **binary 0**

In some cases we can consider B-0

Implementation of binary ASK

Relationship between baud rate and bandwidth in ASK

$$BW=(1+d) \times N_{baud}$$

Where:
BW is the bandwidth;
N_{baud} is the baud rate
f_c=carrier frequency
***d* is a factor related to the modulation process**
N_{baud} is equal with signal rate S

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.

Example

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

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 = 10000 / 2 = 5000 Hz

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

fc (forward) = 1000 + 5000/2 = 3500 Hz

fc (backward) = 11000 – 5000/2 = 8500 Hz

FSK - Frequency Shift Keying

In FSK the frequency of the carrier signal is varied to represent binary 1 or 0.

Both peak amplitude and phase remain constant

FSK : $s(t)=A\cos(2\pi f_{c1}t)$ **binary 1**

$s(t)=A\cos(2\pi f_{c0}t)$ **binary 0**

Relationship between baud rate and bandwidth in FSK

The bandwidth for FSK is equal to the baud rate N_{baud} of the signal plus the frequency shift (difference between the two carrier frequencies)

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

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

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

$$BW = \text{bit rate} + fc1 - fc0 = 2000 + 3000 = 5000 \text{ Hz}$$

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.

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

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

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 : $s(t)=A\cos(2\pi f_c t) = A\cos(2\pi f_c t)$ **binary 1**

$s(t)=A\cos(2\pi f_c t+\pi) = -A\cos(2\pi f_c t)$ **binary 0**

$S_d(t)= A\, d(t)\cos(2\pi f_c t)$

d(t)= +1 for bits "1"

d(t)= -1 for bits"0"

Bit	Phase
0	0
1	180

Bits

Constellation diagram

The 4-PSK characteristics

$S(t)=A\cos(2\pi f_c t)$

$S(t)= A\cos(2\pi f_c t + \pi/2)$

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

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

Dibit	Phase
00	0
01	90
10	180
11	270

Dibit

The 8-PSK characteristics

Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Tribits
(3 bits)

Constellation diagram

Relationship between baud rate and bandwidth in PSK

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.

The 4-QAM and 8-QAM constellations

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.

4-QAM
1 amplitude, 4 phases

8-QAM
2 amplitudes, 4 phases

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

QAM Demodulator

Time domain for an 8-QAM signal

16-QAM constellations

3 amplitudes, 12 phases

16-QAM

4 amplitudes, 8 phases

16-QAM

2 amplitudes, 8 phases

16-QAM

Bit and baud

Bit
Baud rate = N
Bit rate = N
0 0 1 0 1 0 0 0 1 0 1 0 1 0 1 0
Dibit
Baud rate = N
Bit rate = 2N
0 0 1 0 1 0 0 0 1 0 1 0 1 1 1 0
Tribit
Baud rate = N
Bit rate = 3N
0 0 1 0 1 0 0 0 1 0 1 0 1 1 1 0
Quadbit
Baud rate = N
Bit rate = 4N
0 0 1 0 1 0 0 0 1 0 1 0 1 1 1 0

Bit and baud rate comparison

Modulation	Units	Bits/Baud	Baud rate	Bit Rate
ASK, FSK, 2-PSK	Bit	1	N	N
4-PSK, 4-QAM	Dibit	2	N	2N
8-PSK, 8-QAM	Tribit	3	N	3N
16-QAM	Quadbit	4	N	4N
32-QAM	Pentabit	5	N	5N
64-QAM	Hexabit	6	N	6N
128-QAM	Septabit	7	N	7N
256-QAM	Octabit	8	N	8N

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:

$$4800 / 3 = 1600 \text{ baud}$$

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,

$$(1000)*(4) = 4000 \text{ bps}$$

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,

$$72000 / 6 = 12{,}000 \text{ baud}$$

Telephone Modems

Modem Standards

Telephone line bandwidth

A telephone line has a bandwidth of almost 2400 Hz for data transmission.

Modulation/demodulation

Modem stands for modulator/demodulator.

The V.32 constellation and bandwidth

The V.32bis constellation and bandwidth

Traditional modems

56K modems

Sampling and noise
here limits communication
PCM
Telephone
network
ISP
server
Uploading,
quantization noise
Modem
01101
A
Inverse
PCM
Telephone
network
ISP
server
Downloading,
no quantization noise
Modem
01101
A

Modulation of Analog Signals

Amplitude Modulation (AM)

Frequency Modulation (FM)

Phase Modulation (PM)

Analog-to-analog modulation

Types of analog-to-analog modulation

AM - Amplitude Modulation

FM - Frequency Modulation

PM - Phase Modulation

The total bandwidth required for AM can be determined from the bandwidth of the audio signal:

$$BW_t = 2 \times BW_m.$$

Where:

BW_m = bandwidth of the modulating signal (audio)

BW_t = total bandwidth (radio)

Amplitude modulation

x(t)

cos(2 $\pi f_c t$)

AM: $S(t)=[1+n_a x(t)]\cos(2\pi f_c t)$

X(t) –s input signal; **cos(2 $\pi f_c t$) is the carrier**

n_a = modulation index is the ratio of the Amplitude of the iput signal to the carrier

"1" is a dc component that prevents loss of information

Very high frequency signals propagate with very small losses.

Amplitude modulation implementation

AM bandwidth

BW_m = bandwidth of the modulating signal (audio)

BW_t = total bandwidth (radio)

f_c = frequency of the carrier

AM band allocation

AM stations are allowed carrier frequencies anyhere between 530 KHz and 1700 KHz

The bandwidth of an audio signal (speech and music) is usually 5 KHz. Therefore an AM radio station needs a minimum bandwidth of 10 KHz.

The federal Communication Commission (FCC) allows 10 KHz for each AM station.

Example

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:

$$BW = 2 \times 4 \text{ KHz} = 8 \text{ KHz}$$

Frequency Modulation

The total bandwidth required for FM can be determined from the bandwidth of the audio signal:

$$B_{FM} = 2(1 + \beta)B.$$

Where β is usually 4.

Frequency modulation

Frequency modulation

FM bandwidth

BWt = 10 x BWm.

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).

FM band allocation

The FM station are allowed carrier frequencies anywhere between 88MHz and 108 MHz

Station must be separated by a least 200KHz to keep their bandwidths from overlapping.

There are 100 potential FM bandwidth (given 88MHz to 108 MHz as range), 50 can operate at any one time.

Example

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:

$$BW = 10 \times 4 \text{ MHz} = 40 \text{ MHz}$$

Phase Modulation (PM)

- The modulating signal only changes the phase of the carrier signal.
- The phase change manifests itself as a frequency change but the instantaneous frequency change is proportional to the derivative of the amplitude.
- The bandwidth is higher than for AM.

Phase modulation

Note

The total bandwidth required for PM can be determined from the bandwidth and maximum amplitude of the modulating signal:

$$B_{PM} = 2(1 + \beta)B.$$

Where $\beta = 2$ most often.

Example of modulation