Signals and codes

Path and modulation

Communication system

- The goal is to transfer a status message from source to destination.
- Signal quality is decreased by channel noise / interference
- Transferred message might be corrupted / distorted

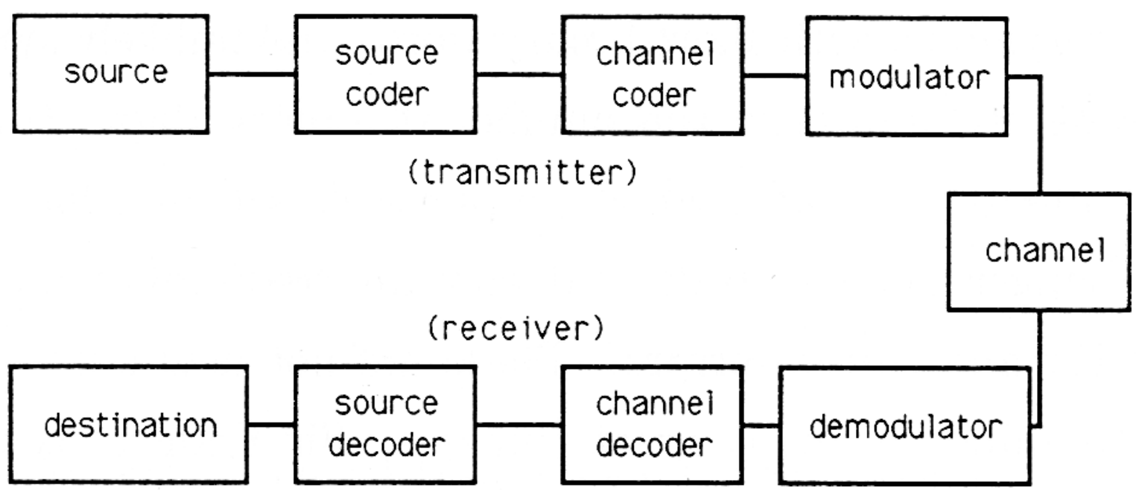
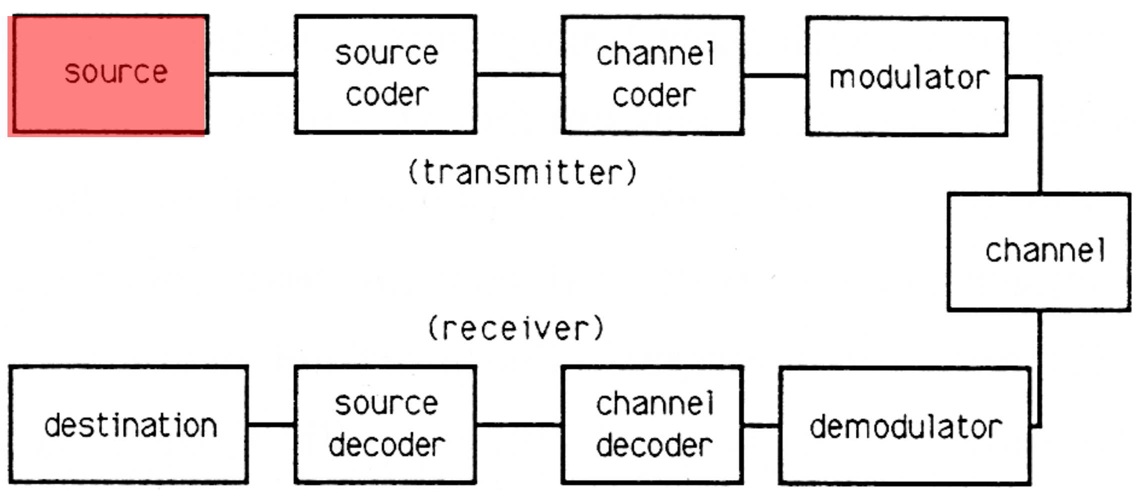


Figure illustrates the basic building blocks that apply to any problem in the theory of (tele-) communication.

Communication system

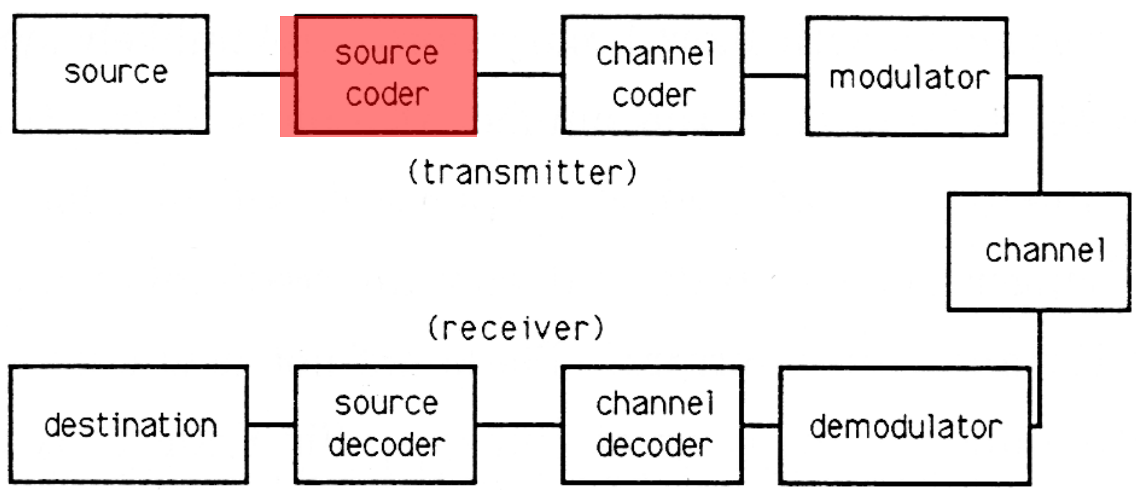


Communication system - source

- The **source** is an arbitrary source of information.

- It can be the time-varying voltage at the output of a vibration sensor (such as an integrating accelerometer for measuring motion or a microphone for measuring sound pressure);
- it can be the charges stored in the CCD array of a solid-state camera;
- it can be the addresses generated from a sequence of keystrokes at a computer terminal;
- it can be a sequence of instructions in a computer program.

Communication system

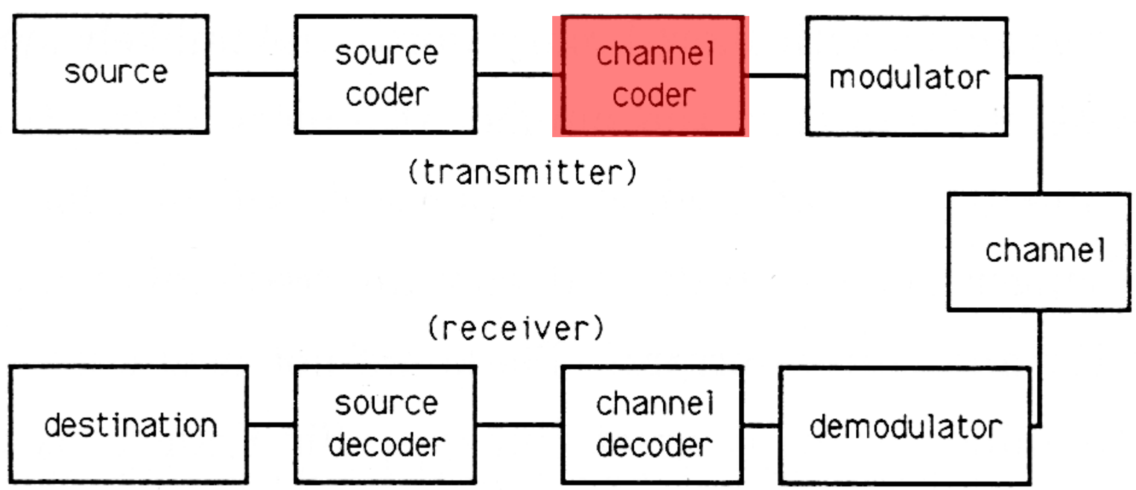


Communication system – source coder

- The **source coder** is a device for turning primitive source outputs into more efficient representations.

- For example, in a recording studio, the source coder would convert analog voltages into digital approximations using an A/D converter;
- a fancy source coder would use a fancy A/D converter that finely quantized likely analog values and crudely quantized unlikely values.
- If the source is a source of discrete symbols like letters and numbers, then a fancy source code would assign short binary sequences to likely symbols (such as e) and long binary sequences to unlikely symbols (such as z).

Communication system

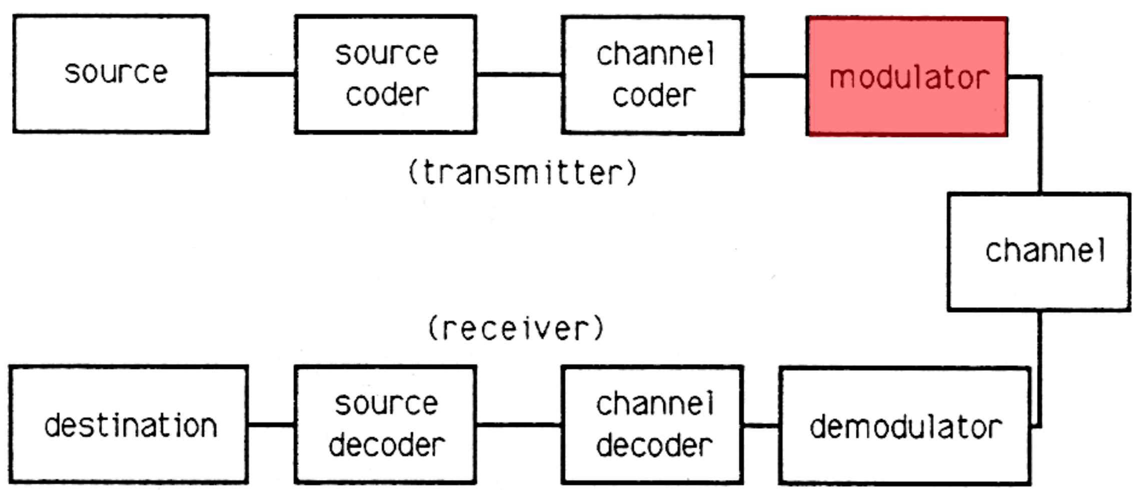


Communication system - channel coder

- The **channel coder** adds “redundant bits” to the binary output of the source coder so that errors of transmission or storage may be detected and corrected.

- In the simplest example, a binary string of the form 01001001 would have an extra bit of 1 added to give even parity (an even number of l's) to the string;
- the string 10110111 would have an extra bit of 0 added to preserve the even parity. If one bit error is introduced in the channel, then the parity is odd and the receiver knows that an error has occurred.

Communication system

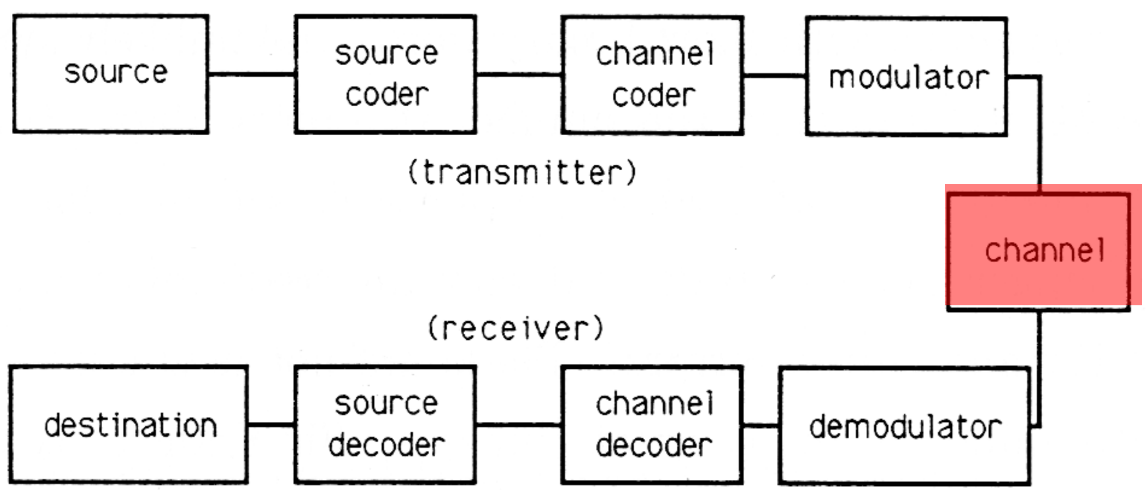


Communication system - modulator

- The **modulator** takes outputs of the channel coder, a stream of binary digits, and constructs an analog waveform that represents a block of bits.

- For example, in a 9600 baud Modem, five bits are used to determine one of 25=32 phases that are used to modulate the signal $A\cos(\omega t+\phi)$. Each possible string of five bits has its own personalized phase, ϕ, and this phase can be determined at the receiver.
- The signal $A\cos(\omega t+\phi)$ is an analog signal that may be transmitted over a channel (such as a telephone line, a microwave link, or a fiber-optic cable).

Communication system

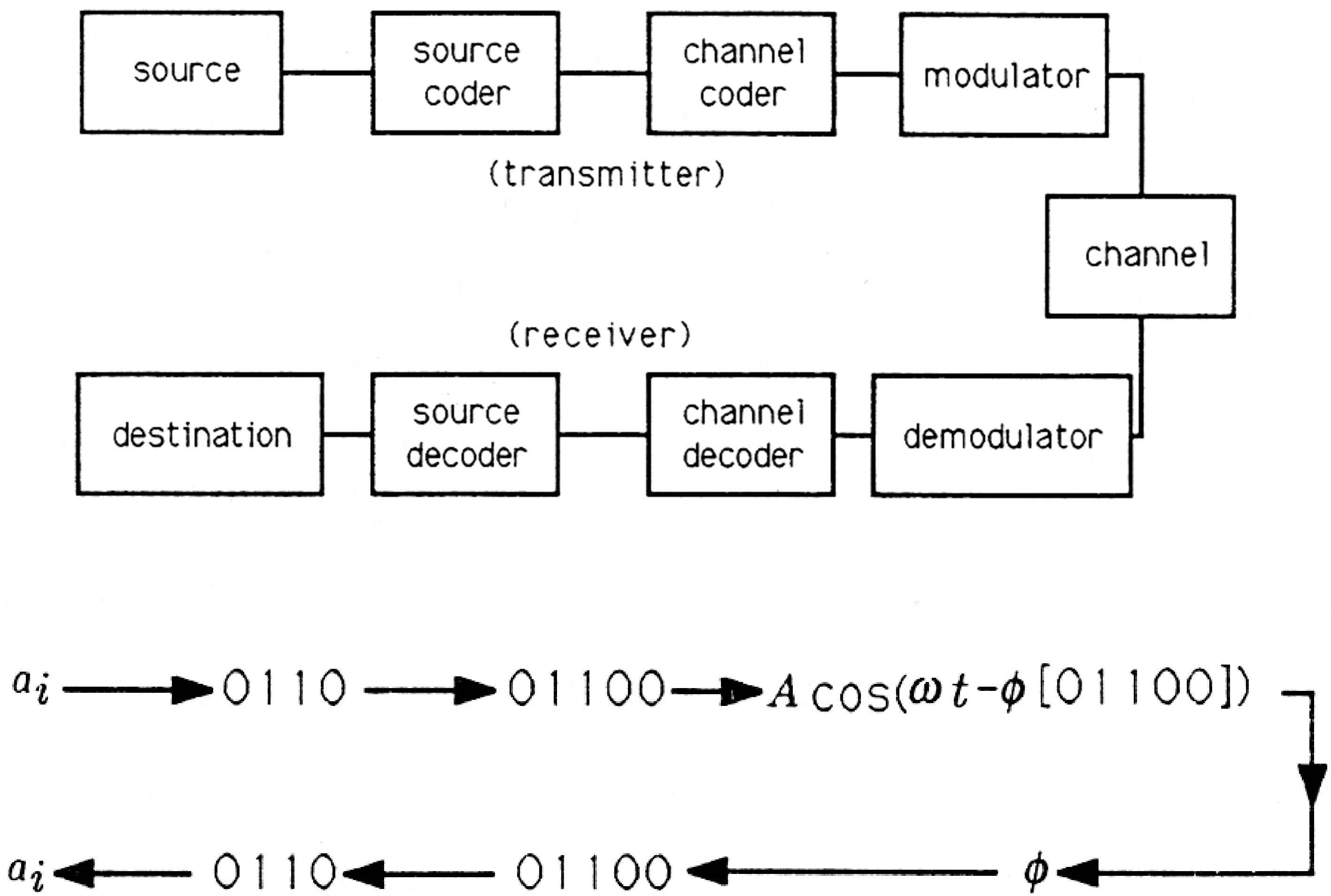


Communication system - channel

- The **channel** has a finite bandwidth, meaning that it distorts signals, and it is subject to noise or interference from other electromagnetic radiation.

- Therefore transmitted information arrives at the demodulator in imperfect form.
- The demodulator uses filters matched to the modulated signals to demodulate the phase and look up the corresponding bit stream.
- The channel decoder converts the coded bit stream into the information bit stream, and
- the source decoder looks up the corresponding symbol.

Communication system



Modulation

What is modulation?

- Modulation is a change or alteration in a signal
  - the process of **varying one or more properties** of a high-frequency periodic waveform, with a *modulating signal* which typically contains information to be transmitted.
  - a high-frequency sinusoid waveform is used as carrier signal, but a square wave pulse train may also be used.

- Any aspect of the signal can be changed:
  - The three key parameters of a periodic waveform are its **amplitude** ("volume"), its **phase** ("timing") and its **frequency** ("pitch"). Any of these properties can be modified in accordance with a low frequency signal to obtain the modulated signal.

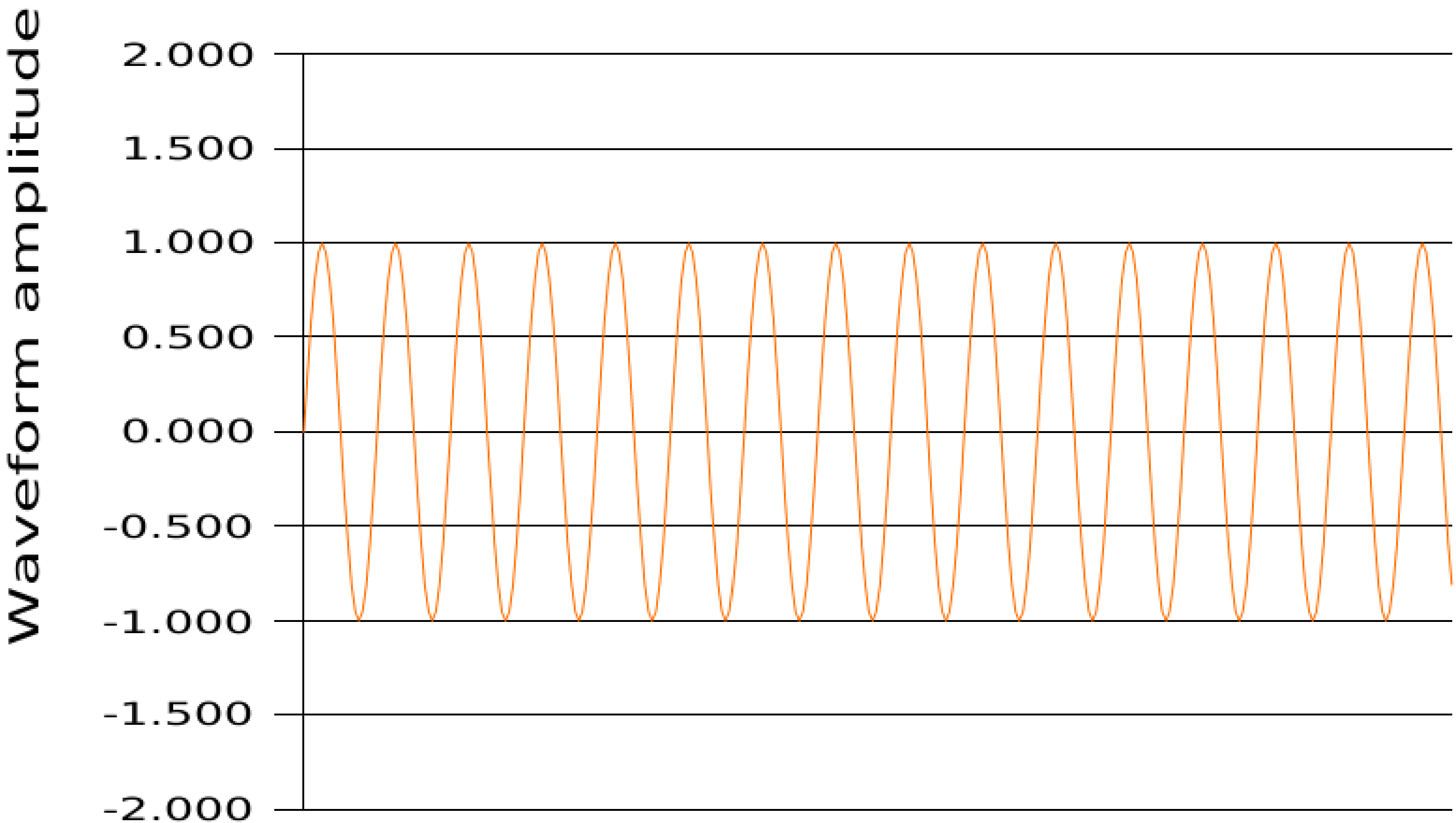
What is modulation?

- **Passband**
  - Modulation of a sine waveform is used to transform a baseband message signal into a passband signal, for example low-frequency audio signal into a radio-frequency signal.
  - In radio communications, cable TV systems or the PSTN for instance, electrical signals can only be transferred over a **limited** passband frequency spectrum, with specific (non-zero) lower and upper cutoff frequencies.
  - Modulating a sine-wave carrier makes it possible to keep the frequency content of the transferred signal as close as possible to the center frequency (typically the carrier frequency) of the passband.

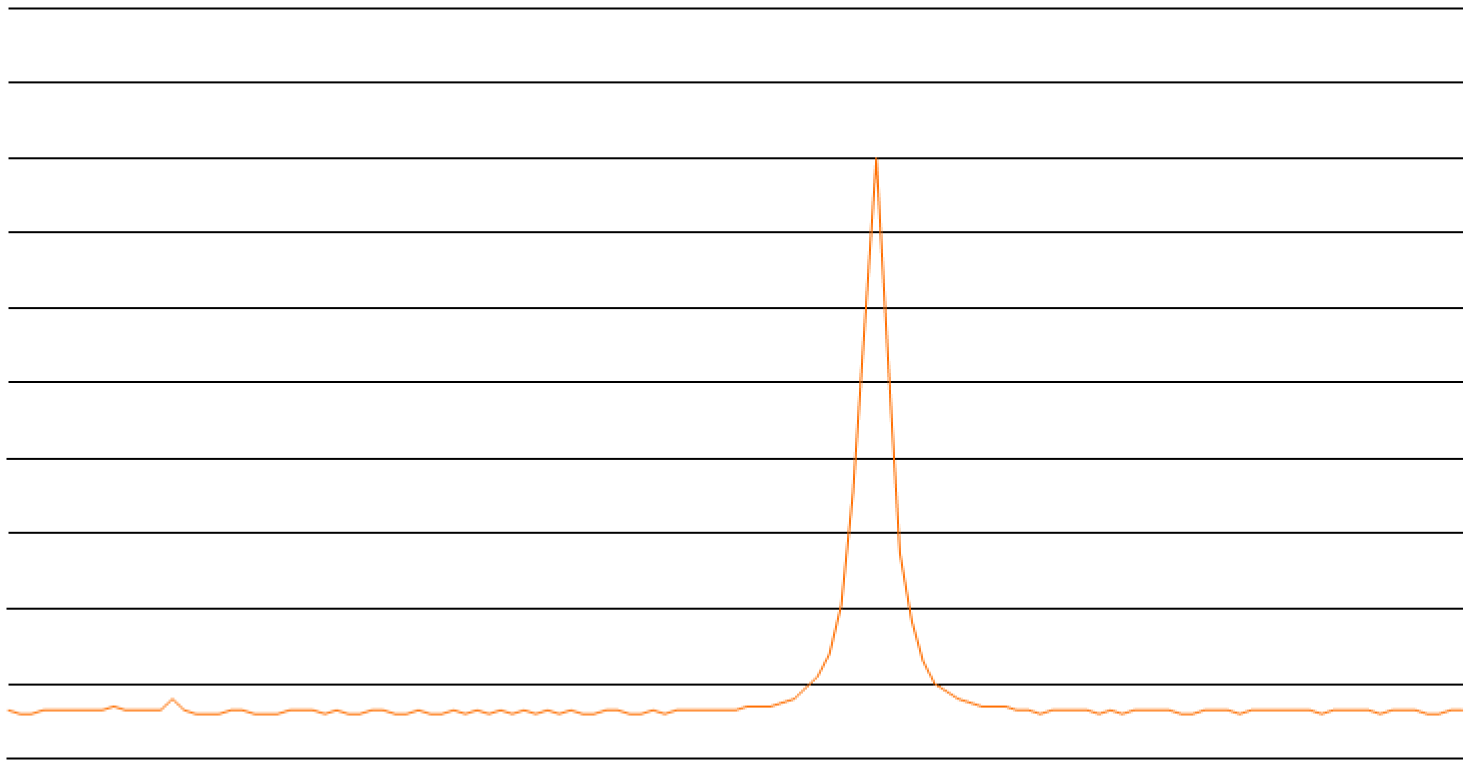
Why modulation is used?

- We modulate a signal to carry a message.
- While a message can be carried over the airwaves without modulation,
  - a modulated signal has **more energy**, $E = \frac{hc}{\lambda}.$
  - **requires less power** to transmit and
  - a **smaller antenna** due to the higher frequency of the carrier wave (1Hz = 75 000 km long antenna).
  - Modulation also lets many different radio, TV, cell phone, etc. users send messages over the airwaves **without interfering** with each other. -> multiplexing
  - Lesser attenuation for certain frequencies in certain environments (eg. Water, metallic cable, etc.)

Un-modulated carrier $s_c(t)$



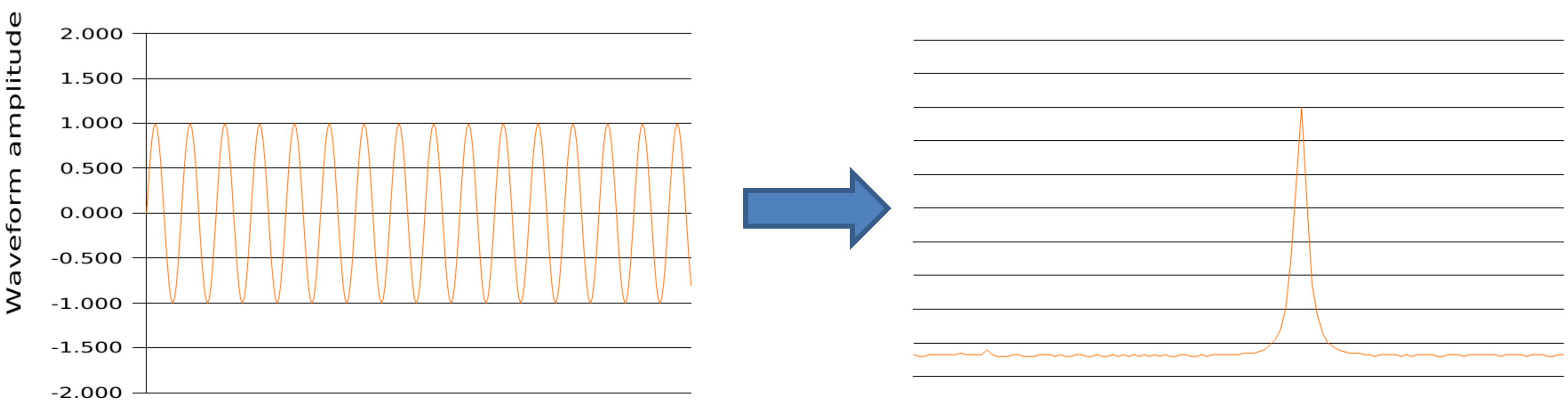
Un-modulated carrier $s_c(t)$



Frequency spectrum

Spectrum

- Most forms of RF modulation involve the generation of an RF carrier signal, which is then modified in some way
- Modifying (modulating) the carrier produces sidebands = other RF frequencies which carry some energy
- The specific sidebands created (frequency and amplitude) depend on the modulation type and the content of the signal



Spectrum and content

- The amount of information you can convey depends on the bandwidth of the transmission, the noise level of the transmission channel, and the amount of error you're willing to accept (the fidelity)
- There is a fundamental limit (the Shannon limit) beyond which you can't pack more information into the channel

- Some modern digital data transmission systems come very close to reaching the Shannon limit
  - Ham voice (“phone”) modes don't come close
  - Digital cellphone comes closer, thanks to digital coding/compression

Overcoming noise

When using modulation

- You can use more bandwidth
- You can reduce the noise level (more sensitive receiver, directional antennas, higher transmit power)

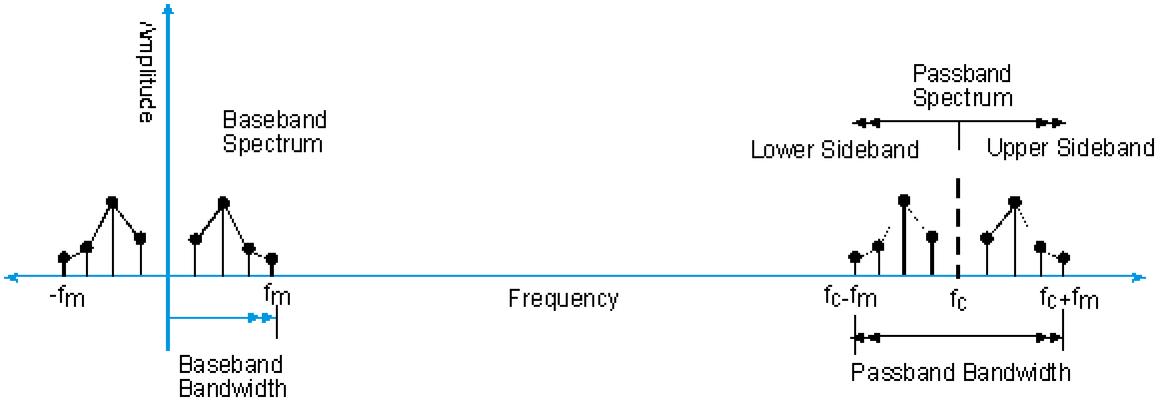
- You can live with it
- You can use less bandwidth and accept a lower information rate (e.g. CW, PSK31)

- It's all about tradeoffs

Modulation - terminology

- **Modulating signal** $s_m(t)$ – typically contains information to be transmitted (to be modulated on carrier signal)
- **Carrier signal** $s_c(t)$ – high frequency periodic waveform or pulse train onto which we modulate the modulating signal
- **Modulated signal** $s(t)$ – resultant signal as a product of modulation
- **Bandwidth** β (B) – a frequency space taken up by a signal

Modulation - terminology



- **Baseband Signal -** The information signal is called the baseband signal. The bandwidth is always a positive quantity so the bandwidth of this signal is f_m.
- **Passband Signal -** The multiplication of this signal with a sinusoid carrier signal translates the whole thing up to f_c. This signal is now called the passband signal.
- **Sidebands** - The upper part of the passband spectrum above the carrier is called the upper sideband and the one below is called the lower sideband.

Types of modulation

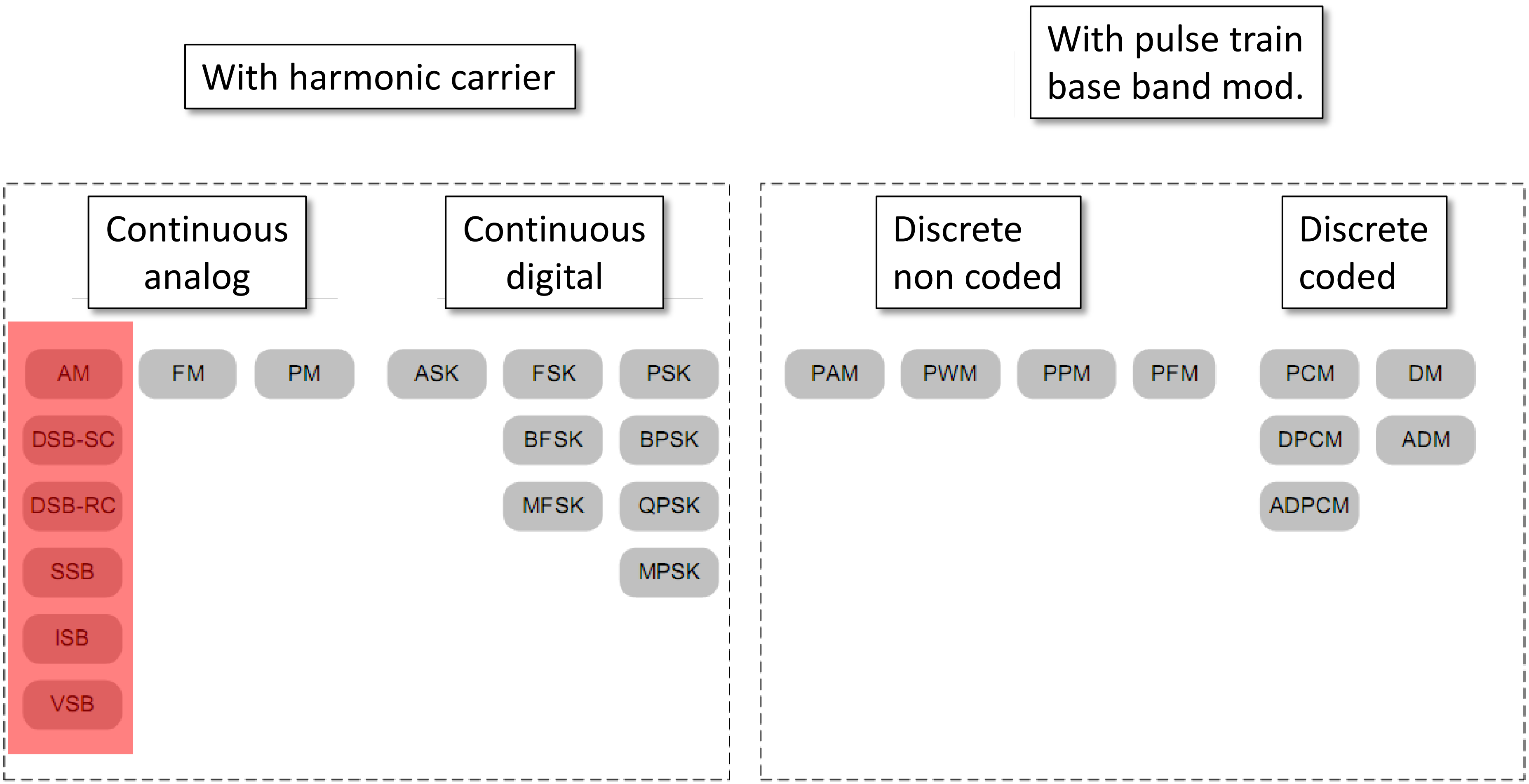
With harmonic carrier

- **Continuous analog**
  - AM
  - DSB-SC
  - DSB-RC
  - SSB
  - ISB
  - VSB
  - FM
  - PM
- **Continuous digital**
  - ASK
  - FSK
  - BFSK
  - MFSK
  - PSK
  - BPSK
  - QPSK
  - MPSK

With pulse train base band mod.

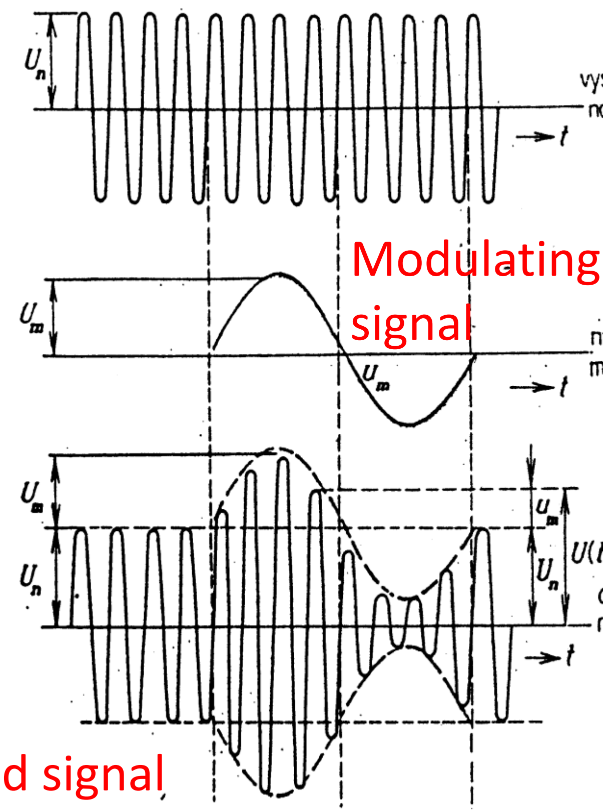
- **Discrete non coded**
  - PAM
  - PWM
  - PPM
  - PFM
- **Discrete coded**
  - PCM
  - DPCM
  - ADPCM
  - DM
  - ADM

Analog modulation – amplitude modulation



AM - waveforms

- the amplitude of high frequency carrier signal is varied in accordance with the instantaneous value of baseband modulating signal
- keeping frequency and phase of carrier signal constant.
- The frequency domain representation of the resultant modulated signal contains carrier signal plus two sidebands of modulating signal (information signal)



AM formulas

$$s(t) = A \cdot \left[1 + M \cdot \cos(\omega_m t + \phi)\right] \cdot \sin(\omega_c t) = \left[1 + s_m(t)\right] \cdot s_c(t)$$

- A represents the carrier amplitude, M which is a constant that demonstrates the modulation index.

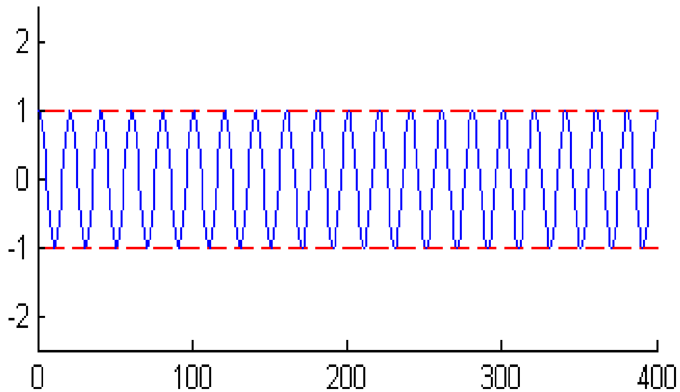
Modulation index

- the **measure of** the amplitude **variation** surrounding an unmodulated carrier. Indicates how much the modulation varies around its "original" level.
- To avoid distortion, modulation depth must not exceed 100 percent. Transmitter systems will usually incorporate a limiter circuit

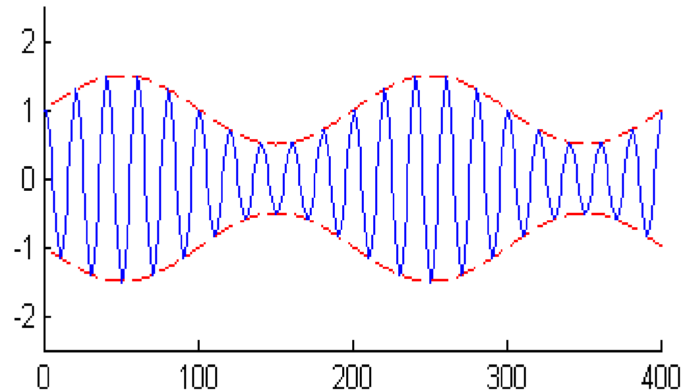
$$M = \frac{\max(s_m(t))}{A}$$

AM examples

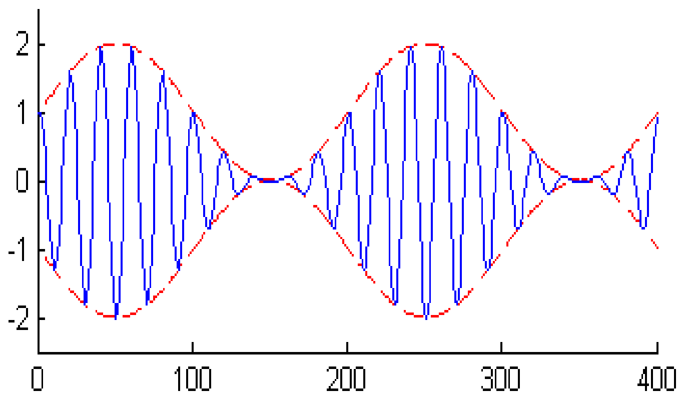
Modulation depth M=0



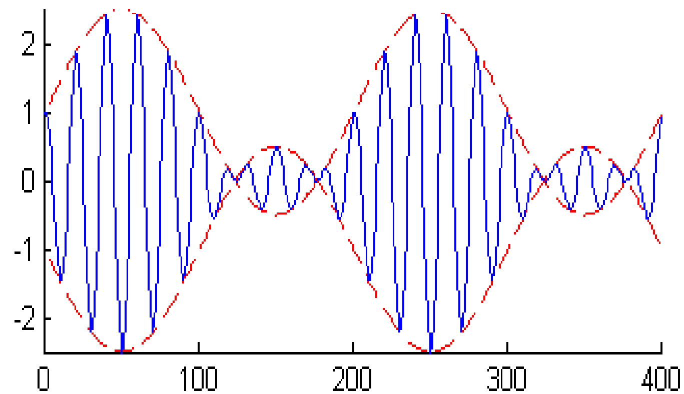
Modulation depth M=0,5



Modulation depth M=1



Modulation depth M=1,5



AM formulas …

- Original term $s(t) = A \cdot \left[1 + M \cdot \cos(\omega_m t + \phi)\right] \cdot \sin(\omega_c t)$

- Expands to
$$\sin(\omega_c t),$$
$$M/2 \cdot \cos(\omega_c t + \omega_m t) \; and$$
$$M/2 \cdot \cos(\omega_c t - \omega_m t)$$

- So the **total signal** consists of the **original carrier** (full amplitude), plus **two sidebands**, located above and below the carrier frequency by a distance equal to the modulating frequency, each with an amplitude of up to half that of the carrier (and thus each has up to ¼ of the power in the carrier)

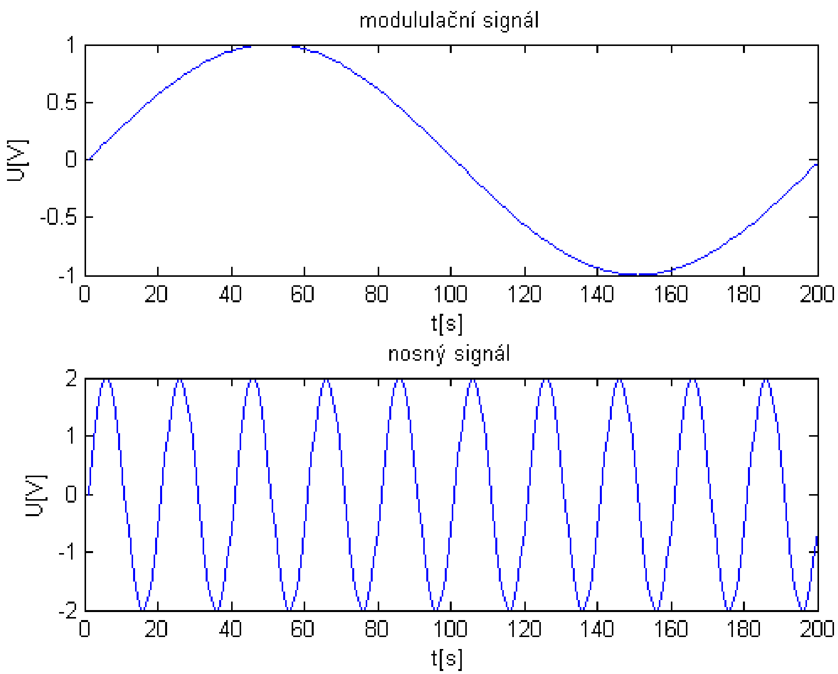
AM sidebands

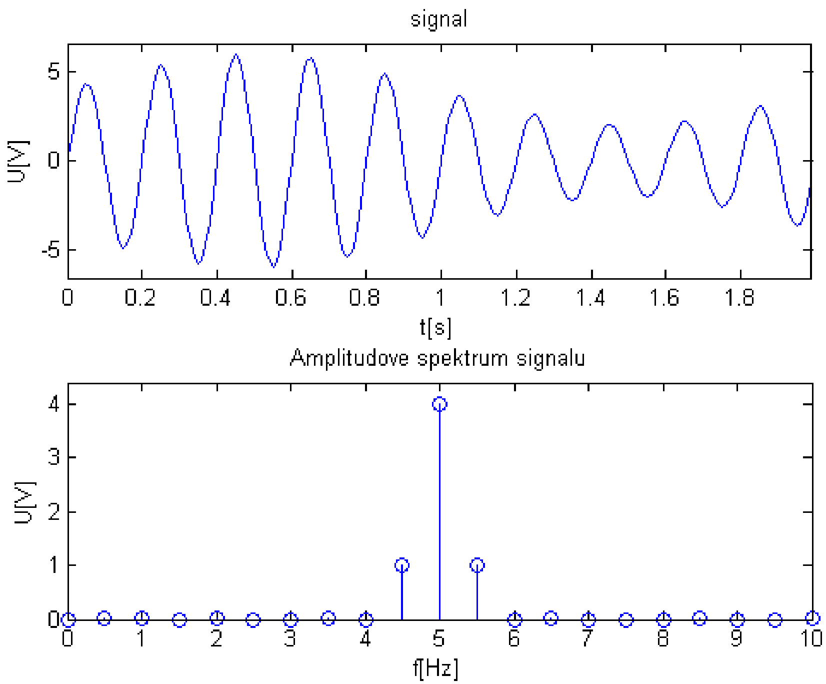
- AM-DSB (with carrier)

$$s(t) = A\cdot[(1+M)\cdot s_m(t)]\cdot s_c(t) = A\cdot[(1+M)\cdot\cos(\pi\cdot t)]\cdot\cos(10\pi\cdot t)$$

$$\omega\cdot t = 2\pi f\cdot t \Rightarrow f = \omega/2\pi$$

$$\pm 0{,}5\ and \pm 5{,}0\,Hz \qquad\qquad \pm 5Hz, \pm 5{,}5\ and \pm 4{,}5\,Hz$$

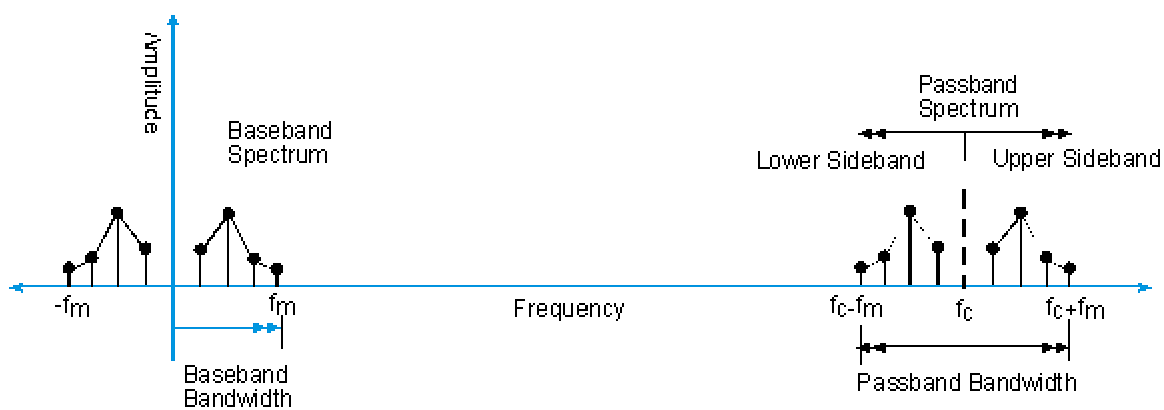




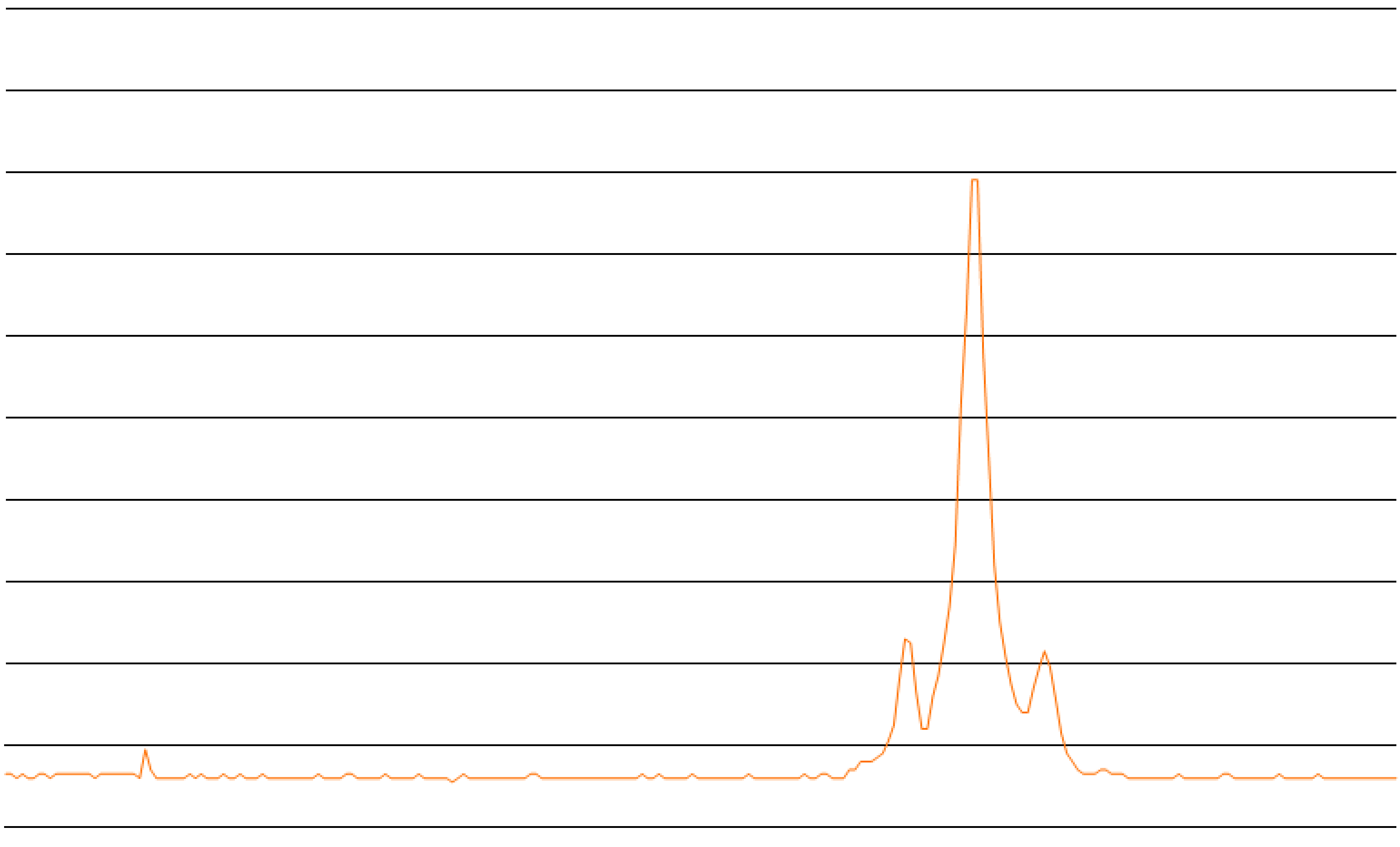
AM bandwidth

Bandwidth

- Amplitude modulation of a carrier wave normally results in two mirror-image sidebands.
- The signal components above the carrier frequency constitute the **upper sideband** (**USB**), and those below the carrier frequency constitute the **lower sideband** (**LSB**).
- In terms of positive frequencies, the transmission bandwidth of AM is twice the signal's original (baseband) bandwidth

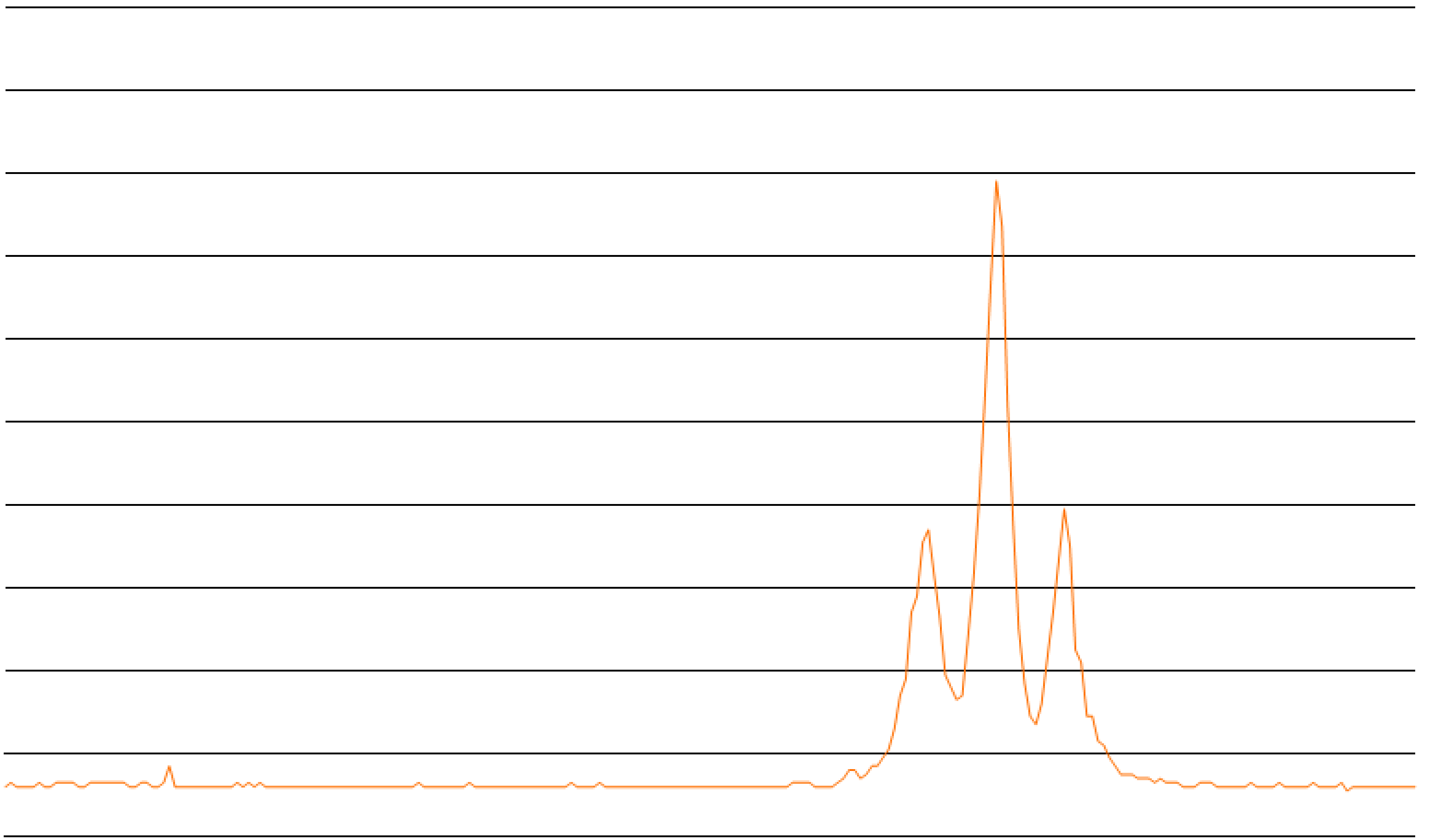


AM, 1kHz tone, 50% modulation



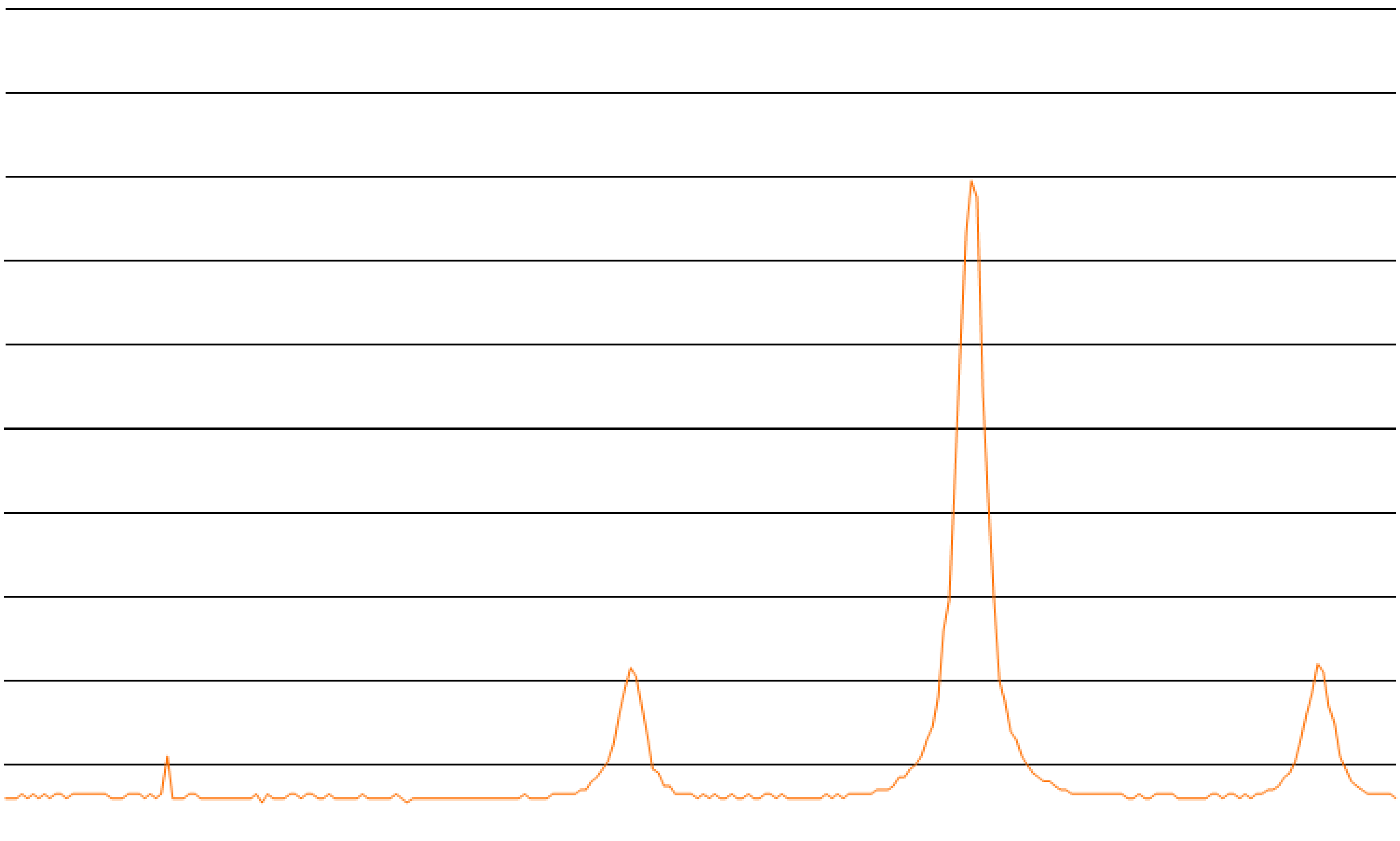
Frequency spectrum

AM, 1kHz tone, 100% modulation



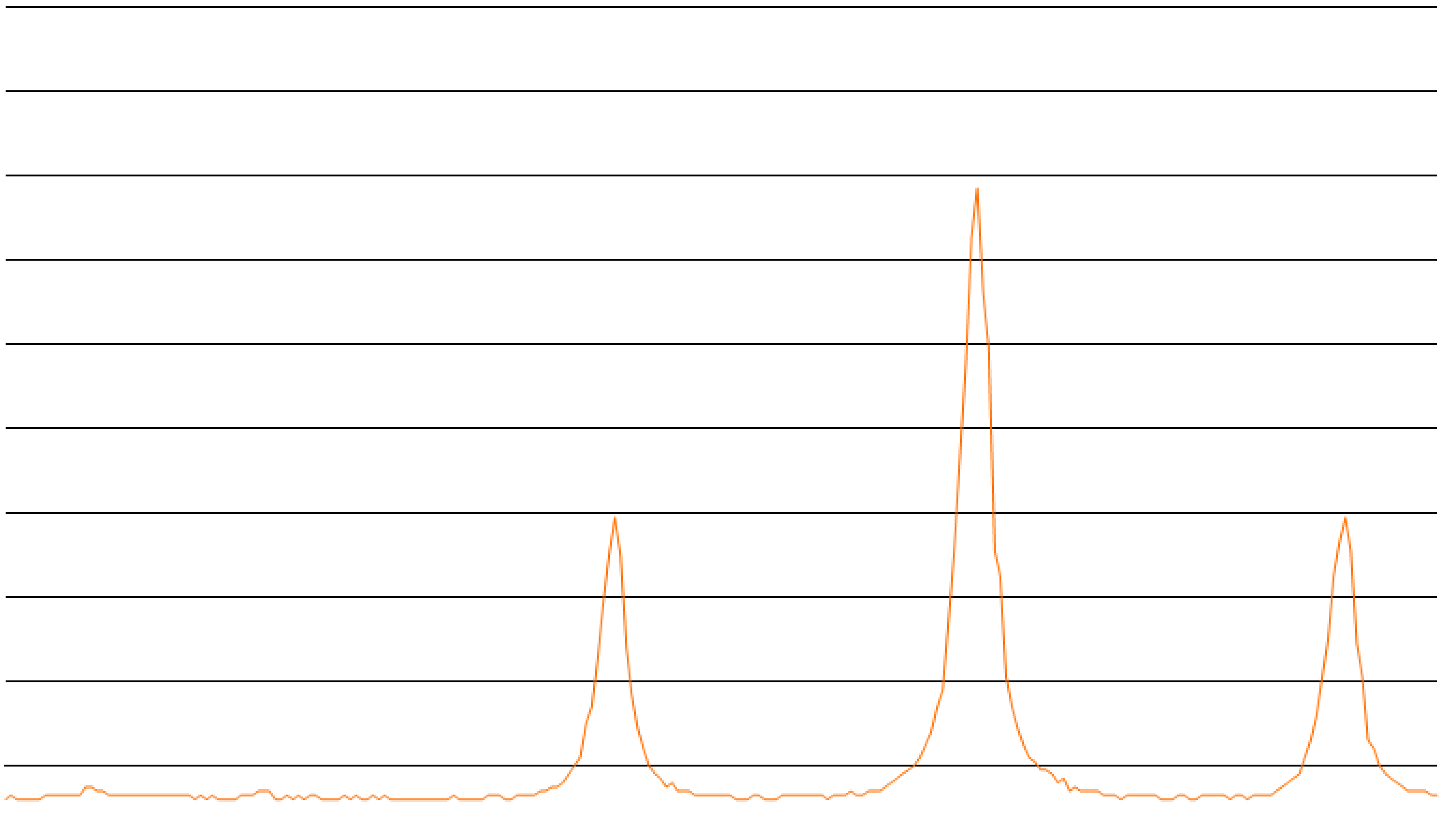
Frequency spectrum

AM, 5 kHz tone, 50% modulation



Frequency spectrum

AM, 5kHz tone, 100% modulation



Frequency spectrum

AM summary

- AM creates an RF signal whose total power varies from moment to moment ...
- ... but the **power level at the carrier freq. doesn't change!**
- At full modulation, total power is 50% more than the carrier power (so 2/3 = carrier, 1/3 = intelligence)
- Peak power (top of the modulated-carrier waveform) is 4 times the average carrier power
- Any non-linear method of combining two signals, or amplifying a signal containing multiple frequencies, has the effect of squaring or multiplying components and thus generates AM sidebands
- **called AM-DSB**

AM technique

- AM is **easy to generate**, either directly (plate modulation) or by amplifying a low-level AM signal (linear amp required!)

- Easy to **demodulate** - uses the same technique, in reverse
- Multiplying the RF sidebands by the carrier frequency creates new sidebands, including a set down at the original audio frequency - FIND OUT from trigonometric functions
- Since the RF signal contains both the sidebands, and the carrier, all we have to do is multiply it by itself!
- Prone to noise interference, precisely because it's amplitude sensitive

AM drawbacks summary

- double-sideband AM (DSB-AM) is spectrally inefficient since fewer radio stations can be accommodated in a given broadcast band.
- With the carrier suppressed, there would be no energy at the center of a group; with a sideband suppressed, the "group" would have the same bandwidth modulating signal
- The transmitter-power efficiency of DSB-AM is relatively poor (about 33%). The benefit of this system is that receivers are cheaper to produce.

AM to overcome drawbacks

To overcame AM –DSB drawbacks we use

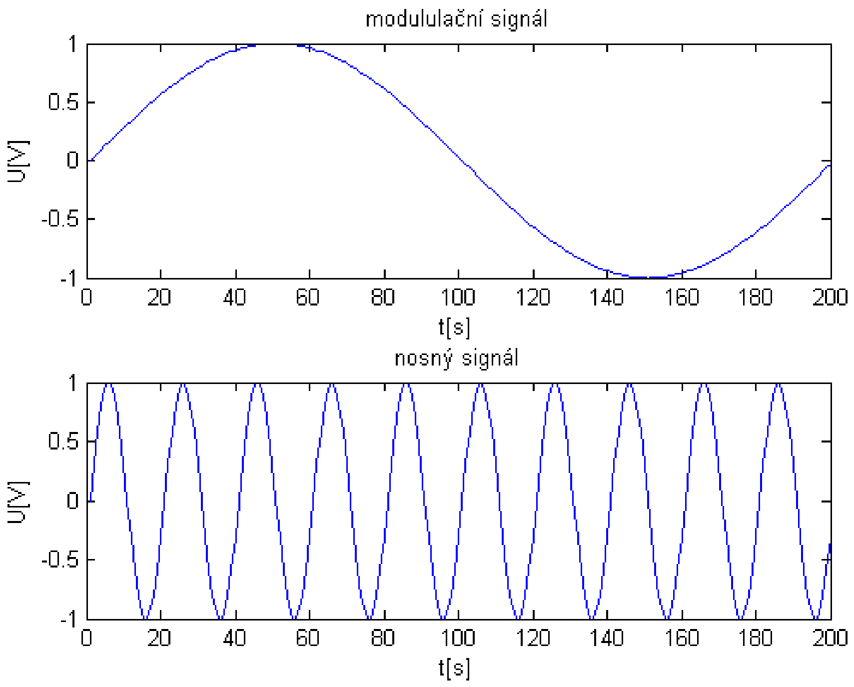
- Double-sideband suppressed-carrier transmission (DSB-SC)
- Double-sideband reduced carrier transmission (DSB-RC)
- Single-sideband with carrier (SSB-WC)
- Independent-side band (ISB)
- Single-sideband suppressed carrier modulation (SSB-SC)
- Vestigial side band modulation (VSB, or VSB-AM)

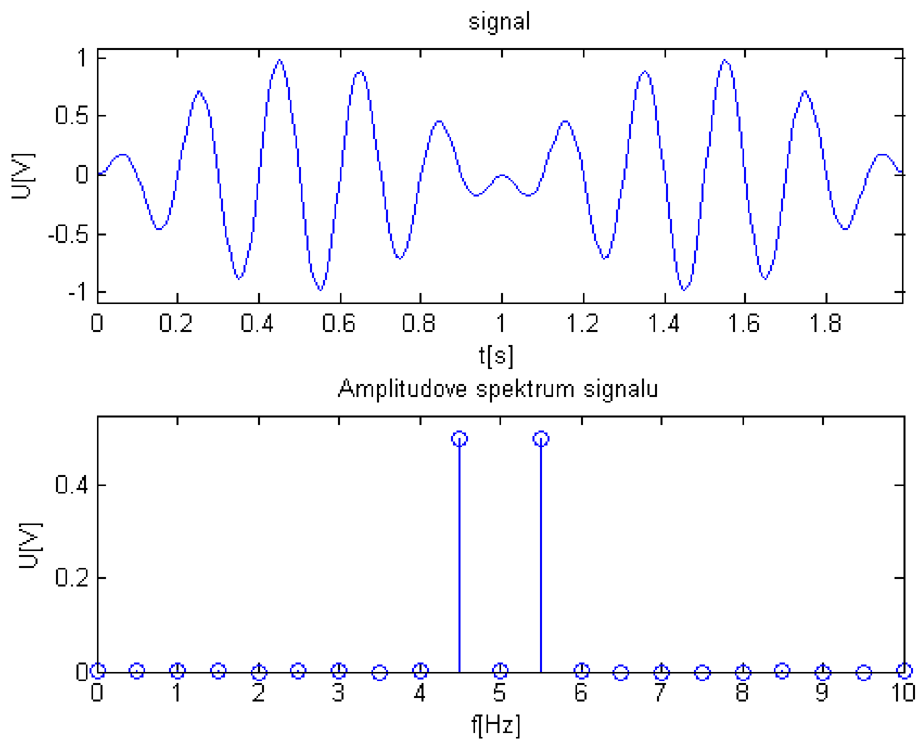
AM-DSB-SC Suppressed carrier

$$s(t) = s_m(t) \cdot s_c(t) = \cos(\pi \cdot t)\cos(10\pi \cdot t) \qquad \omega \cdot t = 2\pi f \cdot t \Rightarrow f = \omega / 2\pi$$

$\pm 0{,}5\ and \pm 5{,}0\,Hz$

$\pm 5{,}5\ and \pm 4{,}5\,Hz$



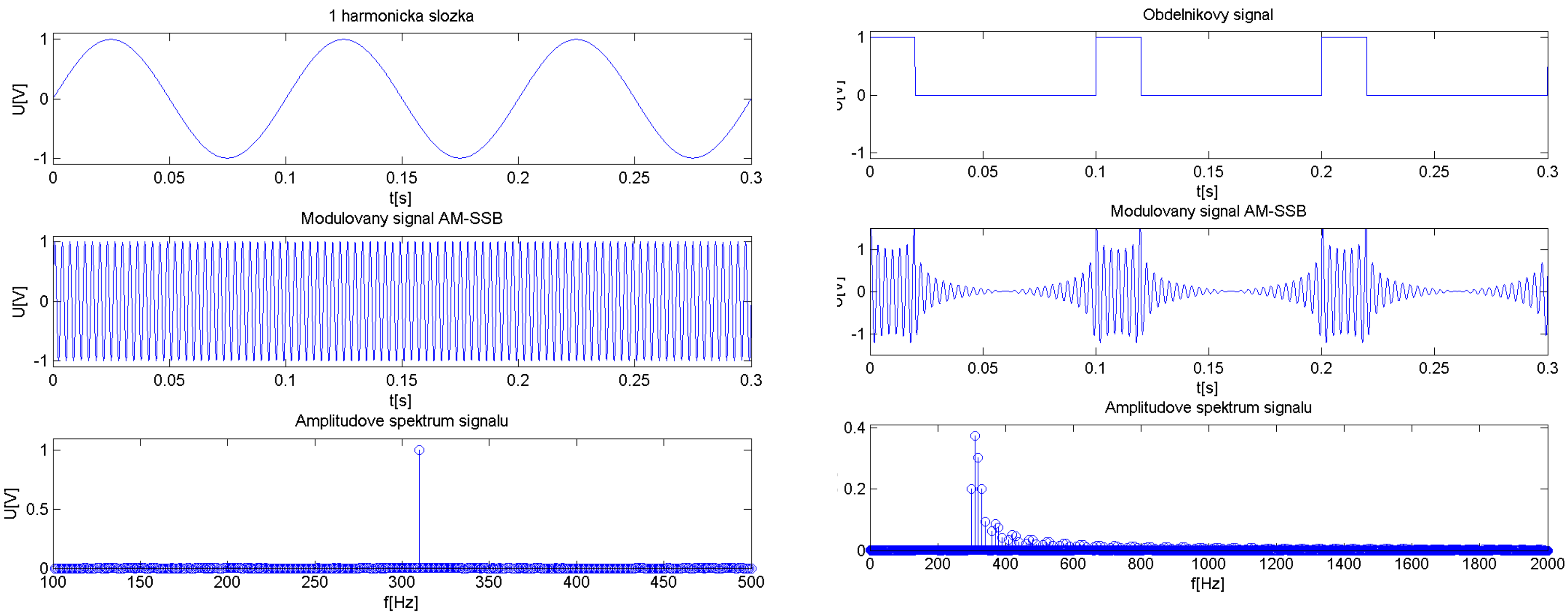


AM-SSB-SC Suppressed carrier

- Generate a low-level AM signal, then eliminate the carrier and one set of sidebands, leaving only the components of the other sideband
- Amplify the remaining sideband signal and transmit

- **More power efficient** than AM – all of the energy goes into information-carrying sidebands, none into the carrier
- Redundant sideband is filtered away before amplification, uses no power
- RF bandwidth same as baseband (audio) bandwidth
- Harder to demodulate than AM because there's no carrier

AM-SSB-SC Suppressed carrier



http://cnyack.homestead.com/files/modulation/modam.htm

AM-ISB Independent sideband

- ISB modulates **two different input** signals — one on the upper sideband, the other on the lower sideband.
- a compromise between double sideband (DSB) and single sideband (SSB) — the other is vestigial sideband (VSB).

- If the sidebands are out of phase with each other, then phase modulation (PM) of the carrier occurs. AM and PM together then create quadrature amplitude modulation (QAM).
- ISB may or may not have the carrier suppressed.
- Suppressed-carrier ISB was employed in point-to-point radiotelephony and radioteletype by shortwave (HF).

AM-VSB vestigial sideband

- A sideband that has been only partly cut off or suppressed. Television broadcasts (in analog video formats) use this method if the video is transmitted in AM.
- The video baseband signal used in TV in countries that use NTSC or ATSC has a bandwidth of 6 MHz. To conserve bandwidth, SSB would be desirable, but the video signal has significant low frequency content (brightness) and has rectangular synchronizing pulses.
- The engineering compromise is vestigial sideband modulation.
- In vestigial sideband the full upper sideband of bandwidth W2 = 4 MHz is transmitted, but only W1 = 1.25 MHz of the lower sideband is transmitted, along with a carrier.

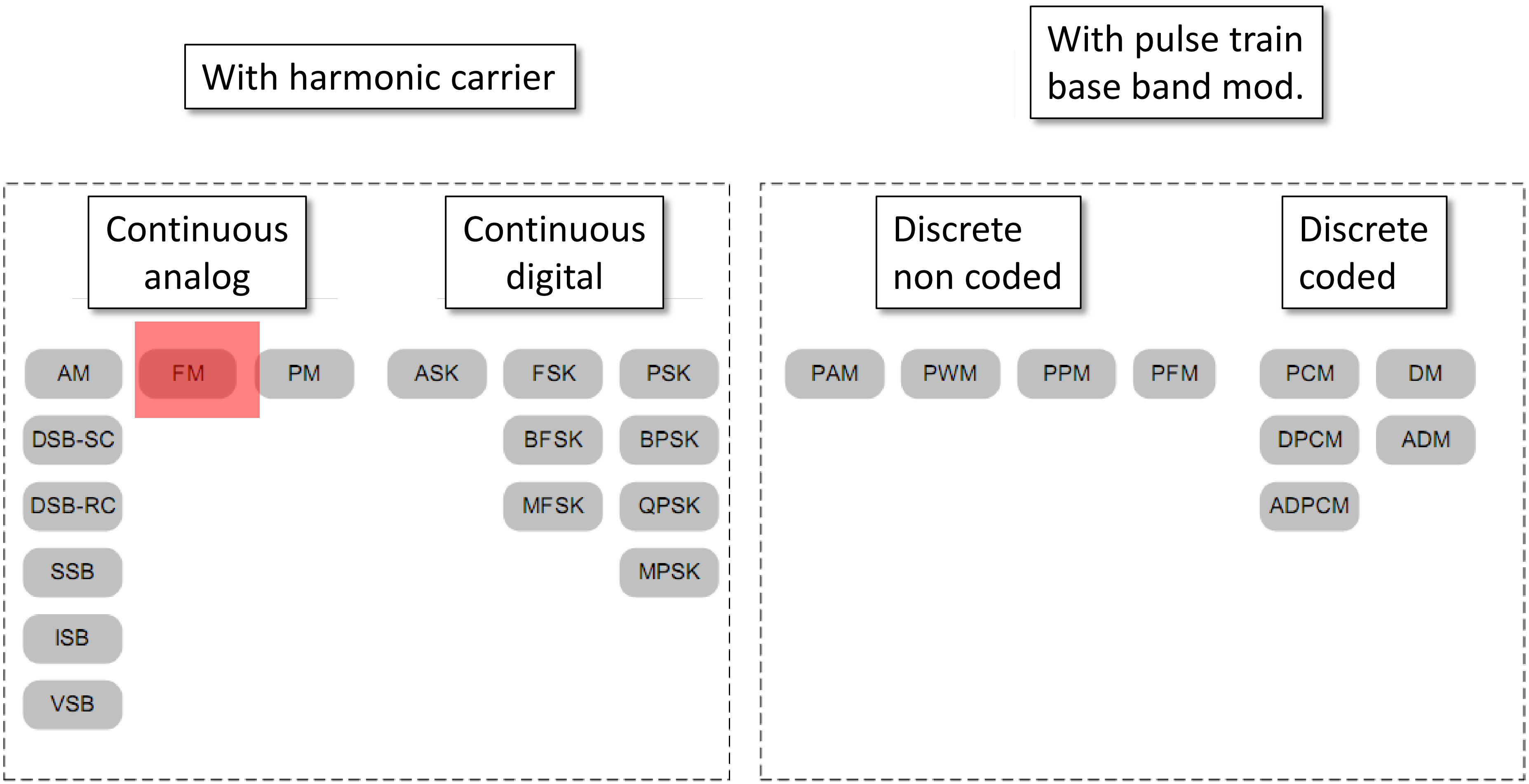
AM - comparison

modulation	bandwidth	efficiency	complexity	use
DSB-WC	2W	<50%	Low	radio
DSB-SC	2W	100%	normal	Low frequency communication systems
SSB-SC	W	100%	high	Voice systems
VSB	W+	100%	high	Wide band systems
VSB-WC	W+	<50%	normal	TV video

Internet examples and resources

- http://cnyack.homestead.com/files/modulation/modam.htm
- http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?reload=true&arnumber=4051940
- http://www.afrotechmods.com/videos/amplitude_modulation_tutorial.htm
- http://demonstrations.wolfram.com/AmplitudeModulation/

Analog modulation – frequency modulation



Frequency modulation

- the method of conveying information over a carrier wave by varying its frequency. Different from the AM in which the amplitude of the carrier wave is varied while its frequency remains constant.
- Dates back to **1936** when Edwin Howard Armstrong described the FM frequency as a method of reducing disturbances in radio transmission.
- Widely used in telecommunication devices to transmit voice without disturbances.
- **The instantaneous frequency of the carrier is directly proportional to the instantaneous value of the input signal**.

Frequency modulation

- Frequency of carrier is varied, depending on modulating signal's value. Amplitude (envelope) of modulated signal does not change.

$$s(t) = A_c \cos\left(\omega_c t + 2\pi \cdot f_\Delta \int_0^t s_m(\tau) d\tau \right)$$

- Simplified for **sinusoidal** baseband signal as

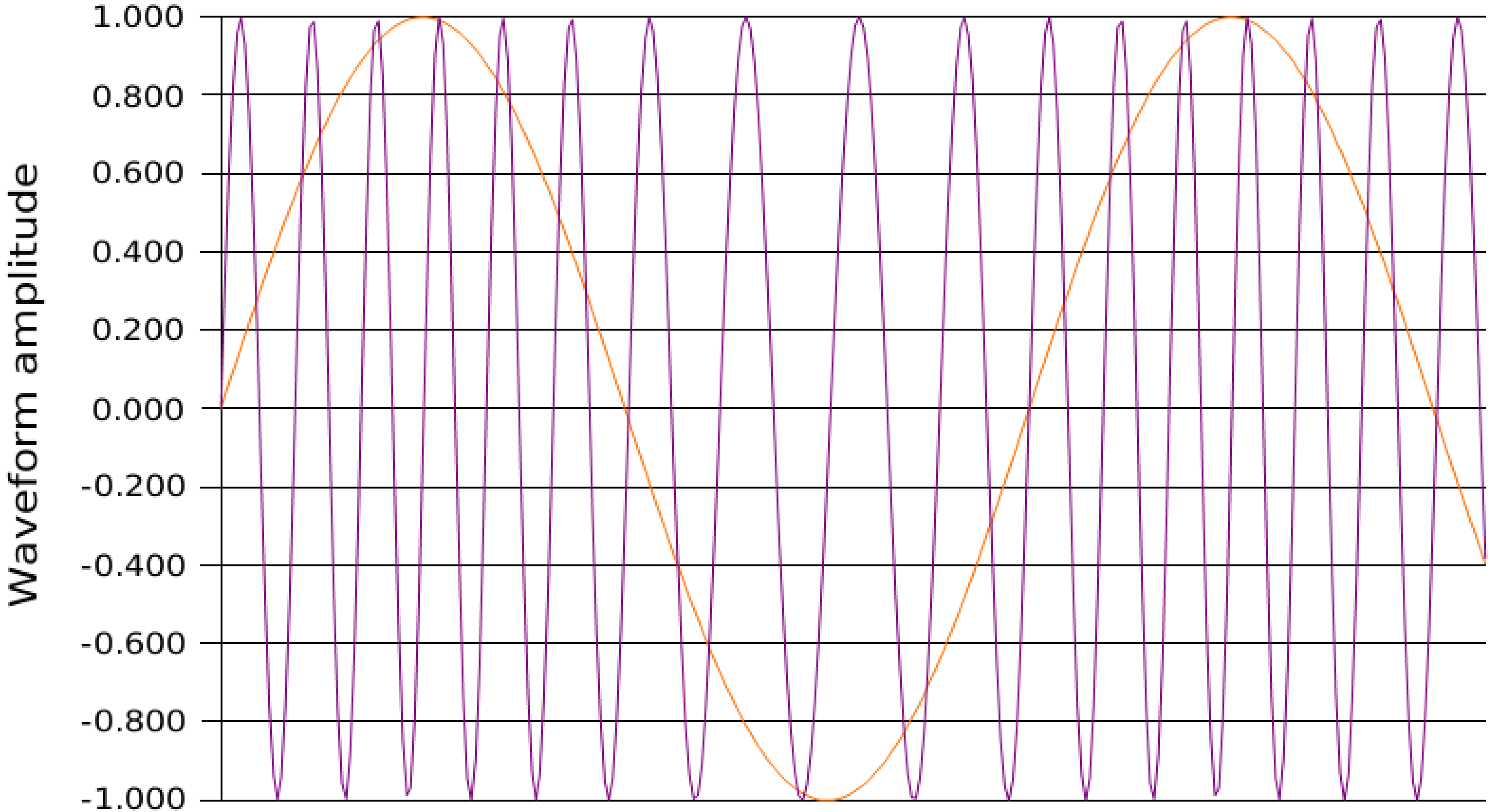
$$s(t) = A_c \cos(2\pi f_c t + \frac{f_\Delta}{f_m} \cos(2\pi f_m t))$$

- Can be expanded into an infinite series involving

$$\cos(2\pi(f_c \pm N f_m)t)$$

http://hermes.eee.nott.ac.uk/teaching/cal/h61sig/sig0019.html

Frequency modulation



Frequency modulation

- Usually done by using a voltage to vary the value of a reactance in an oscillator or tuned-amplifier circuit.
- Modulated signal is then amplified, multiplied up to a higher harmonic, and/or heterodyned to the final frequency
- Like AM, FM **creates sidebands** both above and below the carrier frequency

- Each modulating frequency creates multiple sidebands, separated from the carrier by the modulating frequency and all of its multiples... all the way up to infinity (in theory)
- Sideband amplitude depends on amount of modulation – the “modulation index”

Frequency modulation

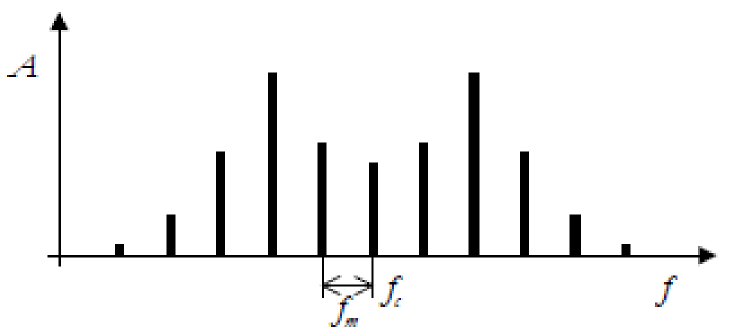
- FM signals are inherently wider than AM signals having the same intelligence bandwidth, due to the presence of multiple sidebands
- **Modulation index** = peak carrier change (deviation) divided by modulating frequency
- At high modulation index, 3 –5 sidebands may have significant power

$$h = \frac{\Delta f}{f_m} = \frac{f_\Delta \left| s_m(t) \right|}{f_m}$$

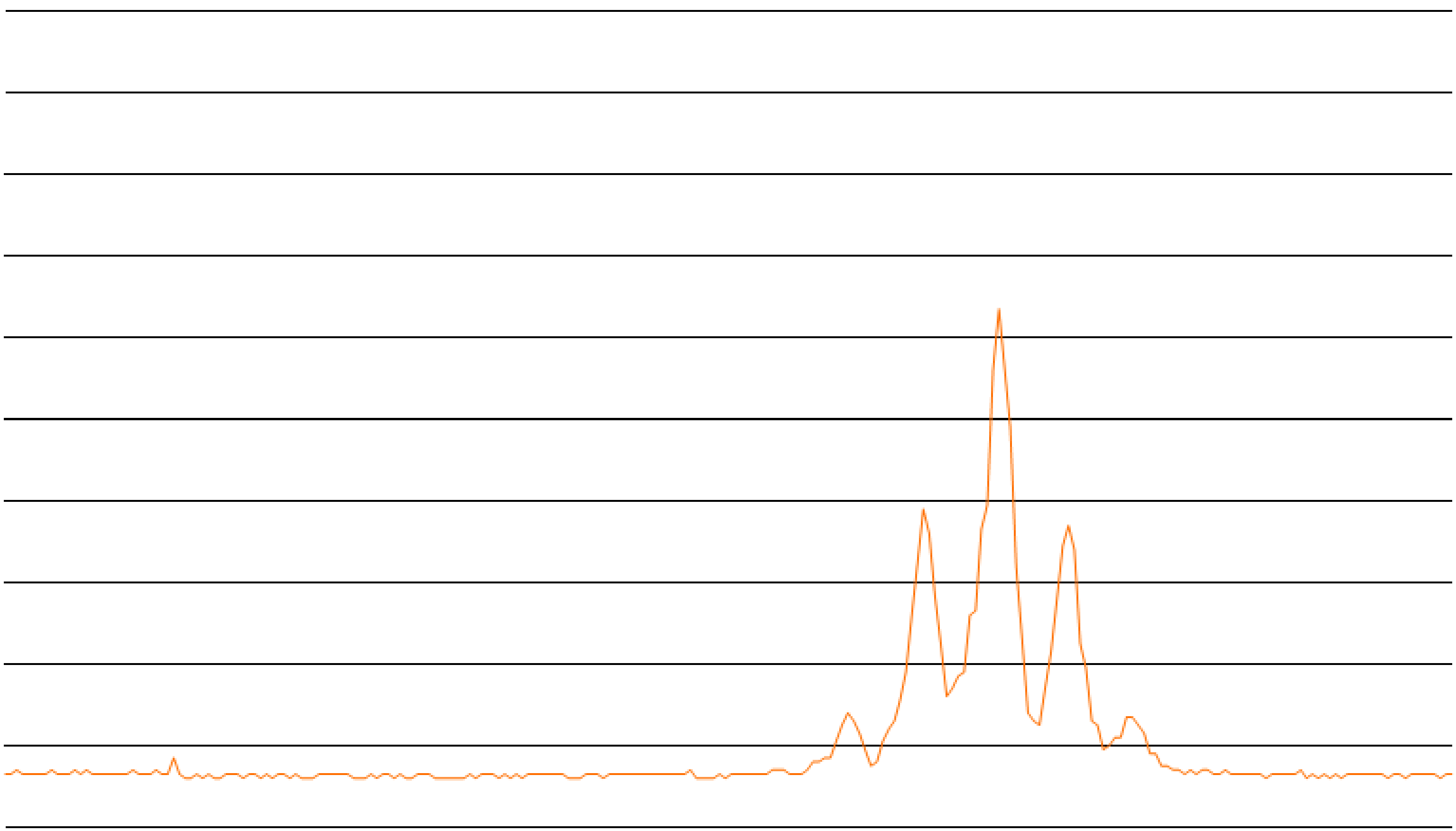
- f_m is the highest frequency of baseband signal
- Δf is frequency deviation, maximum change of frequency of modulated signal to carrier frequency

Frequency modulation

- Total signal power doesn't change ... yet the power for the sidebands has to come from somewhere
- Frequency modulation shifts power away from the carrier frequency, into the sidebands
- At certain modulation indexes, the power at the carrier frequency actually drops to zero–all the power is in the sidebands!

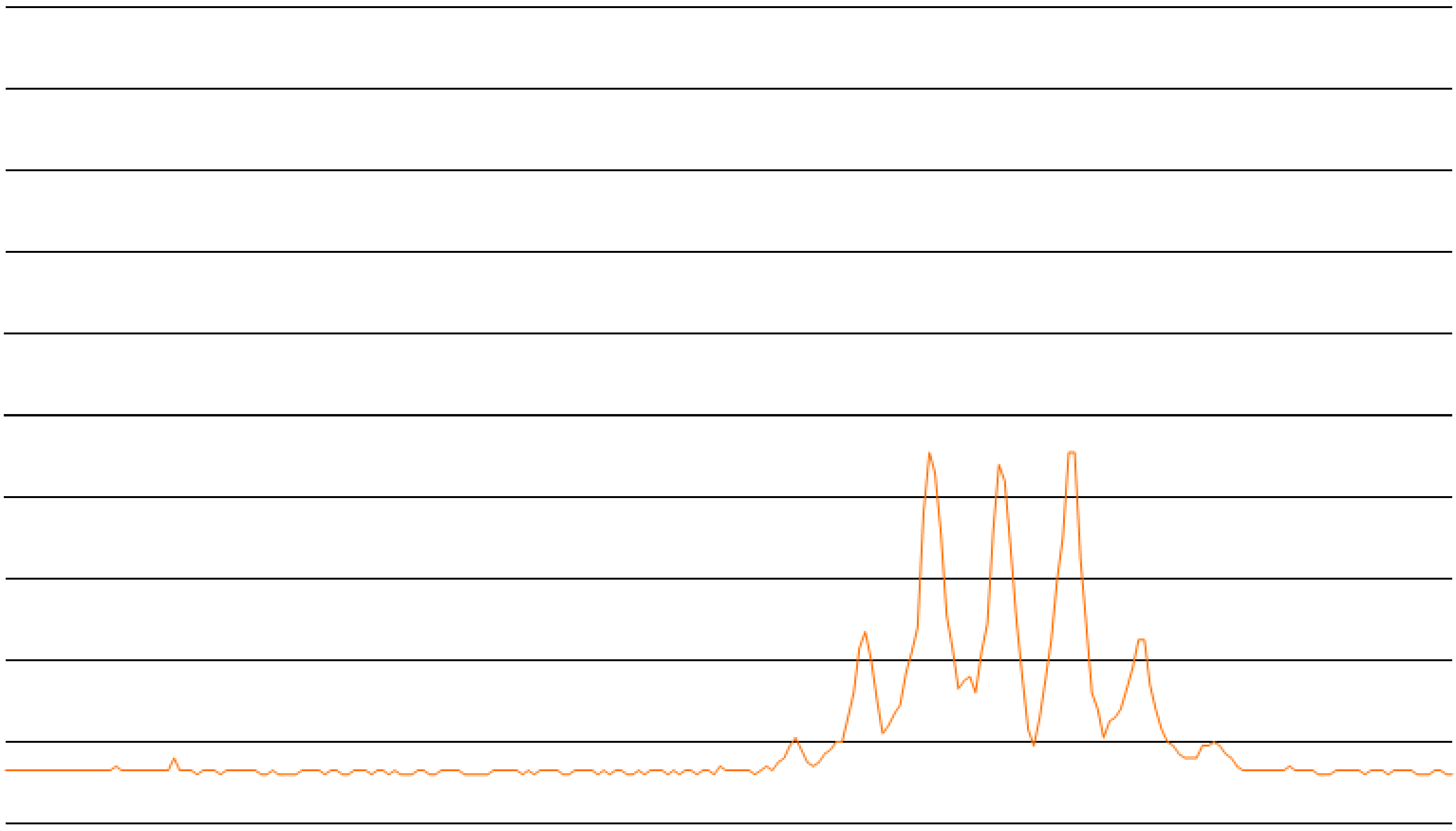


FM, 1kHz signal, 1kHz deviation



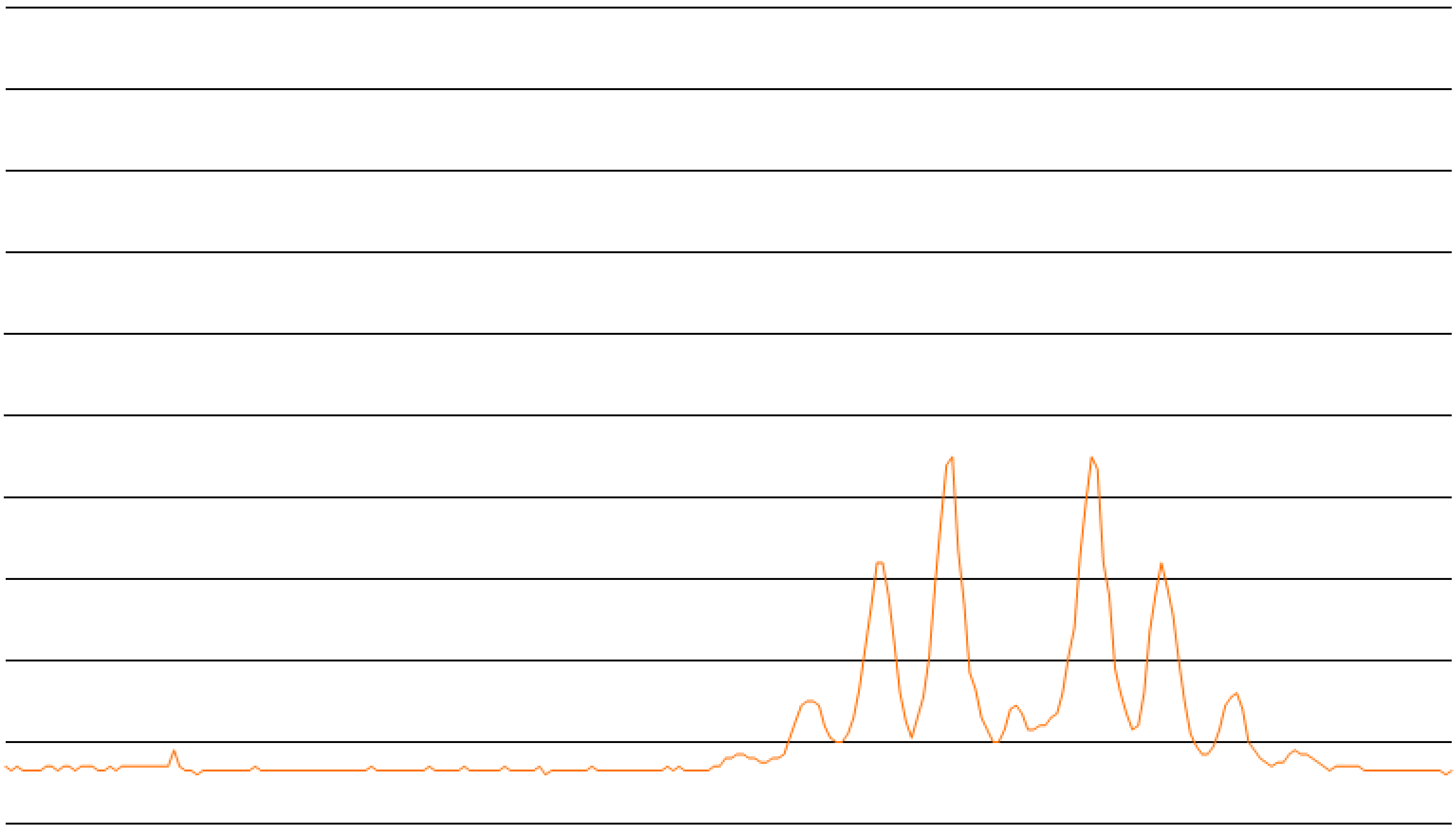
Frequency spectrum

FM, 1kHz signal, 1,5kHz deviation



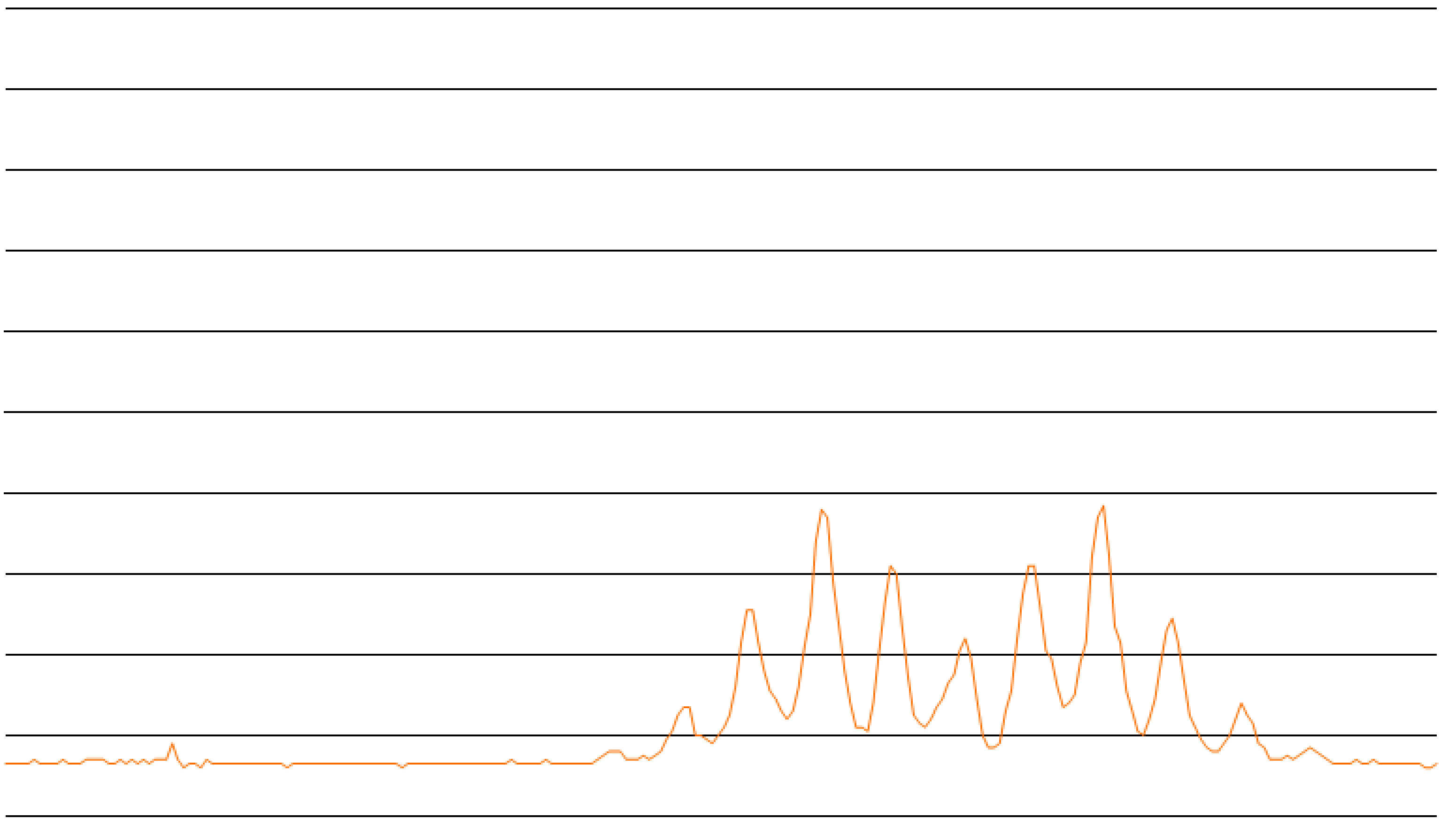
Frequency spectrum

FM, 1kHz signal, 2kHz deviation



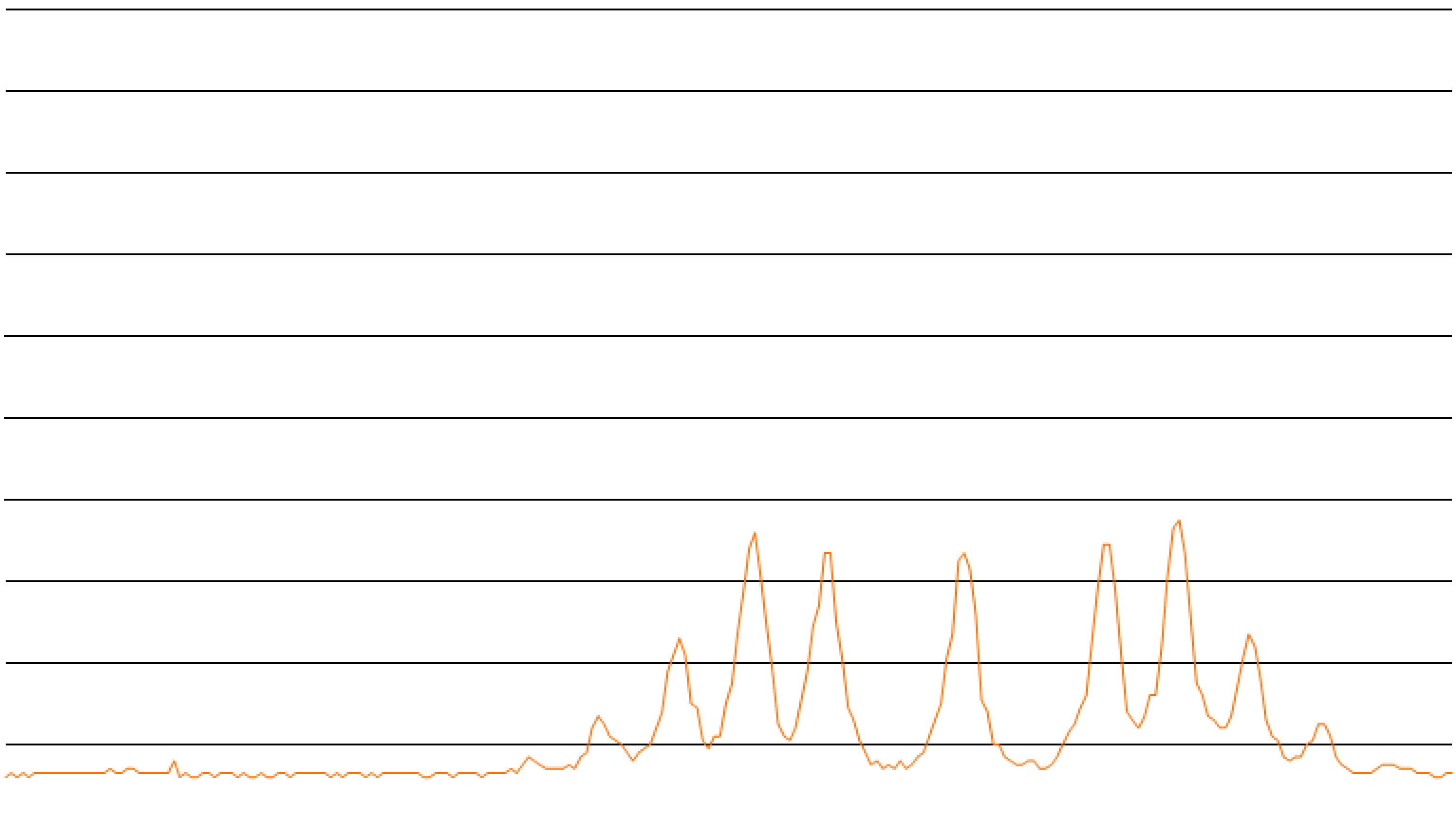
Frequency spectrum

FM, 1kHz signal, 3kHz deviation



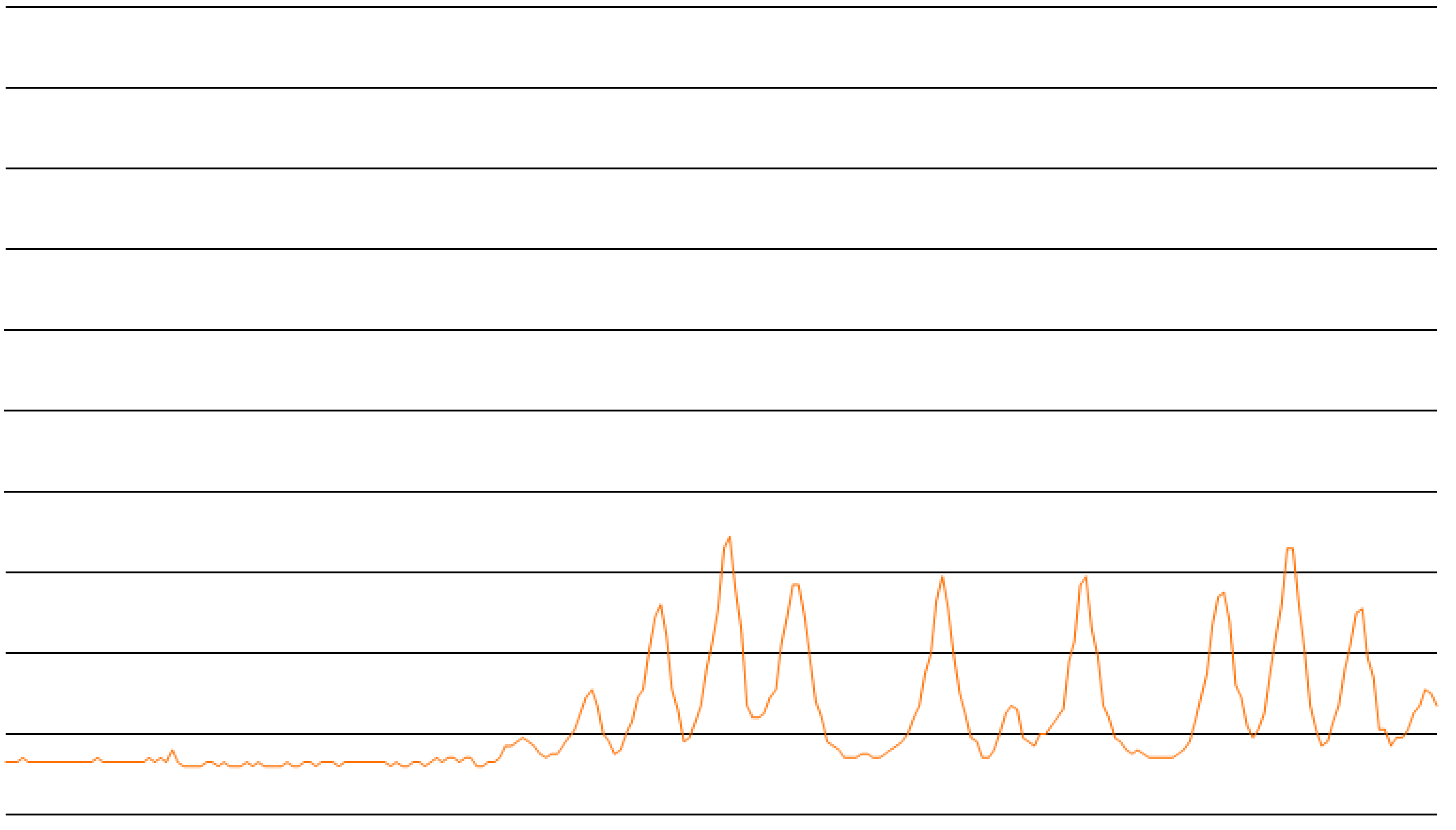
Frequency spectrum

FM, 1kHz signal, 4kHz deviation



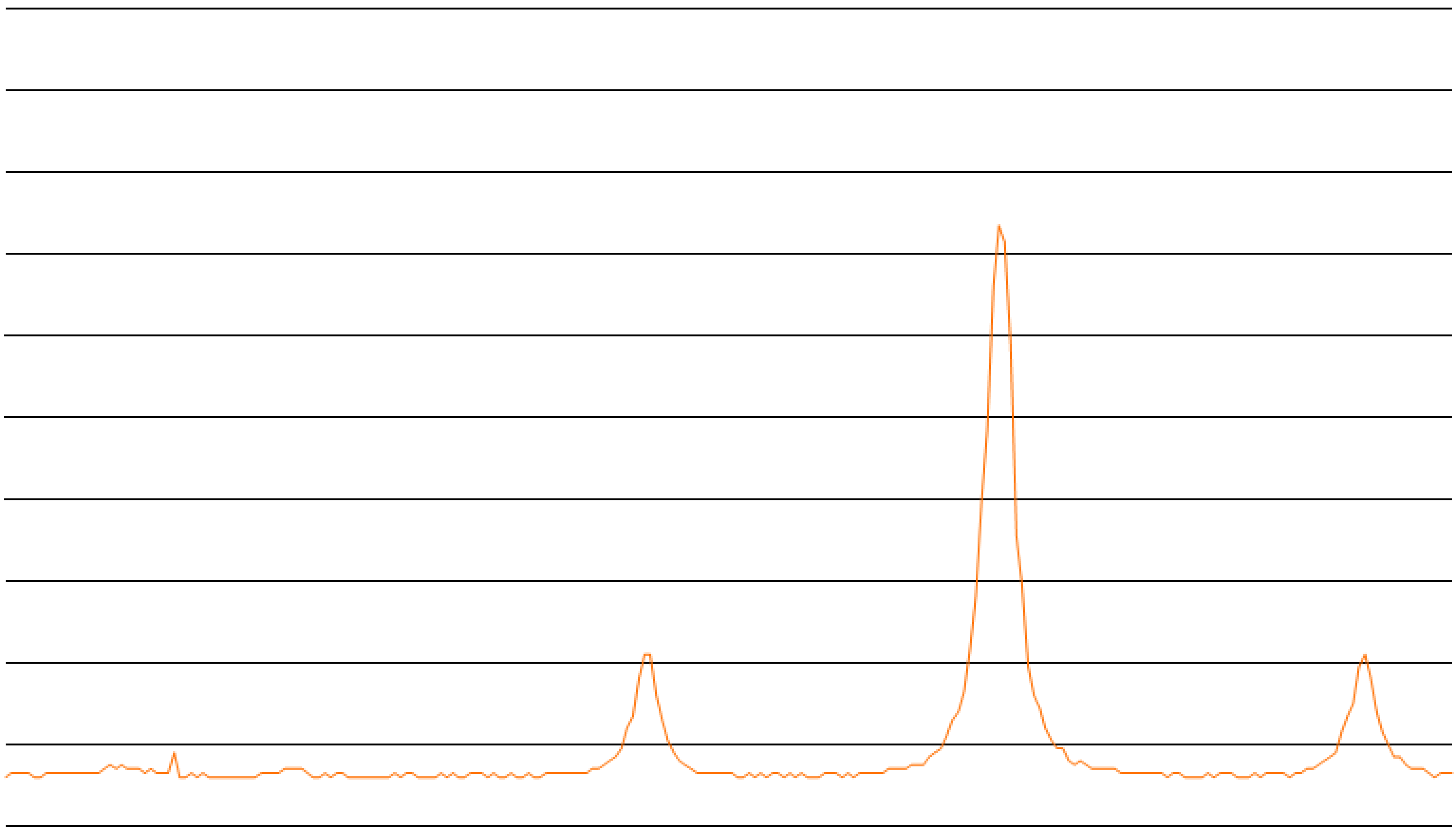
Frequency spectrum

FM, 1kHz signal, 5kHz deviation



Frequency spectrum

FM, 5kHz signal, 2,5kHz deviation



Frequency spectrum

FM Features

- **Resilience to signal level variations**. The modulation is carried only as variations in frequency. That is, any signal level variations will not affect the audio output.

- It is possible to apply the modulation to a low power stage of the transmitter, and it is **not necessary to use a linear form** of amplification to increase the power level of the signal to its final value. Important for FM transmission.
  - For FM transmission, it is possible to use non-linear RF amplifiers to amplify FM signals in a transmitter. This is more efficient than the linear RF amplifier Therefore, for a given power output, less battery power is required.

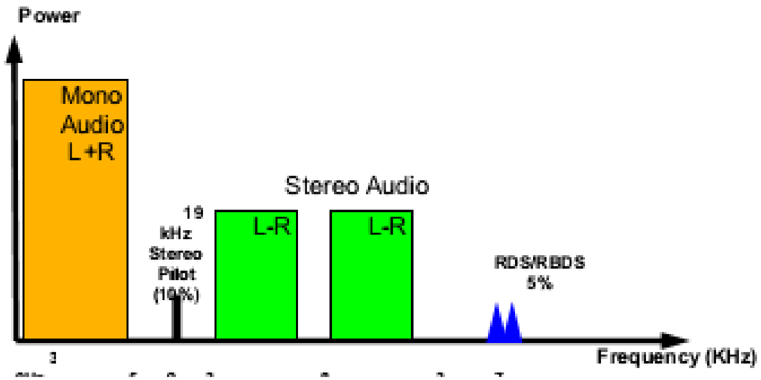
FM Radio concept

- To generate the FM signal, the frequency of the radio carrier must be changed in line with the amplitude of the incoming audio signal.
- When the audio signal is modulated on to the RF carrier wave, the new radio waves move up and down in frequency.
- The rate at which the wave moves up and down is known as "Deviation" and is represented as Kilohertz deviation.
- For example, if the signal wave has a deviation of 4 kHz, then the carrier wave is made to move in 4 kHz.
- VHF transmission uses band between 88 to 108 MHz with large deviation of 75 kHz. It is known as 'Wide band FM or WBFM. Large bandwidth supports good quality broadcasting.

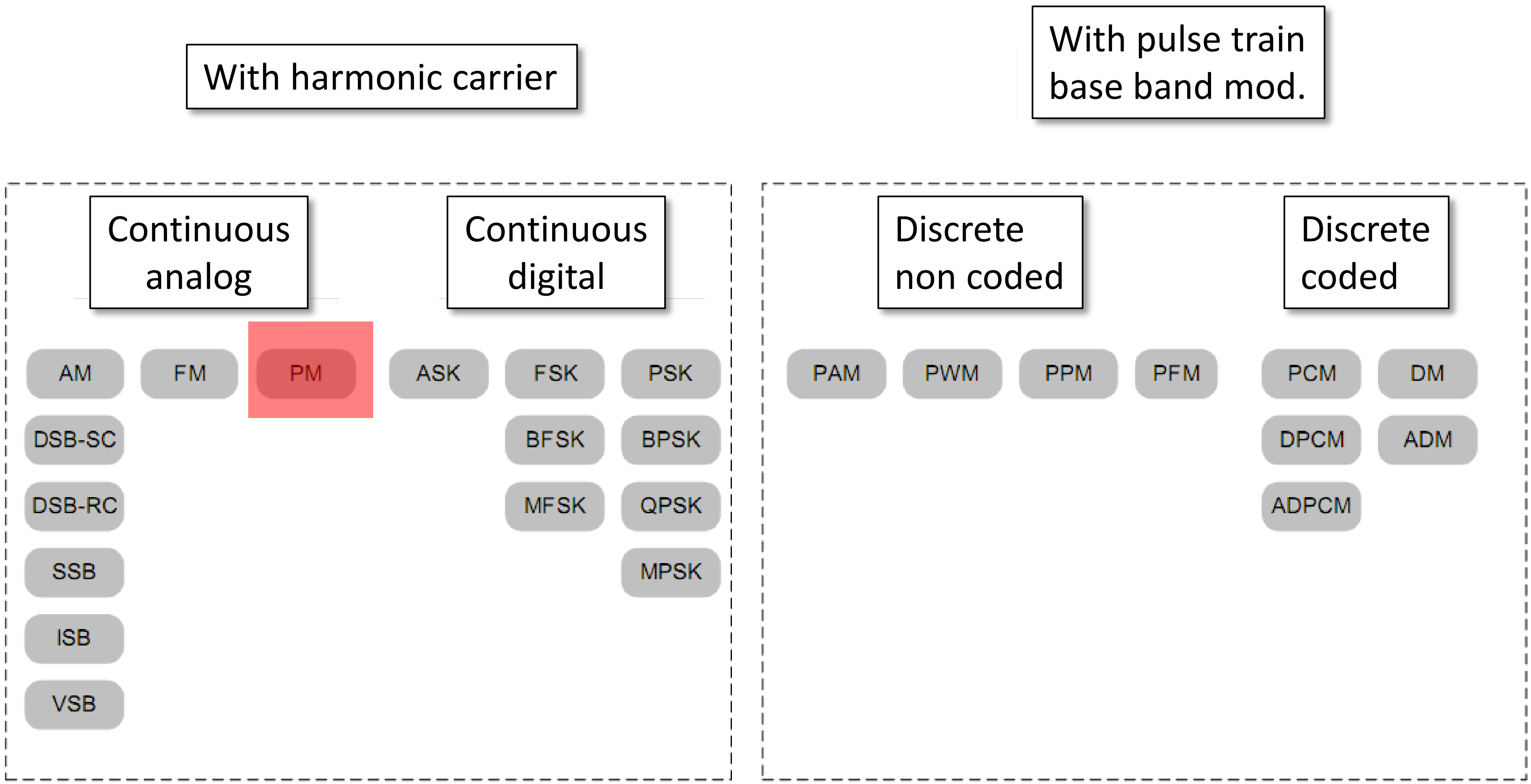
FM stereo - multiplex

- Add left and right signals to create monaural signal (L+R)
- Subtract L-R right signals to create stereo difference signal
- Generate a 38kHz subcarrier frequency modulated by L-R
- Mix subcarrier, 19 kHz pilot signal, L+R monaural audio
- Frequency-modulate RF carrier

- Due to the presence of the 38 kHz subcarrier modulation is the maximum distance covered significantly reduced.

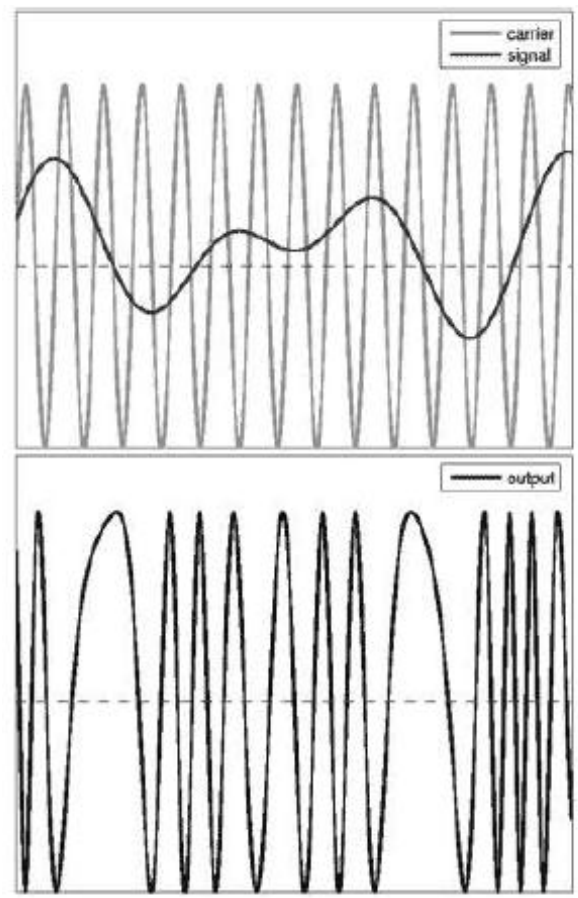


Analog modulation – phase modulation



phase modulation

- Phase modulation (PM) is a form of modulation that represents information as variations in the instantaneous phase of a carrier wave.
- modification in phase according to low frequency will give phase modulation.
- not used for radio transmissions.
- it tends to require more complex receiving hardware and there can be ambiguity problems in determining whether, for example, the signal has changed phase by +180° or -180°.



phase modulation

- PM changes the phase angle of the complex envelope in direct proportion to the message signal.

$$s(t) = A_c \cos\left(\omega_c t + s_m(t) + \phi_c\right)$$

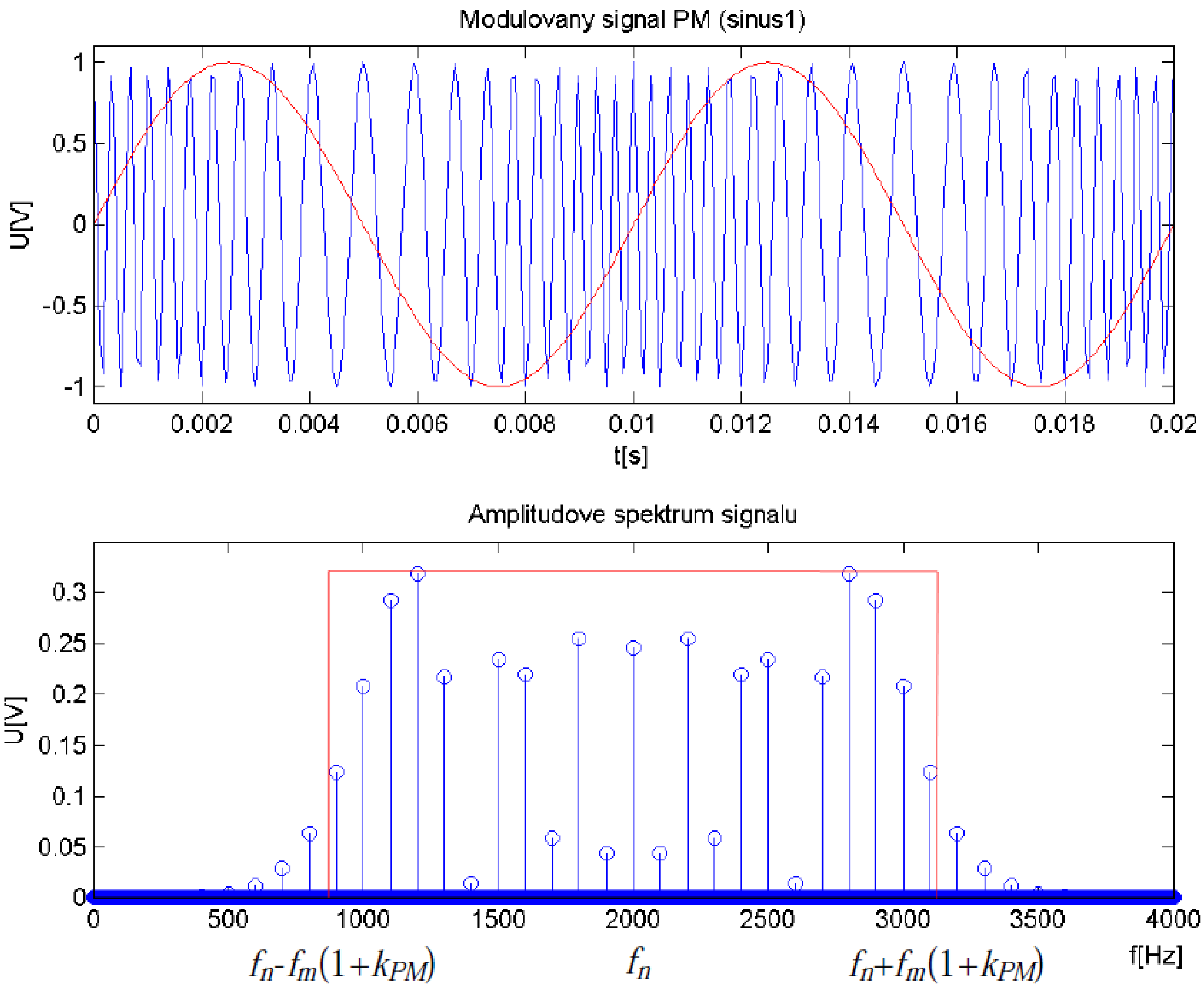
- For small amplitude signals, PM is similar to amplitude modulation (AM) and exhibits its unfortunate **doubling of baseband bandwidth and poor efficiency**.
- For a single large sinusoidal signal, PM is similar to FM, and its bandwidth is approximately

$$\beta = 2\left(h+1\right) f_m$$

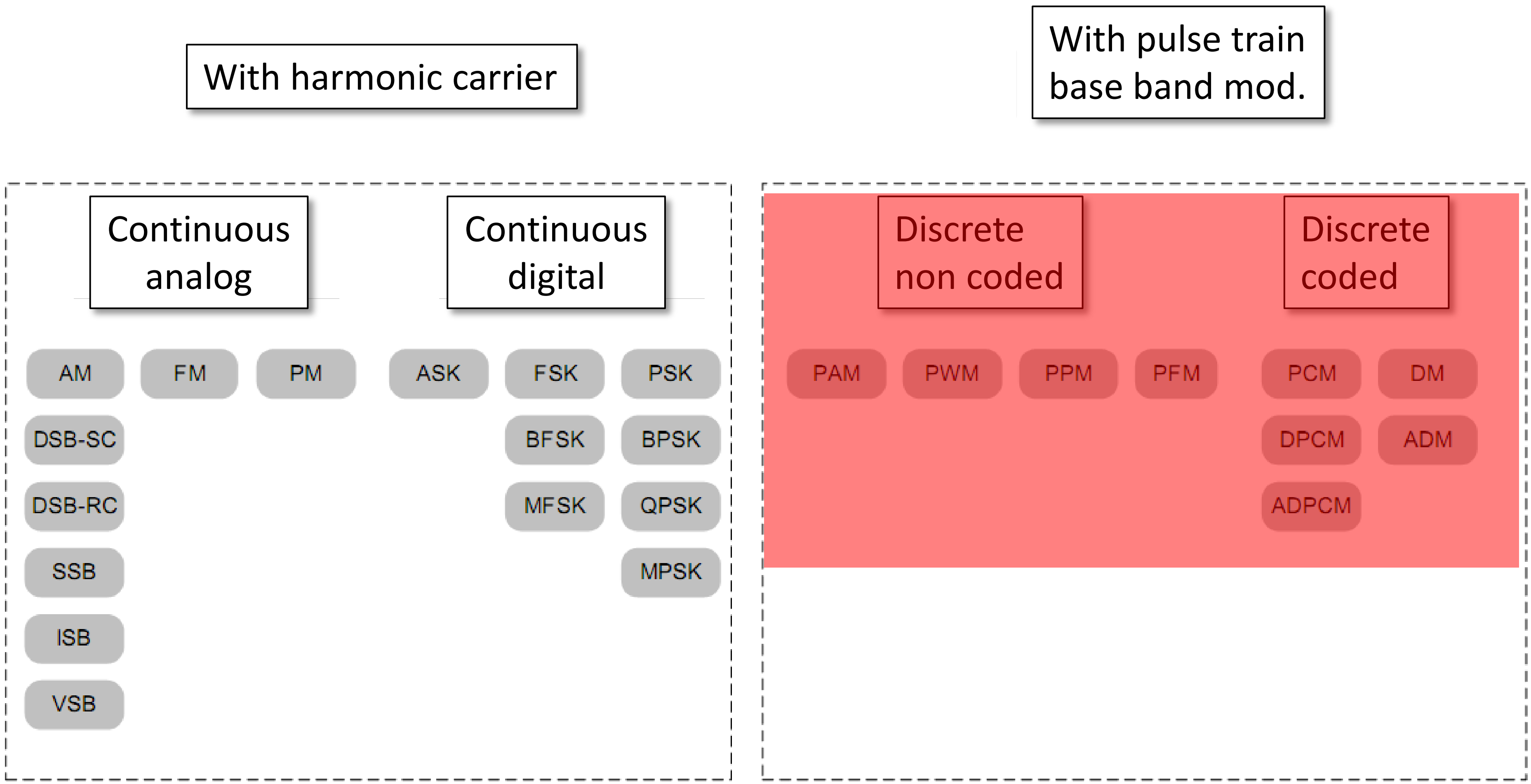
- Where $h = \Delta\theta$ is peak phase deviation

http://hermes.eee.nott.ac.uk/teaching/cal/h61sig/sig0019.html

phase modulation



Pulse modulations



Pulse modulations

Analog-over-analog methods:

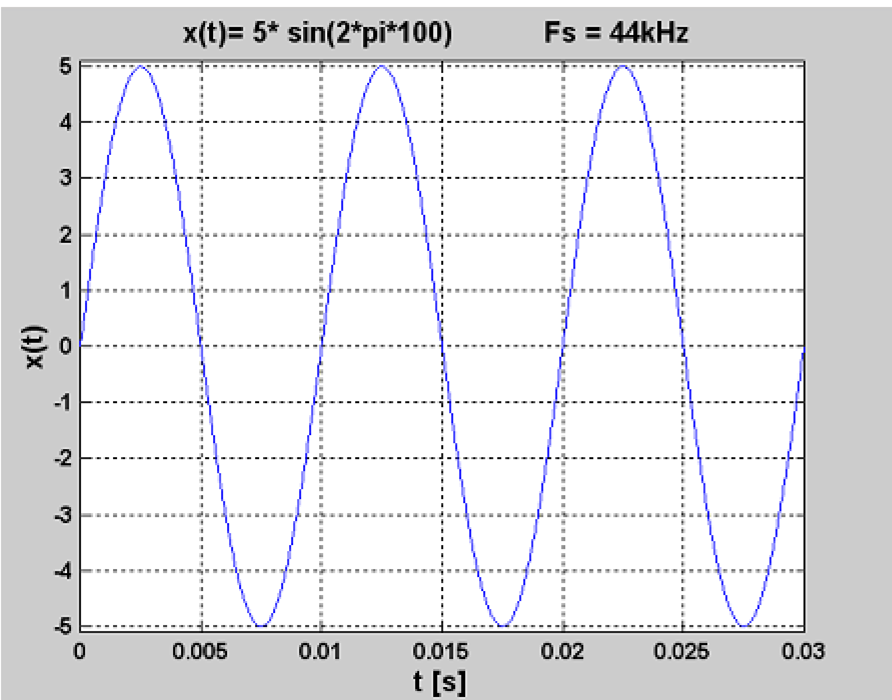
- Pulse-amplitude modulation (PAM)
- Pulse-width modulation (PWM)
- Pulse-position modulation (PPM)

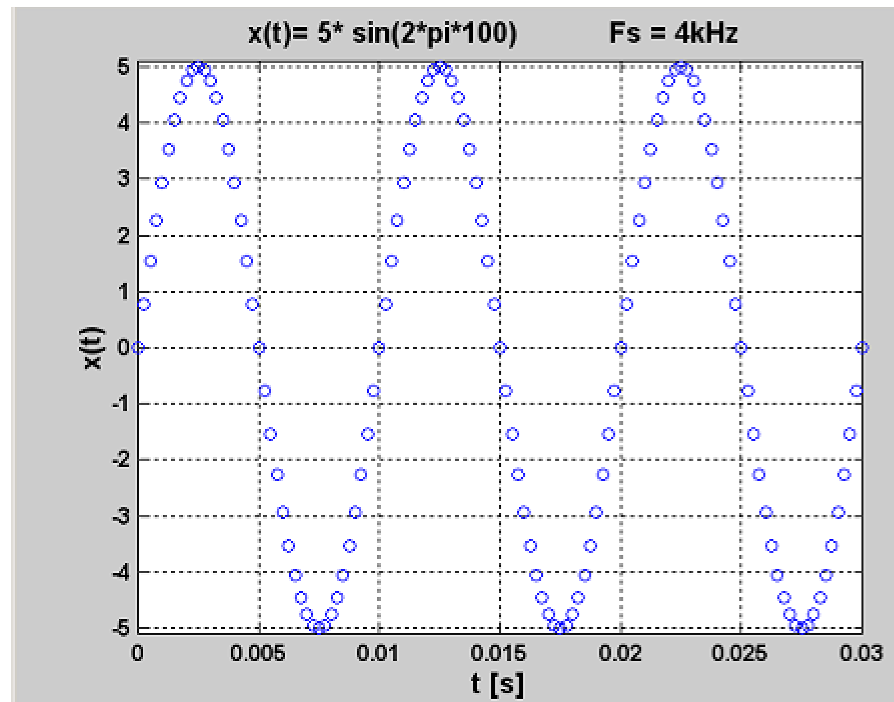
Analog-over-digital methods:

- Pulse-code modulation (PCM)
- Differential PCM (DPCM)
- Adaptive DPCM (ADPCM)
- Delta modulation (DM or Δ-modulation)

Making of pulses – sampling

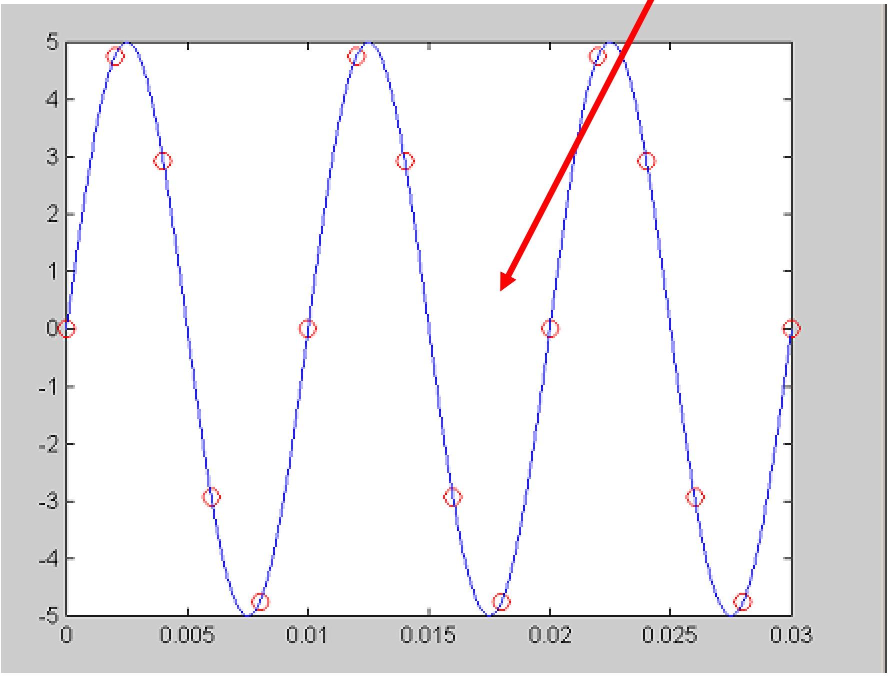
- Sampling in time: $x[i] = x(i*T_s)$
  - T_s .... Sampling period,
  - $F_s = 1/T_s$ .... Sampling frequency

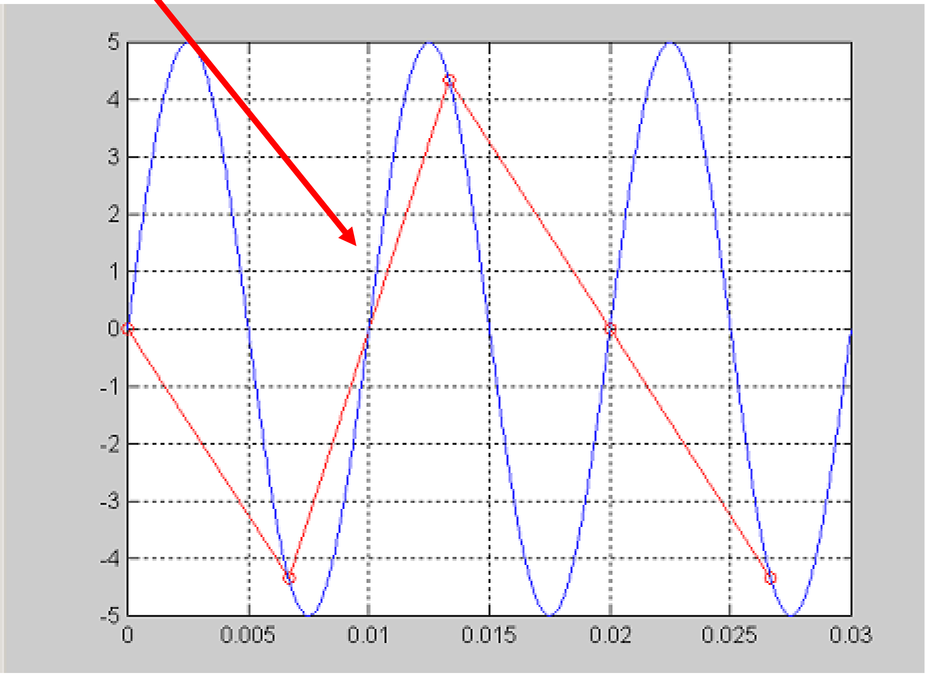




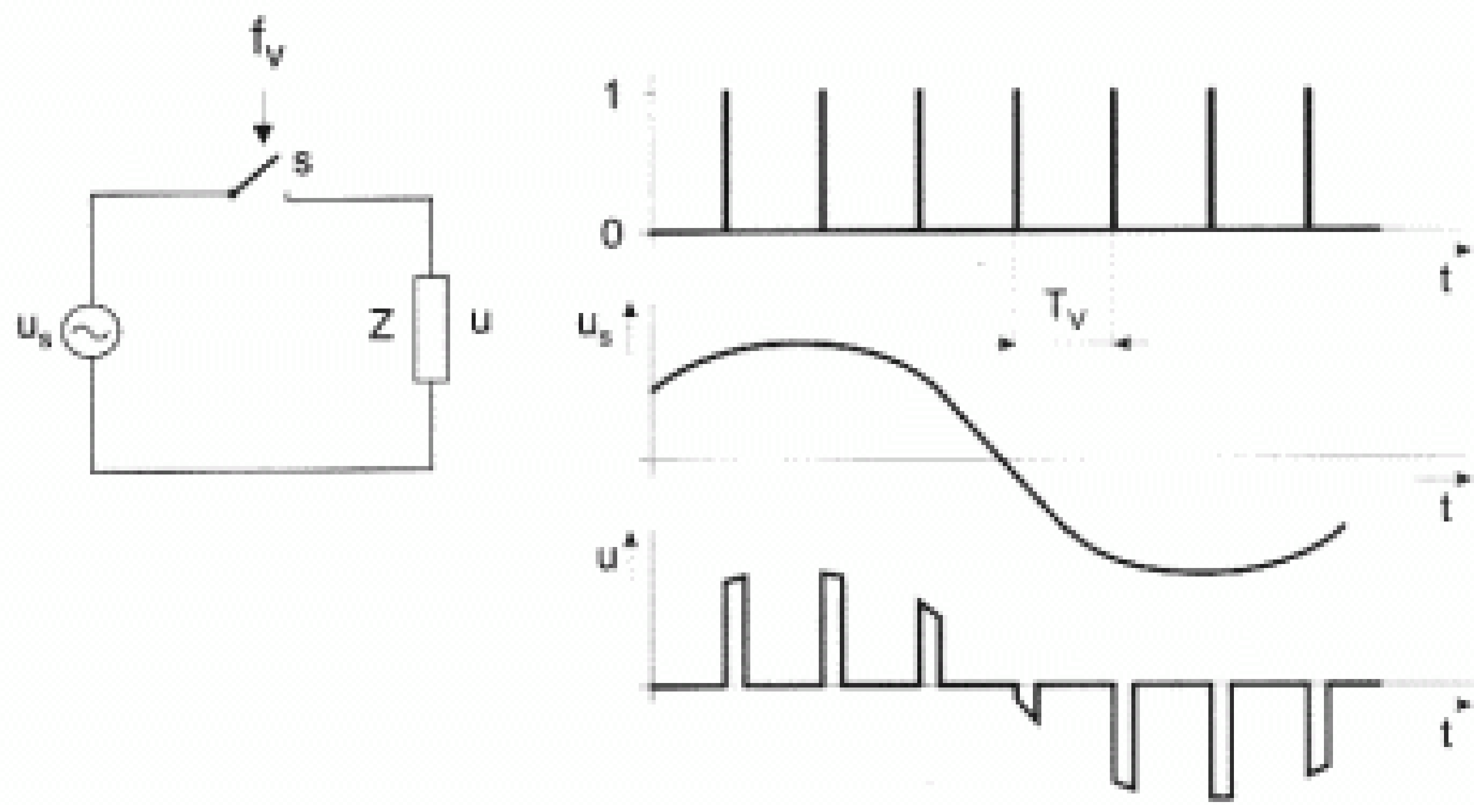
Sampling – time plot

- Signal frequency 100Hz
- Sampling frequency 500Hz a 150Hz

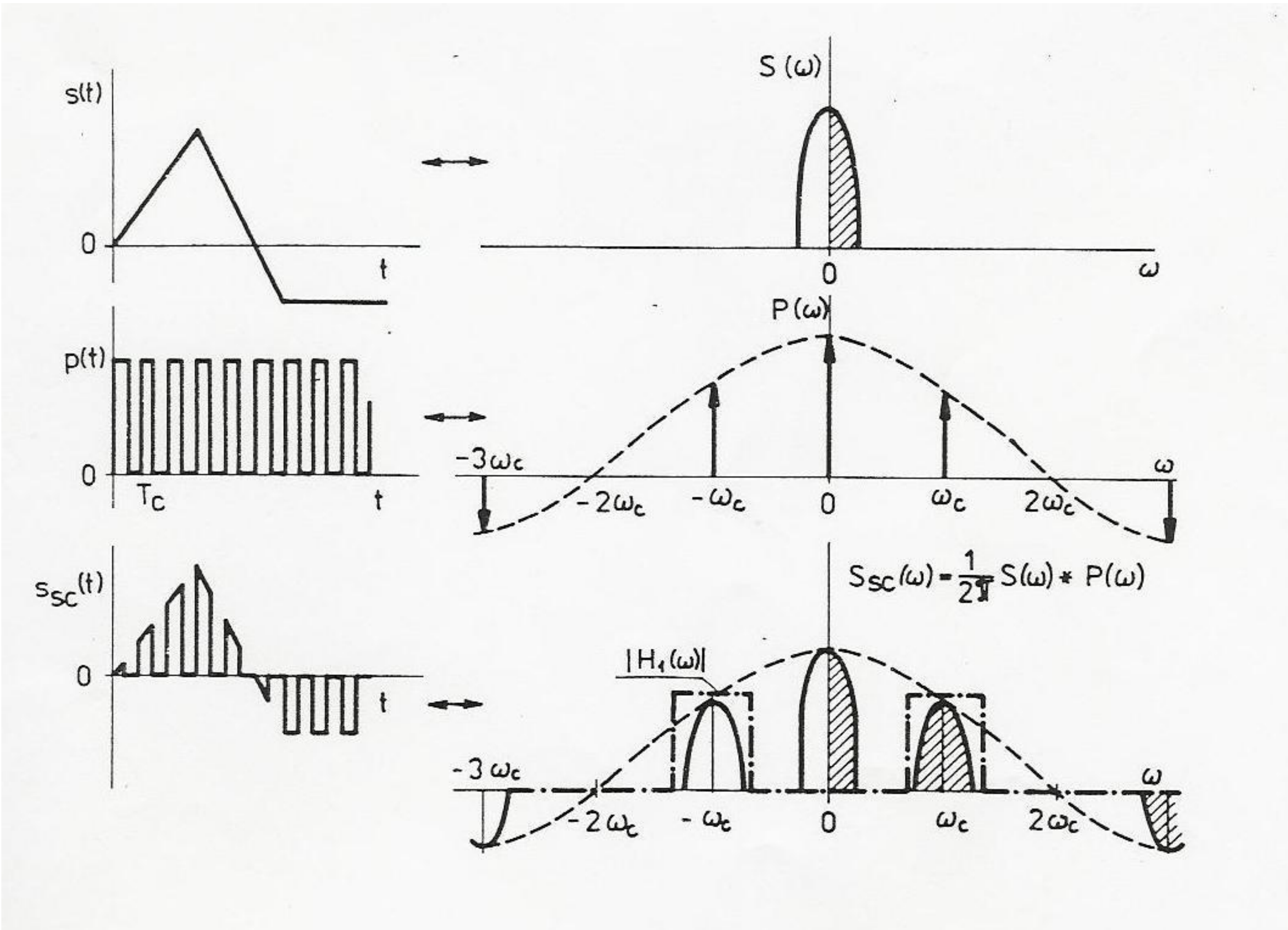




Sampling – time plot



Sampling – time and frequency plot



PAM – Pulse amplitude modulation

With harmonic carrier

- **Continuous analog**
  - AM
  - FM
  - PM
  - DSB-SC
  - DSB-RC
  - SSB
  - ISB
  - VSB
- **Continuous digital**
  - ASK
  - FSK
  - PSK
  - BFSK
  - BPSK
  - MFSK
  - QPSK
  - MPSK

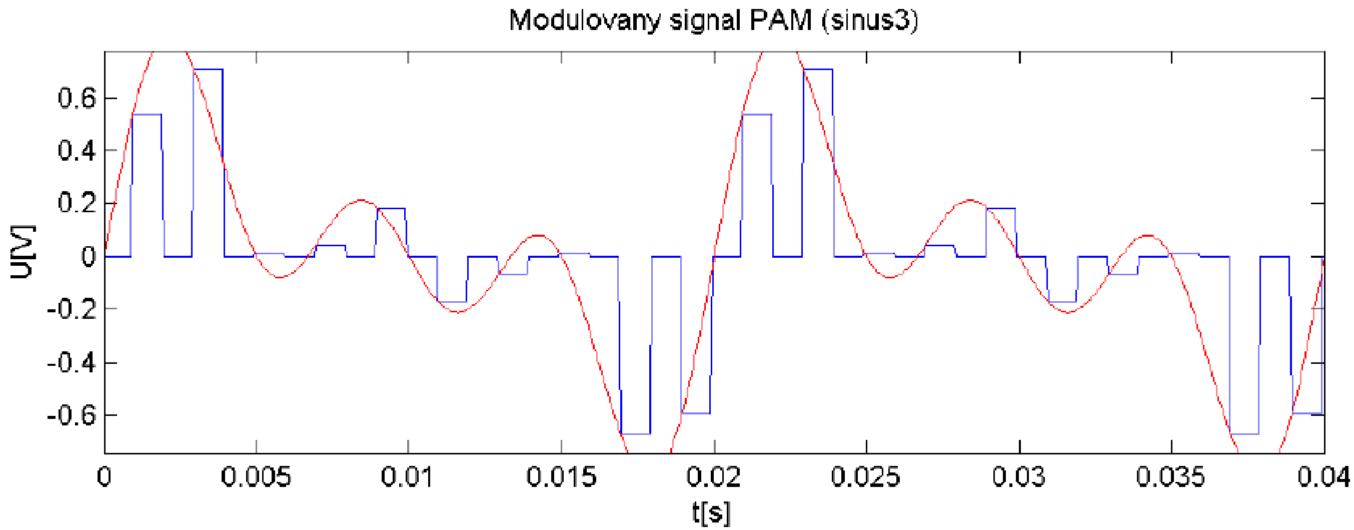
With pulse train base band mod.

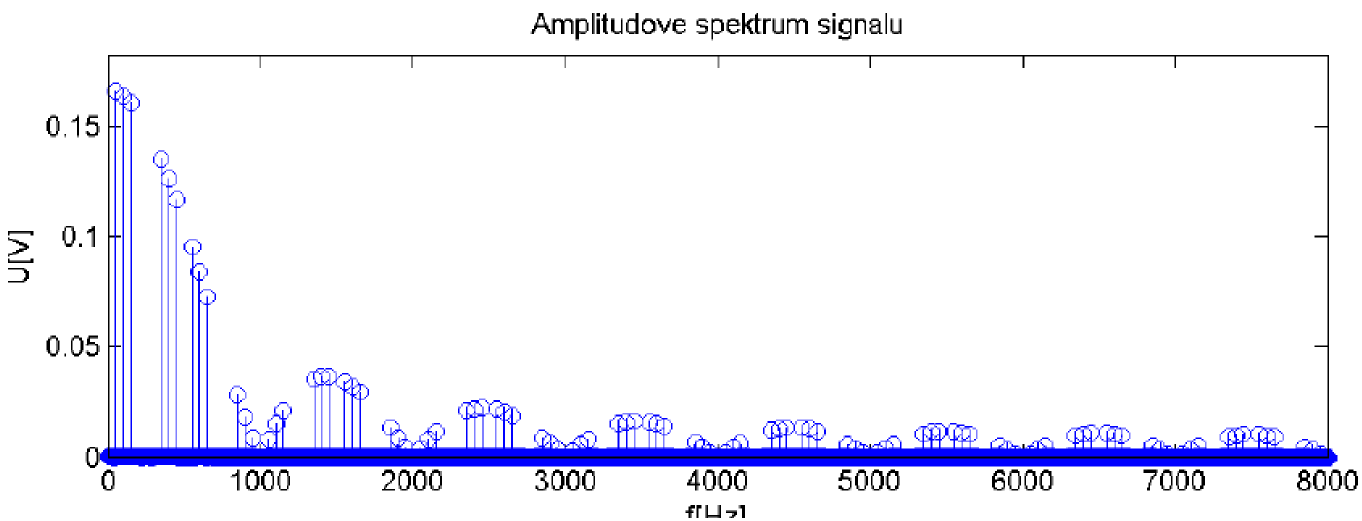
- **Discrete non coded**
  - PAM
  - PWM
  - PPM
  - PFM
- **Discrete coded**
  - PCM
  - DM
  - DPCM
  - ADM
  - ADPCM

PAM – Pulse amplitude modulation

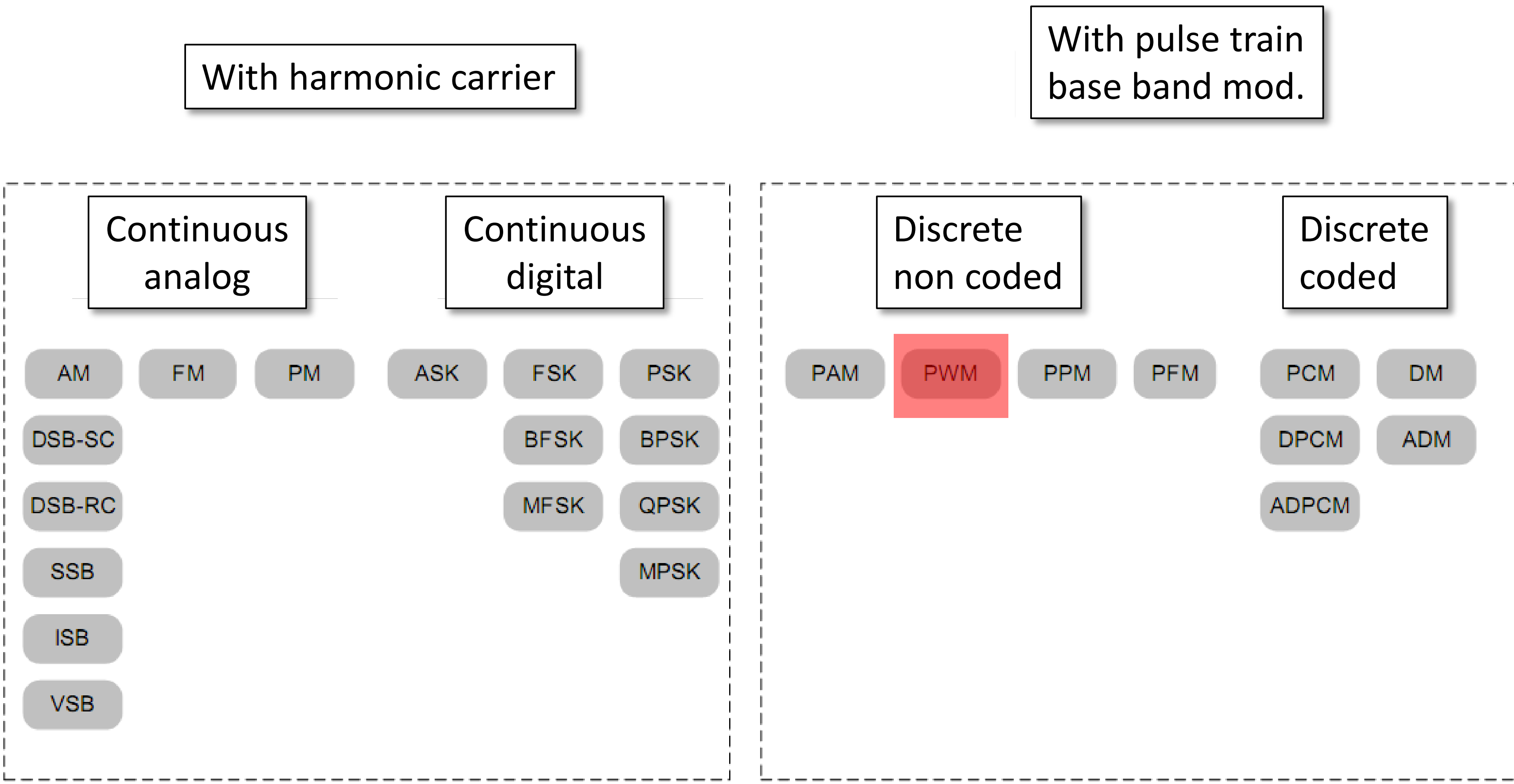
- Signal is sampled at regular intervals, each sample is proportional to the magnitude of the signal at the instant of sampling.
- Sampled pulses may then be sent either directly by a channel or may be modulated using a carrier wave before transmission.
- two types of pulse amplitude modulation:
  - Single polarity PAM: a suitable fixed DC bias is added to the signal to ensure that all the pulses are positive.
  - Double polarity PAM: the pulses are both positive and negative.
- For the generation of a PAM signal we use a flat top type PAM scheme, the noise is interfered at top of the transmission pulse which can be easily removed

PAM – signal example





PWM – Pulse width modulation



PWM – Pulse width modulation

- Pulse-width modulation uses a rectangular pulse wave whose pulse width is modulated resulting in the variation of the average value of the waveform.
- the widths of the pulses correspond to specific data values encoded at one end and decoded at the other.
- Pulses of various lengths (the information itself) will be sent at regular intervals (the carrier frequency of the modulation).

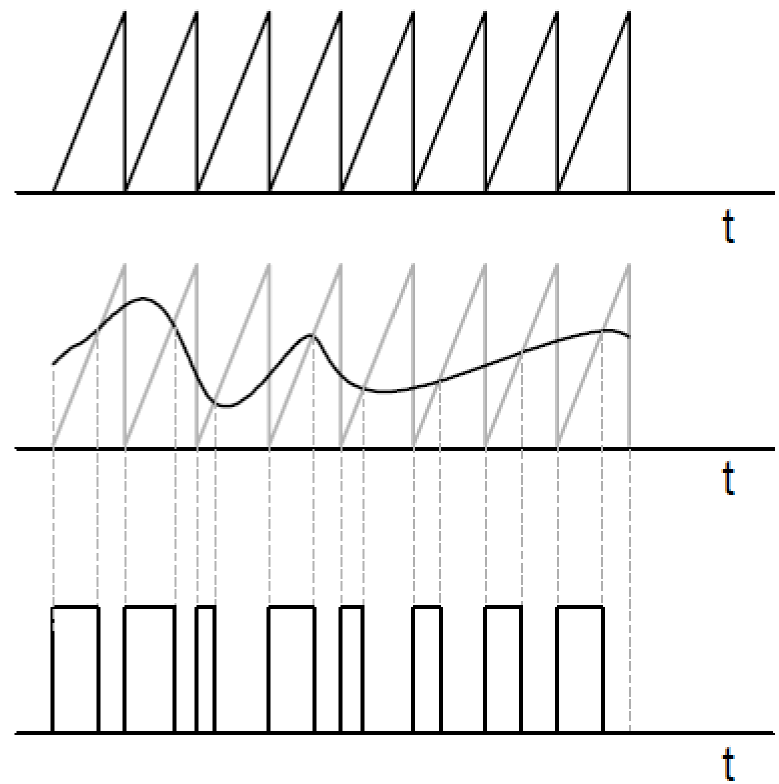
Main but different usage:

- PWM can be used to control the amount of power delivered to a load without incurring the losses that would result from linear power delivery by resistive means.

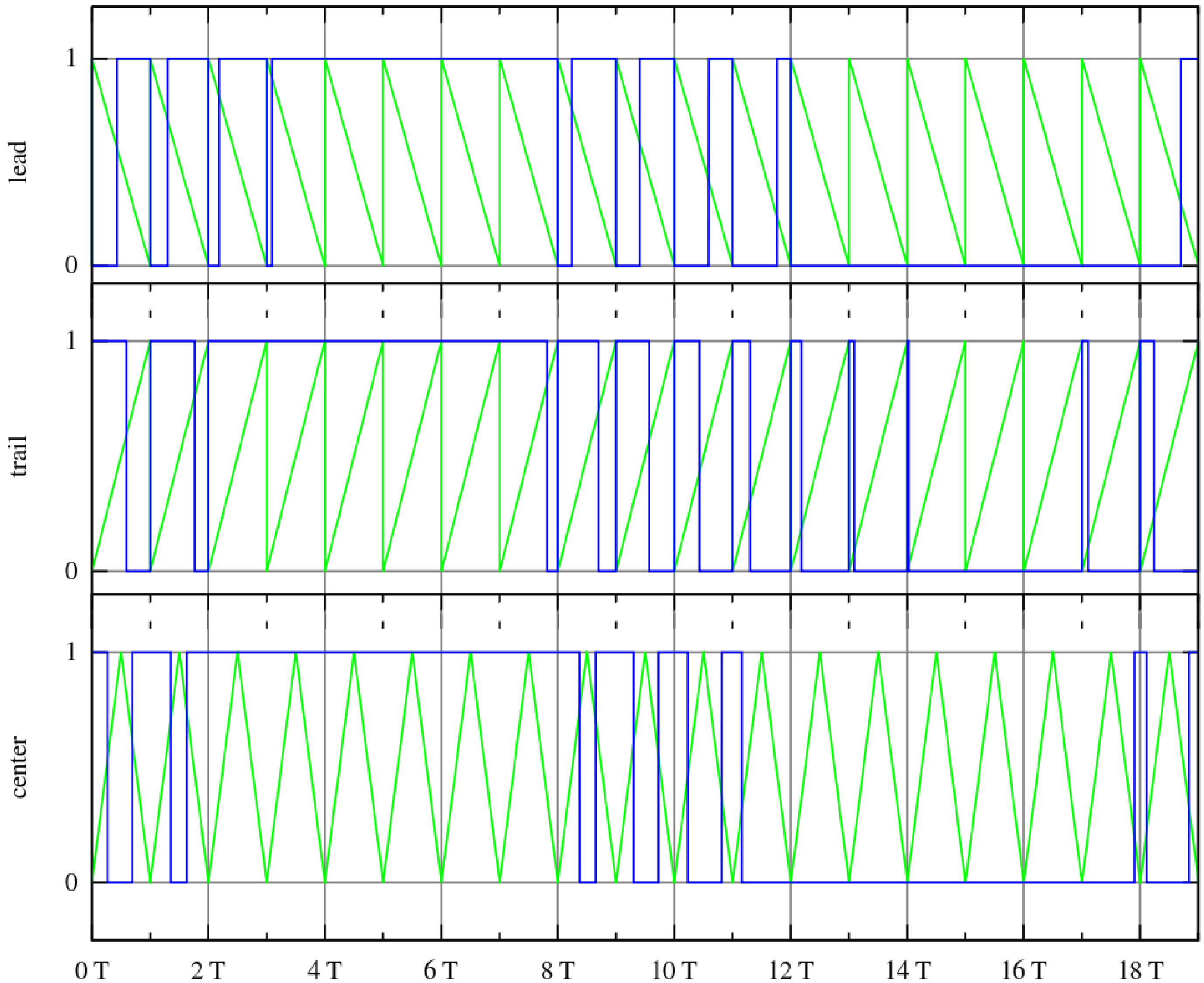
PWM – Pulse width modulation

Three types of pulse-width modulation (PWM) are possible:

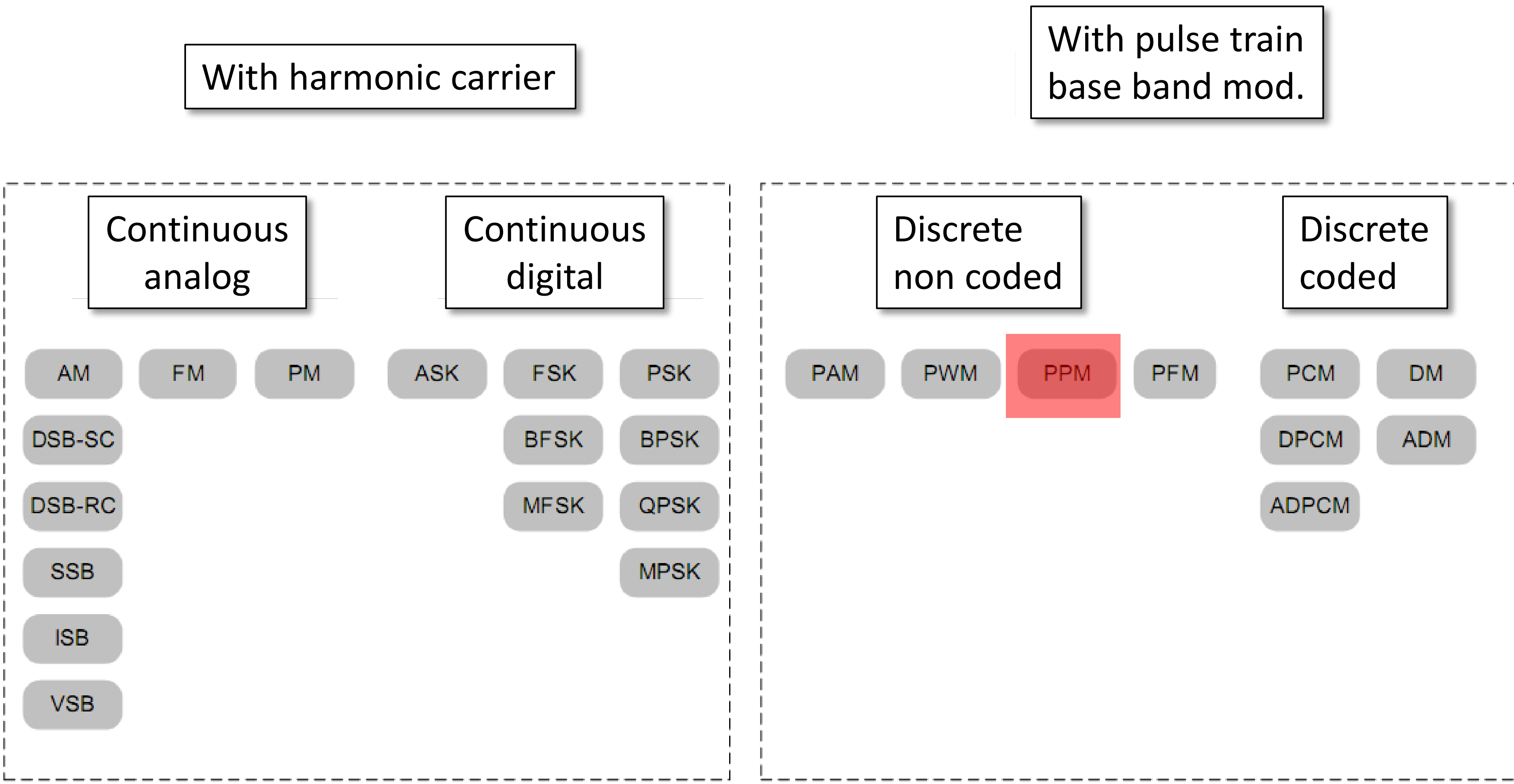
- The pulse center may be fixed in the center of the time window and both edges of the pulse moved to compress or expand the width.
- The lead edge can be held at the lead edge of the window and the tail edge modulated.
- The tail edge can be fixed and the lead edge modulated.



PWM – Pulse width modulation



PWM – Pulse position modulation

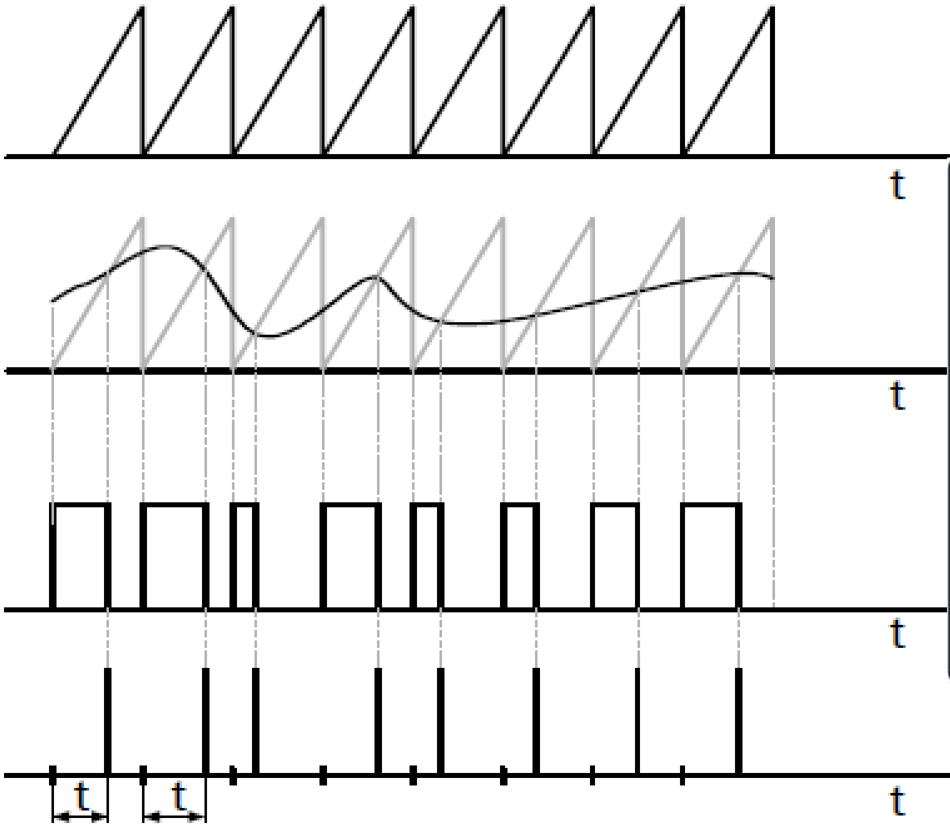


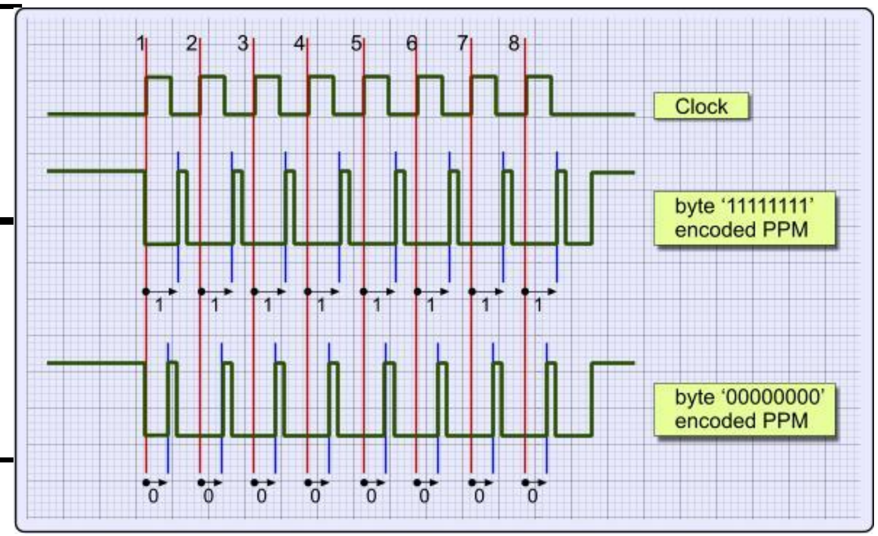
PPM – Pulse position modulation

- data are transmitted with short pulses. All pulses have both the same width and amplitude. The parameter that changes is the **delay** between each pulse.
- the receiver must be properly **synchronized to align the local clock** with the beginning of each symbol.
- often implemented differentially as differential pulse-position modulation, whereby each pulse position is encoded relative to the previous, such that the receiver must only measure the difference in the arrival time of successive pulses.
- widely used for optical communication systems such as optic fiber and IR remote controls, where efficiency is required and little or no external interference occurs.

PWM – Pulse position modulation

- Examples

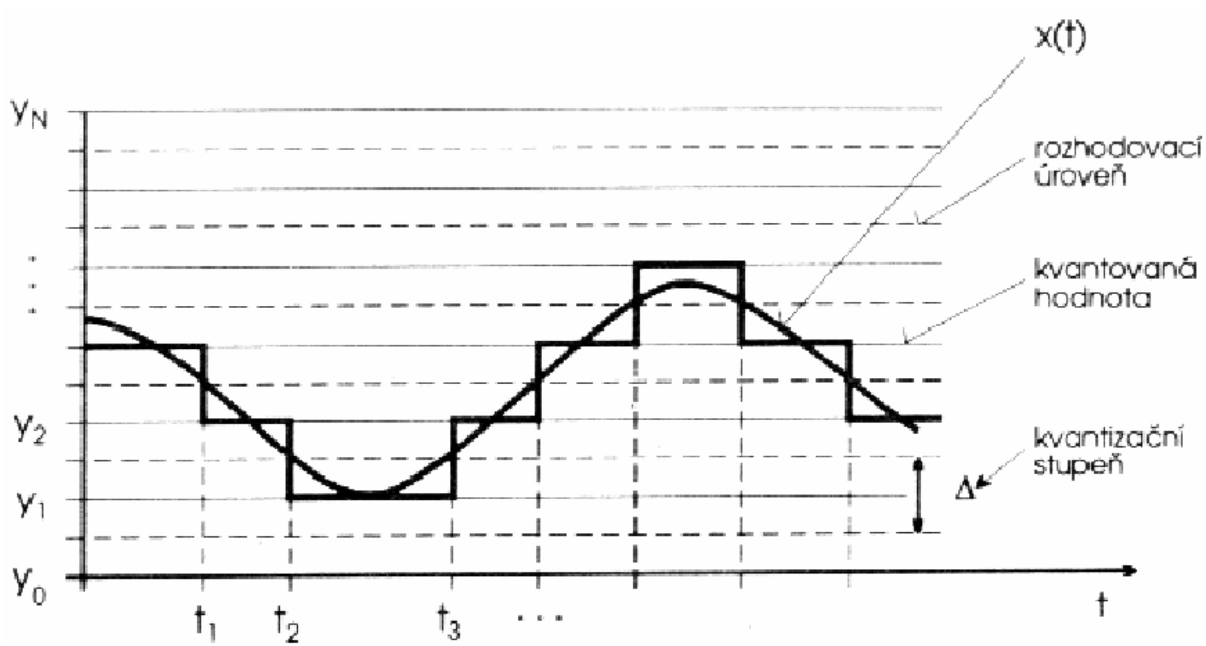




Quantized pulse modulations

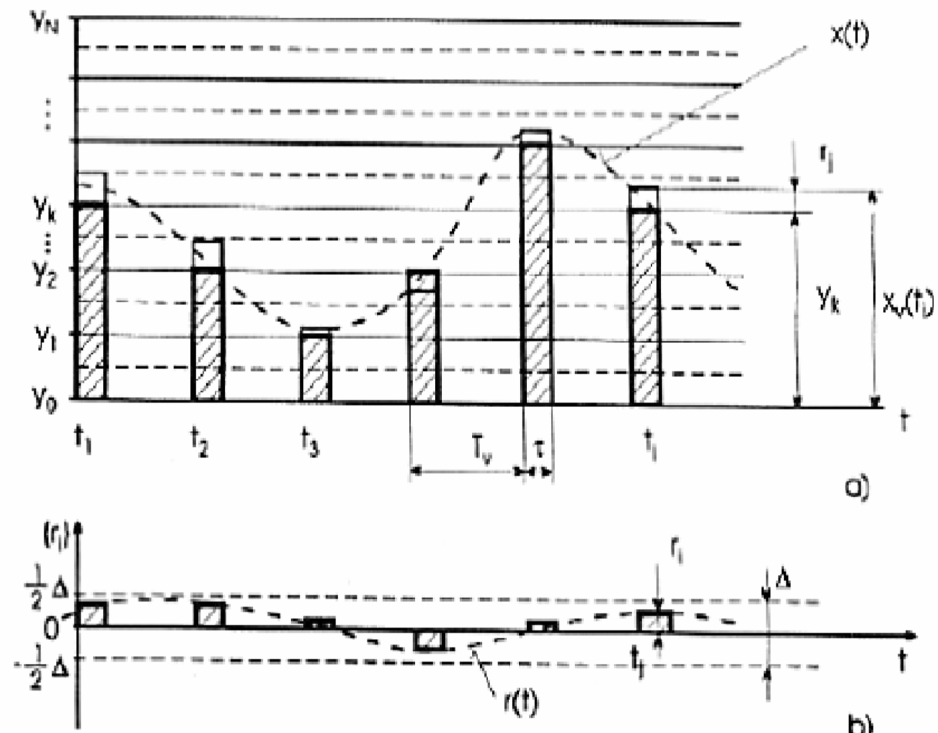
Quantization

- The process of mapping a large set of input values to a smaller set – rounding values to some unit of precision.
- involved in nearly all digital signal processing, as the process of representing a signal in digital form ordinarily involves rounding. Also core of lossy compression algorithms.



Quantization

- The error introduced by quantization is referred to as **quantization** error or **round-off** error.
- r(t) – quantization noise
- non-linear and irreversible process (i.e., because the same output value is shared by multiple input values, it is impossible in general to recover the exact input value when given only the output value).

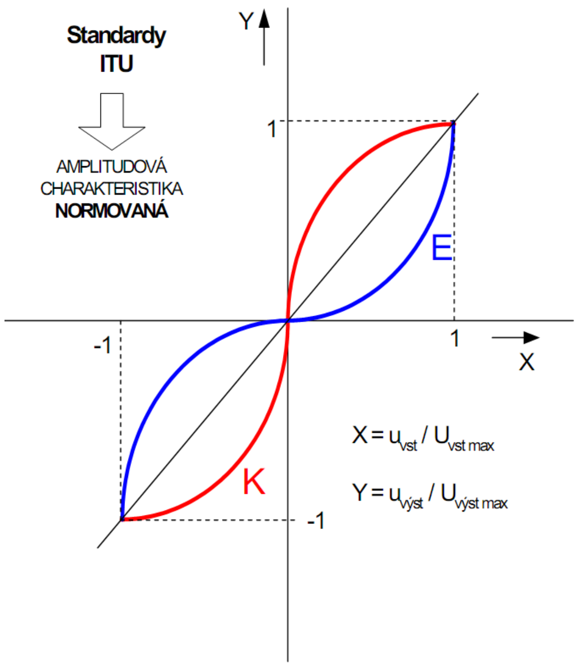


$r_i = x_v(t_i) - y_k \qquad r_{max} = \pm 1/2\ \Delta$

Quantization

Two types

- **rounding quantization**, in many applications, to enable the use of a simple approximate representation for some quantity that is to be measured and used in other calculations. In
- **rate–distortion optimized quantization**, to manage distortion within the limits of the bit rate supported by a communication channel.
- The amount of introduced distortion may be managed carefully by sophisticated techniques. Intervals are not spaced equally



Delta Modulation

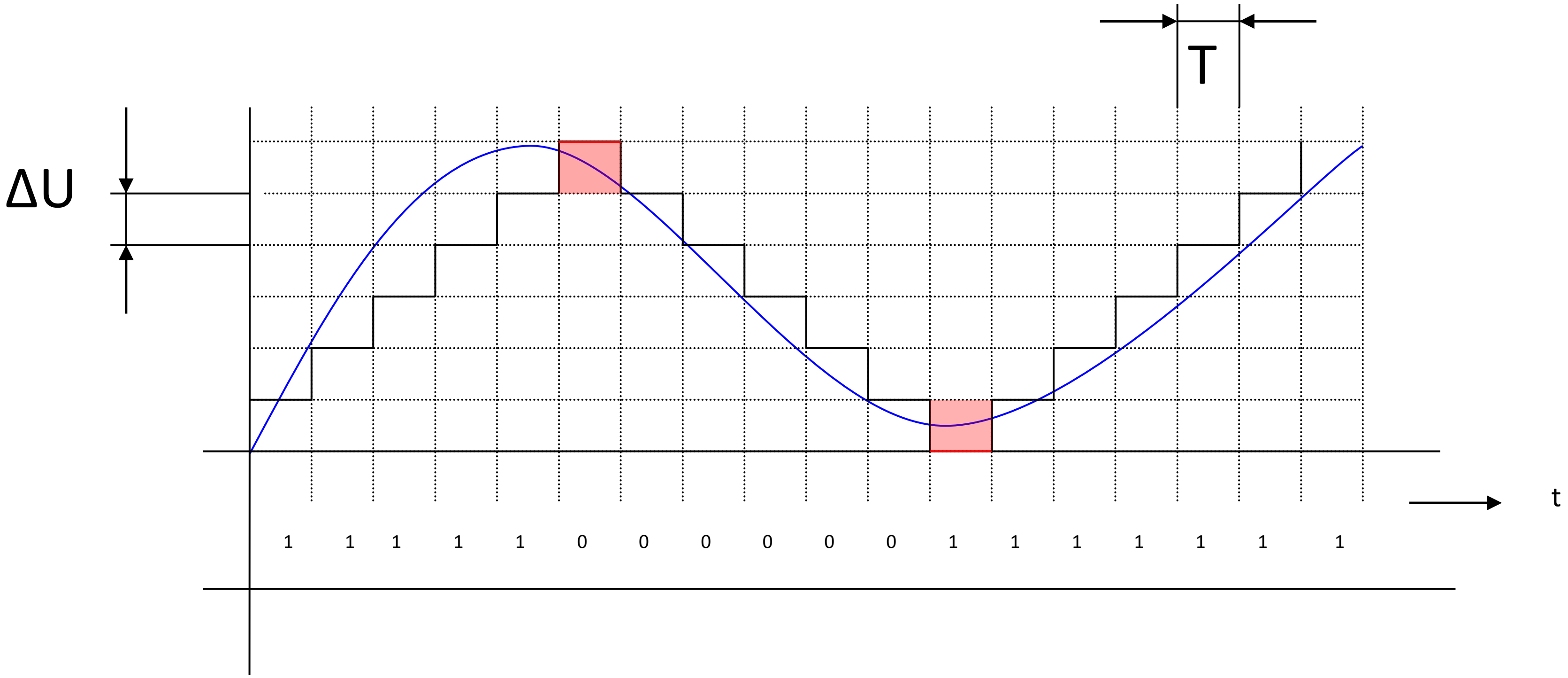
- Resolution of 1 bit - accomplished by successive steps, either up or down, by a preset step size.
- Step size (Δ) is defined for each sampler, the rules are:
  - If the input signal is higher than the current reference signal, increase the reference by Δ, and output a 1.
  - If the input signal is lower than the current reference signal, decrease the reference by Δ, and output a 0.

Benefits:

- 1 bit of resolution, and therefore requires very little bandwidth and very little hardware.
- No preset upper or lower bounds, so Delta modulation can (theoretically) be used to modulate unbounded signals.

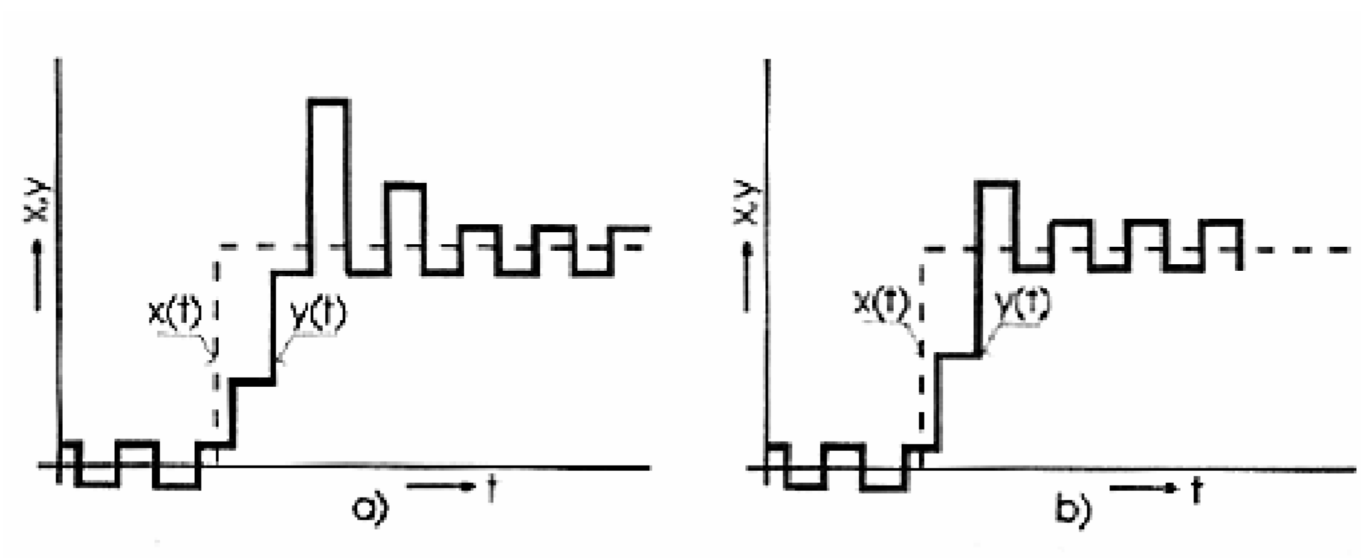
Delta Modulation

- **Slope Overload = **If the input signal is rising or falling with a slope larger than Δ/T, where T is the sampling time,
- In DM we can never have slopes larger than a certain upper limit, and functions that rise or fall at a faster rate, are going to be severely distorted.



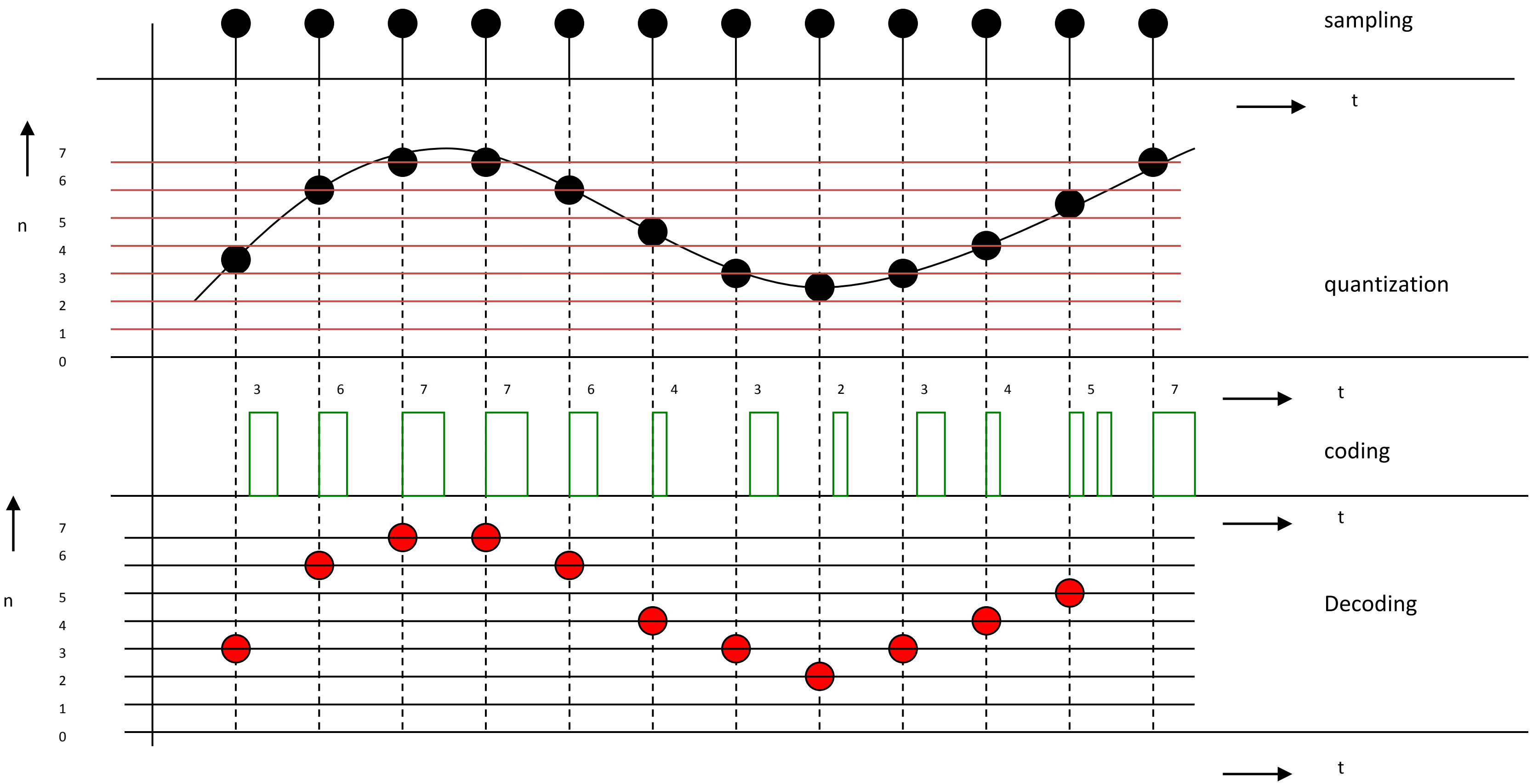
ADM – adaptive delta modulation

- The step size is **not fixed**.
- When several consecutive bits have the same direction value, the encoder and decoder assume that slope overload is occurring, and the step size becomes progressively larger.
- Otherwise, the step size becomes gradually smaller over time. ADM reduces slope error, at the expense of increasing quantizing error.



PCM – Pulse code modulation

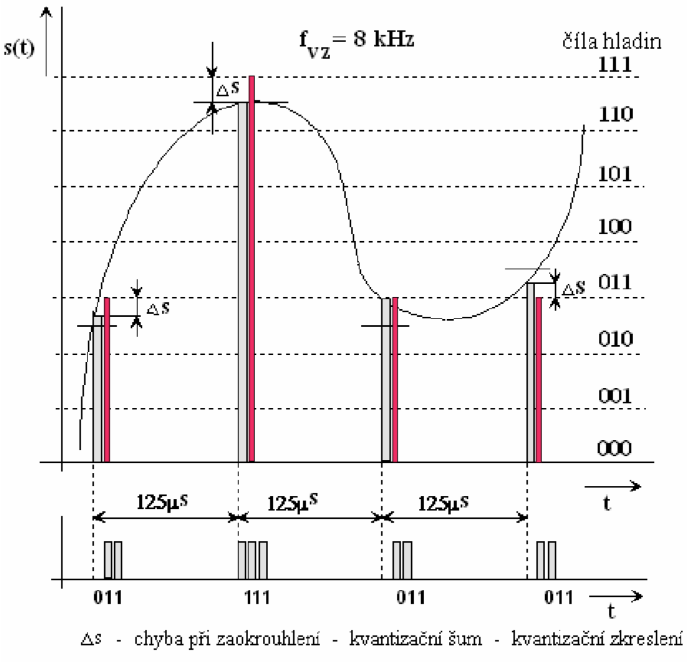
- principle



PCM in telephony

- PCM have two basic properties that determine their fidelity to the original analog signal.
- the **sampling rate**, which is the number of times per second that samples are taken; and
- the **bit depth**, which determines the number of possible digital values that each sample can take.

Kvantované vzorky



DPCM and ADPCM

- **DPCM** encodes the PCM values as differences between the current and the predicted value.
- An algorithm predicts the next sample based on the previous samples, and the encoder stores only the difference between this prediction and the actual value. If the prediction is reasonable, fewer bits can be used to represent the same information.
- For audio, this type of encoding reduces the number of bits required per sample by about 25% compared to PCM.

- Adaptive DPCM (**ADPCM**) is a variant of DPCM that varies the size of the quantization step, to allow further reduction of the required bandwidth for a given signal-to-noise ratio.

Continuous digital modulations

Continuous digital modulations

- an analog carrier signal is modulated by a discrete signal. The changes in the carrier signal are chosen from a finite number of M alternative **symbols** (the *modulation alphabet*).

Fundamental digital modulation methods (based on keying):

- **PSK** (phase-shift keying), a finite number of phases are used.
- **FSK** (frequency-shift keying), a finite number of frequencies are used.
- **ASK** (amplitude-shift keying), a finite number of amplitudes are used.
- **QAM** (quadrature amplitude modulation), a finite number of at least two phases, and at least two amplitudes are used.

Continuous digital modulations

discrete signals

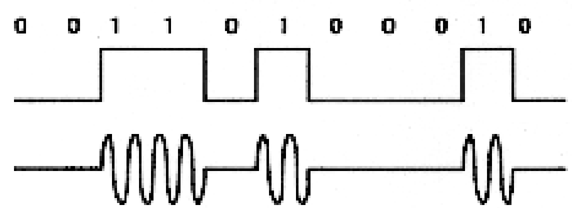
- Can be transferred over metallic / optical cables. Modulation by high frequency allows to multiplex more signals at one channel
- Could not be transferred over the air link.

Continuous digital modulations are:

- 2 state modulations, modulation signal is digitally modulated in a baseband (PCM, DM, + AM, FM PM)
- Multiple state modulations - more than just two states can be transferred by one symbol

ASK - Amplitude-shift keying

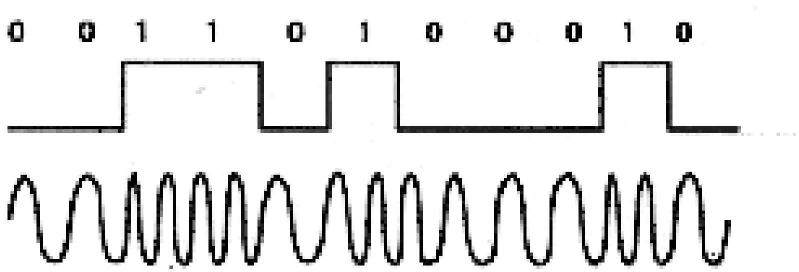
- is a form of modulation that represents digital data as variations in the amplitude of a carrier wave.
- uses a finite number of amplitudes, each assigned a unique pattern of binary digits. Each pattern of bits forms the symbol that is represented by the particular amplitude.
- Frequency and phase of the carrier are kept constant.
- PCM/AM = ASK.



- **OOK** = ASK that operates as a switch, using the presence of a carrier wave to indicate 1 and its absence to indicate 0. Called on-off keying, and is used at radio frequencies to transmit Morse code (referred to as continuous wave operation),

FSK – Frequency-shift keying

- digital information is transmitted through discrete frequency changes of a carrier wave.
- The simplest FSK is *binary FSK* (BFSK). BFSK uses a pair of discrete frequencies to transmit binary (0s and 1s) information.



- If waveforms that represent 0s and 1s do not have any relation to bit rate, phase inconsistencies occur on transitions.

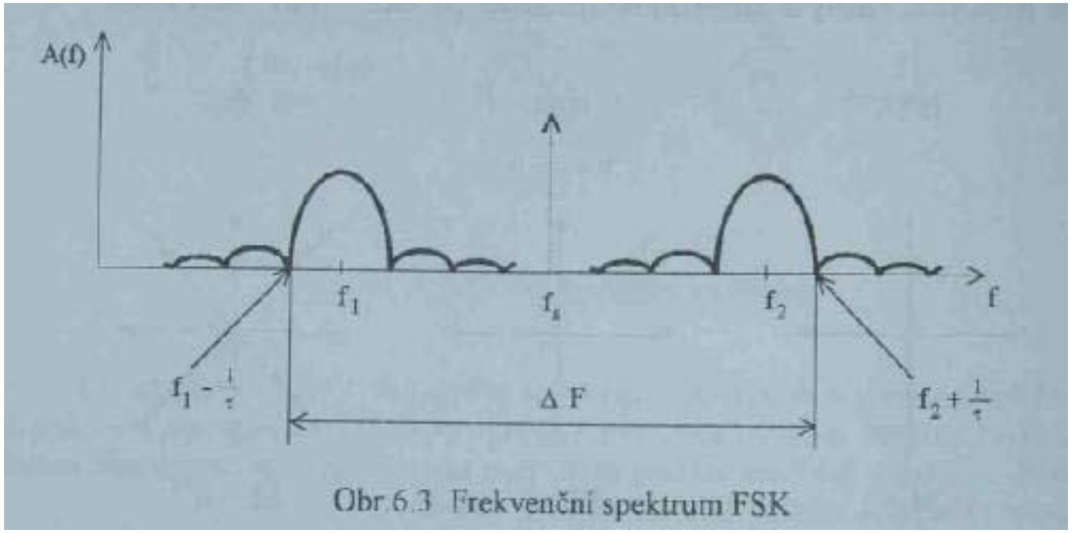
FSK – Frequency-shift keying

- *Minimum frequency-shift keying* (MSK) is a particular spectrally efficient form of coherent FSK.
- In MSK the difference between the higher and lower frequency is identical to half the bit rate.
- The waveforms used to represent a 0 and a 1 bit differ by exactly half a carrier period.
- Δf frequency deviation is ¼ of modulation frequency (bit rate) modulation index is ¼, that is smallest MI = narrow bandwidth

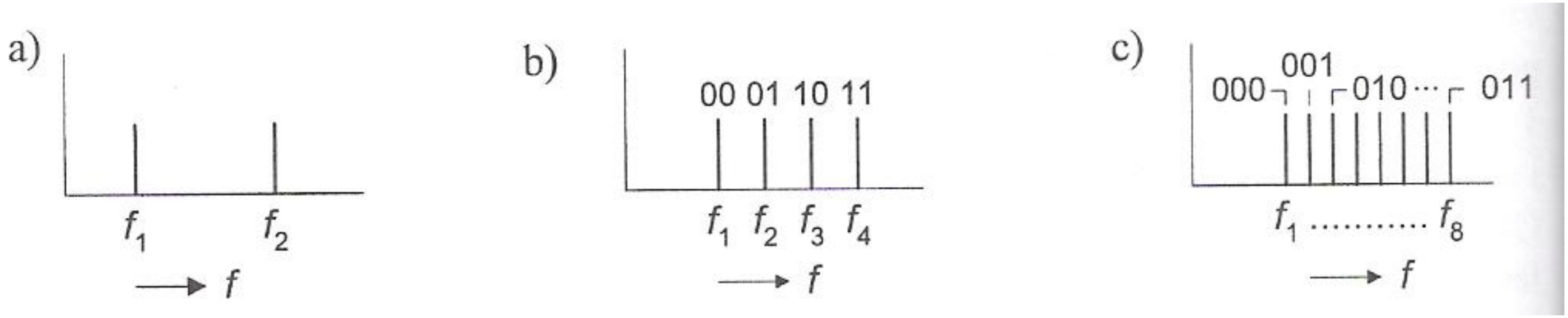
- Bandwidth computed by Carson's rule $B_{FSK} = 2(B_0 + \Delta f)$
  B_0 is bandwidth of modulation signal and Δf is deviation frequency

FSK – Frequency-shift keying

- Bandwidth of FSK



- Discrete multiple state FSK: 2FSK; 4FSK; 8FSK;



PSK - Phase-shift keying

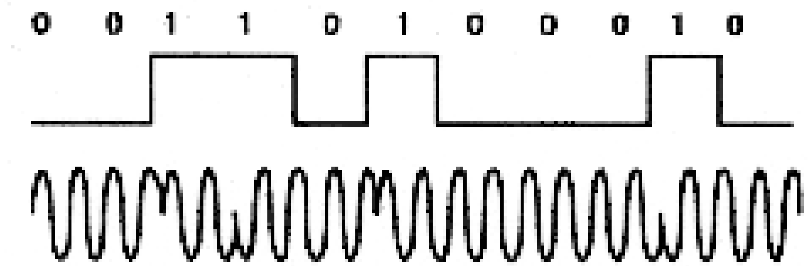
- digital information is transmitted through discrete phase changes of a carrier wave.

Two variants

- Each pattern of bits forms the symbol that is represented by the particular phase. The demodulator determines the phase of the received signal and maps it back to the symbol. This requires comparison of the phase of the received signal to a reference signal = coherent systems (**CPSK**).
- Changes in phase of a single broadcast waveform can be considered the significant items. The demodulator determines the **changes** in the phase of the received signal rather than the phase (relative to a reference wave) itself. = **differential phase-shift keying (DPSK)**.

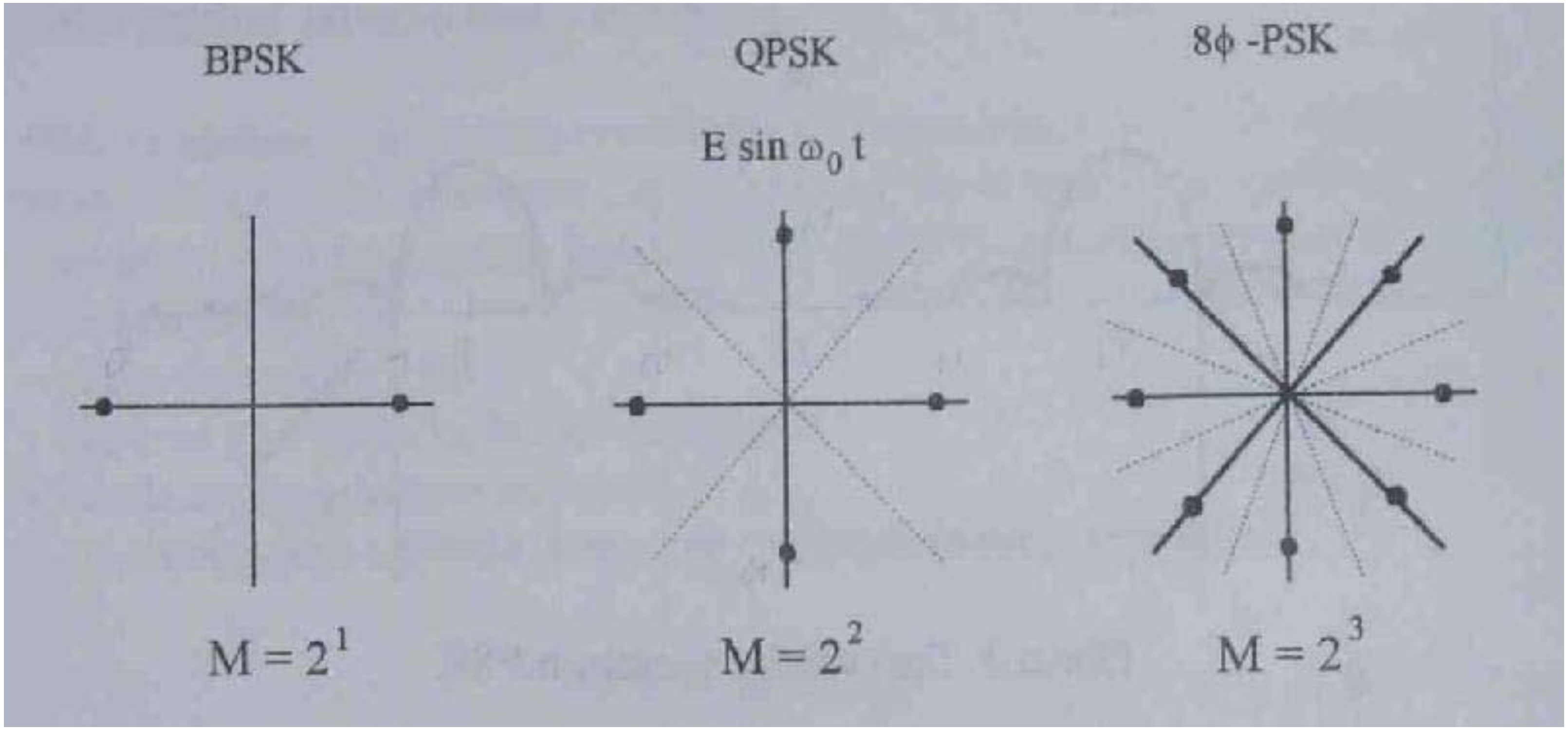
PSK - Phase-shift keying

- BPSK = Phase could acquire 2 discrete values. i.e. 0º a 180º. Amplitude is constant.



- Bandwidth is proportional to bit rate of modulating signal. best achievable B is $B_{PSK} = f_b = 1/T_b$.

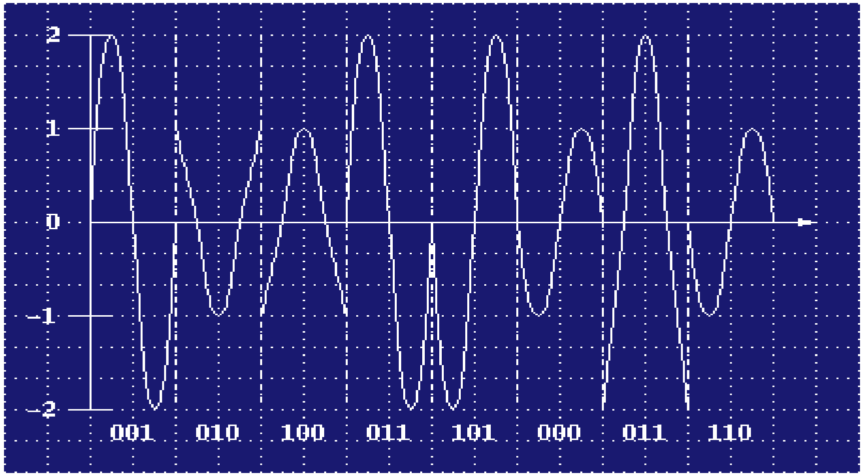
PSK - Phase-shift keying



- More states increases modulation frequency but also increases noise (decreases SNR)

QAM – Quadrature amplitude modulation

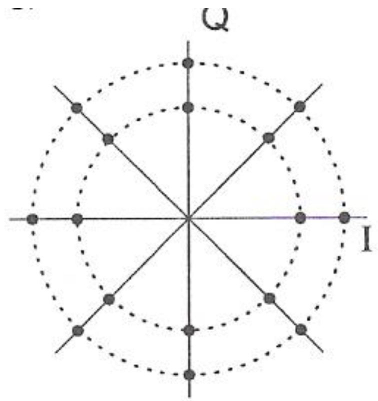
- Combination of PSK and ASK
- Channel capacity is derived from carrier frequency and desired SNR



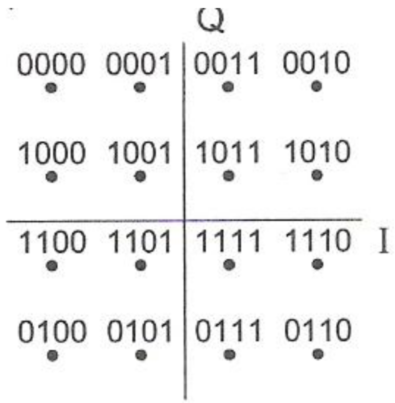
001010100011101000011110

Bit value	Ampl.	Phase shift
000	1	None
001	2	None
010	1	1/4
011	2	1/4
100	1	1/2
101	2	1/2
110	1	3/4
111	2	3/4

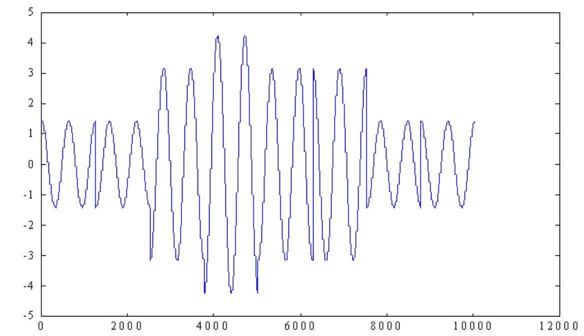
QAM – Quadrature amplitude modulation



8PSK/2AM



16QAM



16QAM – time plot

Spread spectrum modulation

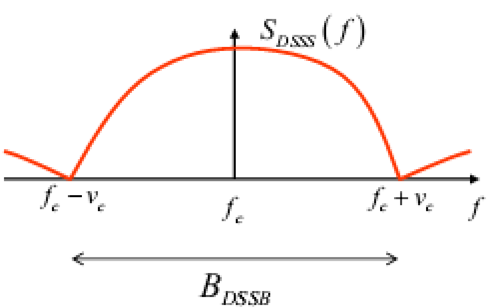
- uses modulation by pseudo random bit sequence PRBS.
- PRBS is independent to modulation signal and has to be same in receiver and transmitter.
- Spreads the energy of modulation signal to wider frequency bandwidth = uses more bandwidth.
- Resilient to narrow band noise.
- Methods of SS
  - DS SS direct sequence, system with direct modulation of modulation signal by PRBS
  - FH SS – frequency hopping, changes carrier frequency according to PRBS
  - TH SS – time hopping,

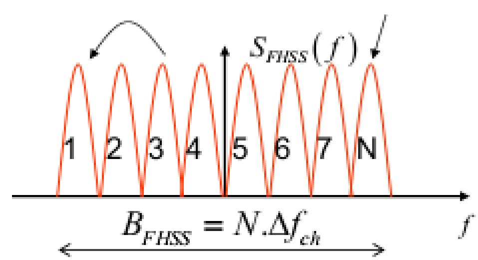
Spread spectrum modulation

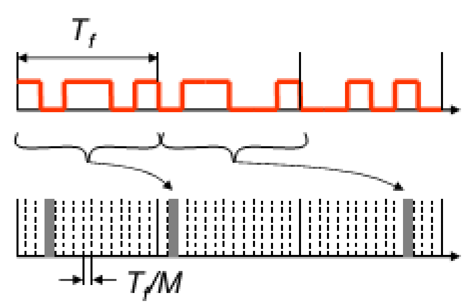
- Military requirements for radio transmitting
  - Hide signal to other parties
  - Communication in noisy environment
  - Harder targeting/pinpointing of the receiver

= spread spectrum communication

- Used in military and civil systems







Line coding

Line coding

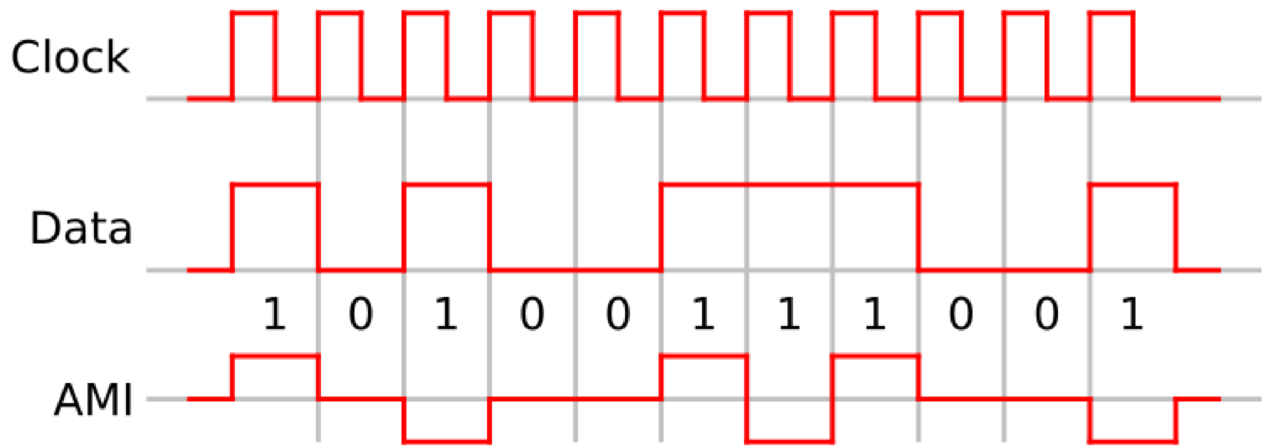
- Line coding, also called digital baseband modulation / transmission, is a code chosen for use within a communications system for **baseband transmission purposes**.
- Line coding is often used for digital data transport. the digital signal is transported by an amplitude- and time-discrete signal that is optimally **tuned for the specific properties** of the physical channel (and of the receiving equipment).

- The waveform pattern of voltage or current used to represent the 1s and 0s of a digital data on a transmission link is called *line encoding*.
- The common types of line encoding are unipolar, polar, bipolar, and Manchester encoding.

Line coding

Used for:

- For reliable **clock recovery** at the receiver. A clock period is recovered by observing transitions in the received sequence, so that a maximum run length guarantees such clock recovery.
- For **removing of DC component**. Most long-distance communication channels cannot transport a DC component.



Line coding

- Manchester,
- Differential Manchester
- Return Zero (RZ),
- Non Return to Zero Inverted (NRZI)
- Alternate Mark Inversion (AMI)
- HDB3
- Code Mark Inversion (CMI)
- 4B5B (5B6B, …)
- 2B1Q

Manchester

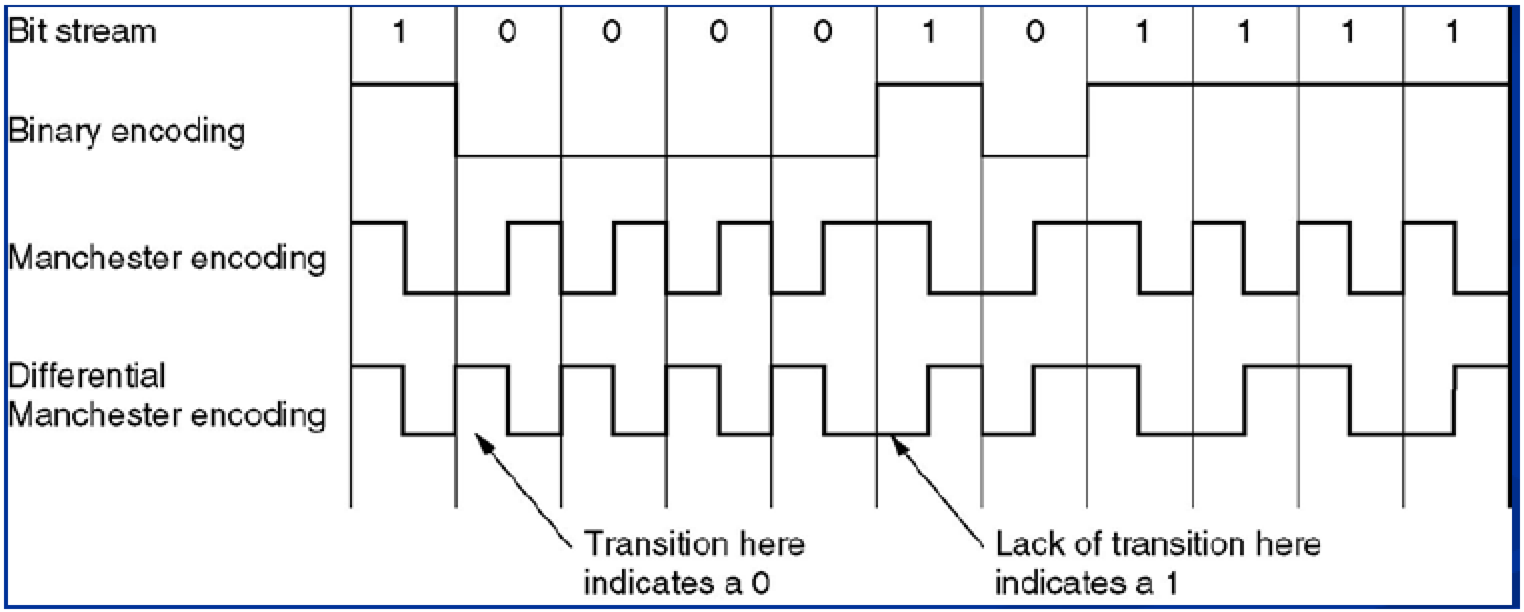
Manchester

- Each bit is transmitted in a fixed time (the "period").
- A **0** is expressed by a low-to-high transition, a **1** by high-to-low transition (*according to G.E. Thomas' convention -- in the IEEE 802.3 convention, the reverse is true)*.
- Transitions signifying **0** or **1** occur at the midpoint of a period.
- Transitions at the start of a period are overhead and don't signify data.

Differential Manchester

- Transitions at the midpoint of a period don't signify data.
- Transitions at the start of a period signify 0 and 1 (0 = transition – both directions, 1 = lack of transition).

Manchester, differential Manchester – example



Return Zero Return Zero (RZ) / Non Return to Zero Inverted (NRZI)

RZ

- Three voltage states/levels (-1,0,1)
- First half of the bit interval encodes bit value
  - +1 encodes binary 1
  - -1 encodes binary 0
- Second half of the bit interval stays always 0

NRZI

- Two voltage states/levels
- Binary 1 = signal transition
- Binary 0 = signal stays the same

Alternate mark inversion AMI / HDB3

AMI

- Three voltage states/levels (-1,0,1)
- Binary 0 = 0 voltage level
- Binary 1 = expressed sequentially by +1 or -1
- Signal change can also be used to mark some important place in transmitted signal
- Problem with synchronization of receiver in long zero sequence

HDB3

- Adaptation of AMI, after 3 binary zeros insert binary 1
- Do not respect polarity change rule = recognized in this way

Code mark inversion CMI / and others

CMI

- Used to transfer AMI / HDB3 over optical cable (just two levels are possible – light/dark).
- 3 levels are expressed as combination of 2 bit values

4B5B (5B6B,…)

- Mapping of 4 bits to selected 5 (5 to 6) bit sequences
- Maximum difference, some sequences signal special sates
- Used in ethernet

2B1Q

- Mapping 2 bit symbols to 4 levels of output voltage

Resources

1. http://en.wikipedia.org/wiki/Modulation
2. http://vsagar.com/2011/12/12/modulation-transmit-signals-fundamentals-modulation-demodulation/
3. http://www.complextoreal.com/base.htm
4. http://en.wikipedia.org/wiki/Shannon%E2%80%93Hartley_theorem
5. http://electroschematics.com/5677/frequency-modulation/

Lectures:

1. http://www.youtube.com/watch?v=PmuZnJfheK4&feature=relmfu (PM/FM)
2. http://www.youtube.com/watch?v=-u2Nnp6dz68&feature=relmfu (SSB)
3. http://www.youtube.com/watch?v=l_SqkcP6hZ4&feature=relmfu (PCM)
4. http://www.youtube.com/watch?v=KXFF8m4uGDc&feature=relmfu (Principles of Digital Communications)

Book: **RF/Microwave Circuit Design for Wireless Applications**