UNIVERSITÀ DEGLI STUDI DI PADOVA

Spectrum analyzer with digital IF

Lecture #13

Electronic measurements

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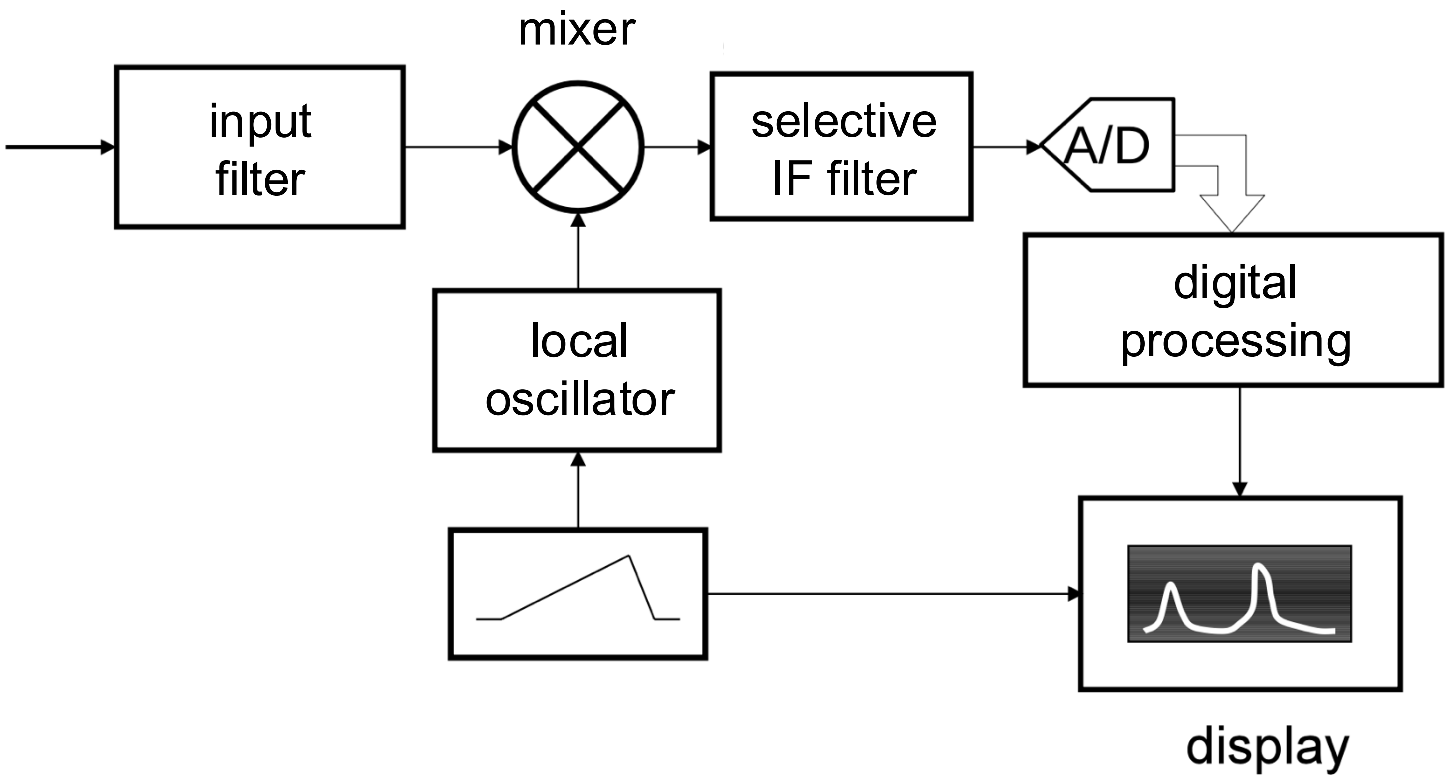
Sampled IF filter output

- Digital signal processing in the **intermediate frequency section** of a spectrum analyzer
  - High-speed, high-resolution **ADCs**
  - High-stability **oscillators**



Sampled IF filter output

- IF filter output spectrum ⇒ frequency band centred exactly on the **filter frequency f_{IF}**
- Width determined by the **filter resolution bandwidth**
- Filter output $y(t)$ **band limited pass-band signal**

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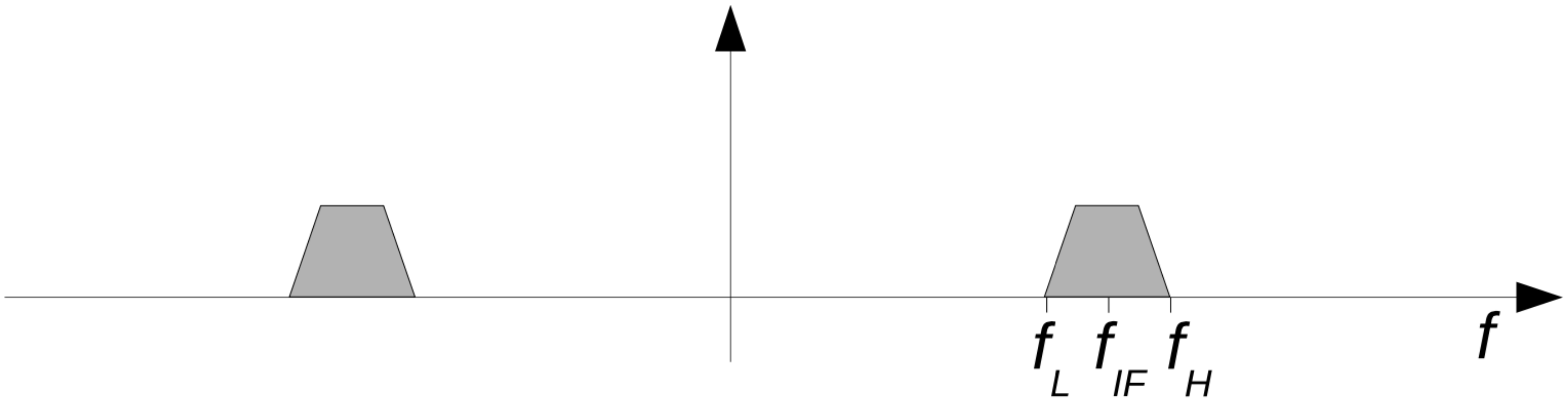
Undersampling

Undersampling

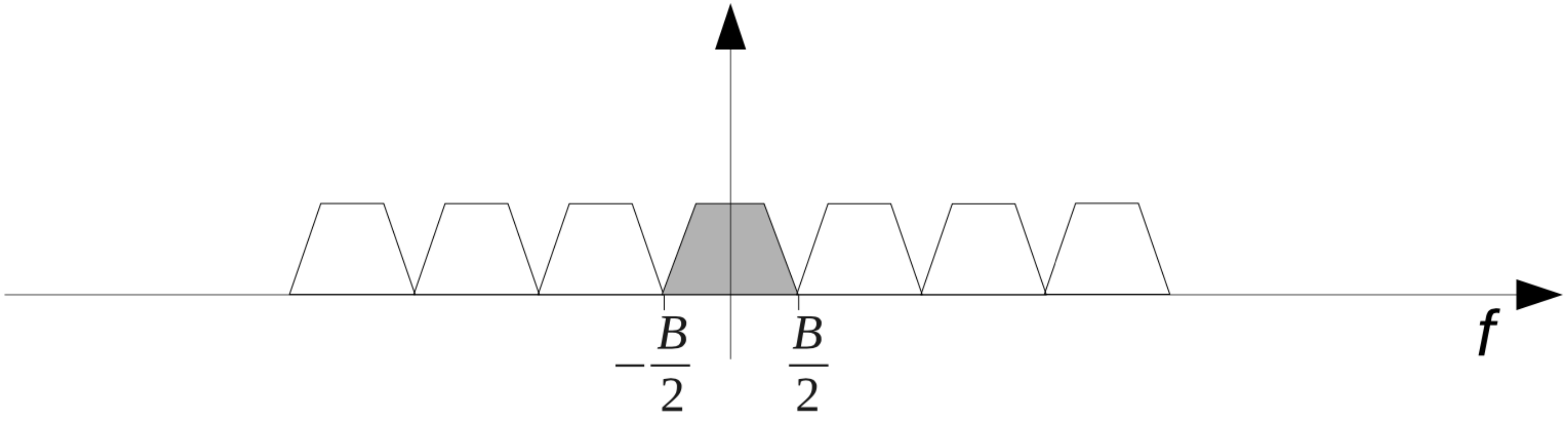
- f_L and f_H lower and upper limit of the IF filter bandwidth $\Rightarrow B = f_H - f_L$
- Maximum bandwidth of the filter output $y(t)$
- $f_L = f_{IF} - \frac{B}{2}$
- $f_H = f_{IF} + \frac{B}{2}$

- **Sampling theorem:** $f_S > 2 \cdot f_H$
- For a band limited signal, however, failure to satisfy this condition **does not necessarily imply a distortion** of the spectrum caused by aliasing
- The periodic repetitions of the signal spectrum caused by sampling **may not overlap**

Undersampling



(a) band-pass signal;



Undersampling

- $f_S > B$
- $B \ll f_H$
- $\frac{f_H}{B} = k, \quad k$ integer $\Rightarrow$ Condition related **to IF filter design parameters**

- ADC converter at the IF filter output, operating at a **sampling rate determined by the IF filter bandwidth**

- **Traditional** swept-frequency spectrum analyzer ⇒ **Narrow band IF filter**
- Spectrum analyzer with **digital IF section** ⇒ **Less restrictive conditions**

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Accurate analysis through **digital signal processing**

I-Q modulation

- IF filter output:

$$y(t) = K_M \left\{ \frac{1}{2} \cos 2\pi f_{IF} t [i(t)] + \frac{1}{2} \sin 2\pi f_{IF} t [q(t)] \right\} =$$

$$= \frac{K_M}{2} \left\{ \frac{e^{j2\pi f_{IF} t} + e^{-j2\pi f_{IF} t}}{2} [i(t)] + \frac{e^{j2\pi f_{IF} t} - e^{-j2\pi f_{IF} t}}{2j} [q(t)] \right\} =$$

$$= \frac{K_M}{2} \left\{ [i(t) + jq(t)] \frac{e^{-j2\pi f_{IF} t}}{2} + [i(t) - jq(t)] \frac{e^{j2\pi f_{IF} t}}{2} \right\}$$

- $i(t) + jq(t)$ complex base-band signal $a(t)$
- $i(t)$ **in-phase component**
- $q(t)$ **quadrature component**

I-Q modulation

- Frequency domain expression

$$Y(f) = \frac{K_M}{2}\{[I(f - f_{IF}) + jQ(f - f_{IF})] + [I(f + f_{IF}) - jQ(f + f_{IF})]\}$$

- $A(f) = I(f) + jQ(f)$

$$Y(f) = \frac{K_M}{2}\{[A(f - f_{IF})] + [A^*(f + f_{IF})]\}$$

- $i(nT_s)$ and $q(nT_s)$ sampled components

$$y(nT_s) = \frac{K_M}{2}\{\cos 2\pi f_{IF} nT_s[i(nT_s)] + \sin 2\pi f_{IF} nT_s[q(nT_s)]\}$$

I-Q demodulation

- $y(nT_s)$ is sent to **two multipliers in parallel**:
  - $y(nT_s) \cdot \cos 2\pi f_{DDC} nT_s$
  - $y(nT_s) \cdot \sin 2\pi f_{DDC} nT_s$

- Low-pass filtering
  - $i(nT_s) \cdot \cos 2\pi (f_{DDC} - f_{IF}) nT_s$
  - $q(nT_s) \cdot \cos 2\pi (f_{DDC} - f_{IF}) nT_s$

- If $f_{DDC} = f_{IF} \Rightarrow$ Base-band components

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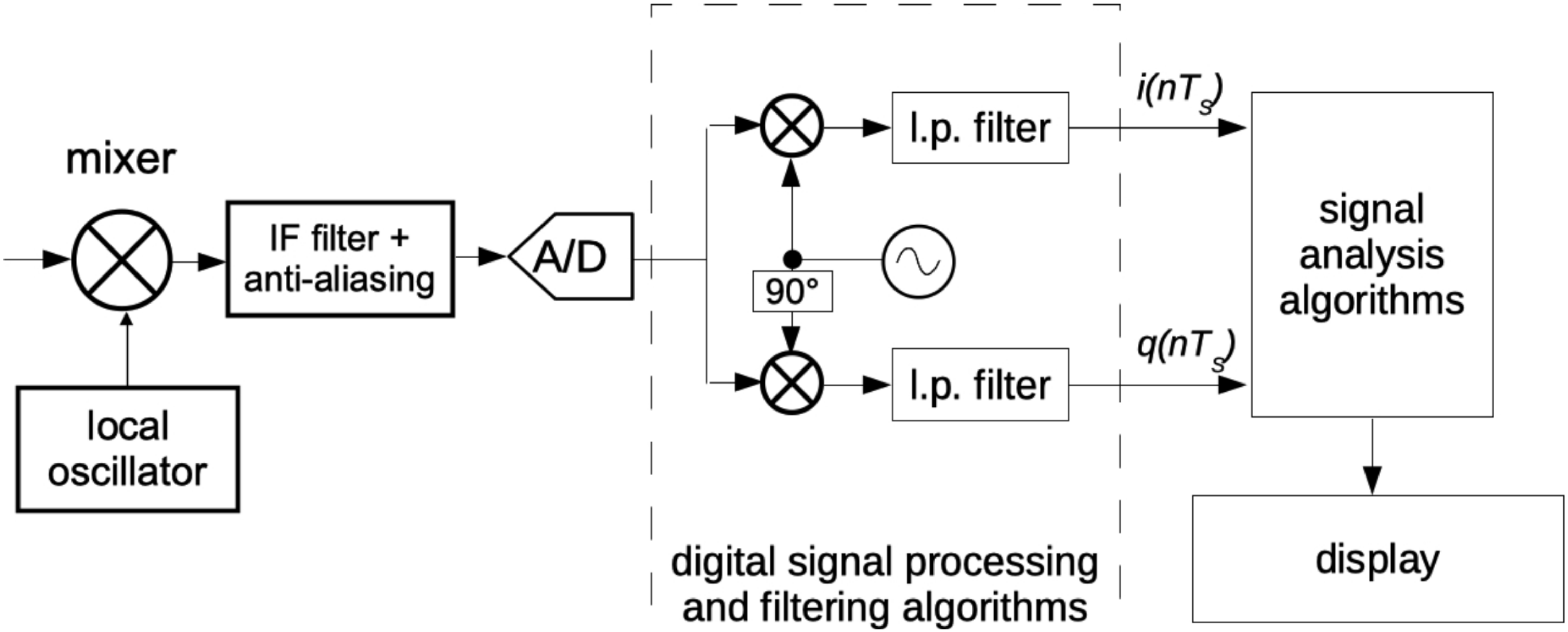
Digital down-converter (digital demodulator)

Vector signal analyzer (VSA)



Specifications and requirements

- ADC converter performances

- **ADC resolution:**
  - Lower bound ⇒ Noise floor
  - **ADC signal to quantization noise ratio** = $\sim 6 \cdot \mathrm{b}$ dB
  - 80 dB dynamic range ⇒ $\mathrm{b} = 14$

- **Sampling clock stability**
  - **Jitter**: variation of the sampling instant from the nominal time
  - Statistical characterization σ_t
  - Phase noise standard deviation $\sigma_\phi = 2\pi f_s \sigma_t$

Vector signal analyzer (VSA)

- Extend the range of **possible measurements**
- **Multi-domain analysis**
- Analysis of **digital modulations**

- **Digital IF filter** → Rather large bandwidth values

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Selector for the frequency intervals of interest in a variety of radio-frequency (RF) communication systems

- Within the allocated frequency intervals, **high bit rate wireless technologies** occupy specified sub-bands of width in the order of some MHz

Vector signal analyzer (VSA)

- **Communication channel analysis**

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- **Superheterodyne**

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- **Frequency shift** of the centre frequency of the input signal to coincide with the IF filter centre frequency

- Since analysis algorithms must be allowed to operate on the signal in its entirety, IF filter bandwidth should **correspond to that of the whole channel**

- **Large bandwidth**

Vector signal analyzer (VSA)

- **Maximum value of the resolution bandwidth**
  - Analysis of high data rate wireless channels

- **Minimum value of the resolution bandwidth**
  - Accurate measurements of spectrum

- **High resolution ADC**
  - Avoid aliasing → IF filter is also a pass-band anti-aliasing filter (IF filter implementable as a multi-stage to increase out-of-band attenuation)

VSA signal processing

- **First signal processing stage**
  - **Digital Down Conversion** → baseband in-phase and quadrature components
  - Sampling decimation

- **FFT analysis**
- **Digital demodulation algorithms**
  - Modulation domain analysis

- Conversion into digital data sequences

Reference measuring receiver

VSA signal processing

- **Known modulation of the received signal**

- Analysis of the received signal
  - **Oscilloscope**: observation of in-phase and quadrature component
  - **Spectrum analyzer**: spectral measurements

- VSA
  - Triggering
  - Synchronization
  - Decoding

VSA signal processing

- **Performance goals in a communication system**
  - **Spectral efficiency** → optimal use of the electromagnetic spectrum
  - **Immunity** to noise and interference
  - **Reduced power consumption** → in particular, for wireless applications such as mobile telephony, sensor networks and Internet of Things (IoT) applications

- Modulation domain analysis is also important in **wired** communications
  - Broadband digital subscriber lines
  - Power line communication
  - Industrial communications

Vector (I-Q) diagrams

- Measured data displayed by means of **two-dimensional maps** referred to the in-phase and quadrature baseband signal components
- **Vector Diagrams**
- **Complex signal** $a(nT_s) = i(nT_s) + jq(nT_s)$
- Orthogonal plane having **I and Q as its axes**
- Evolution over time of a **vector trajectory**

- **Modulated signals:** decomposition into two orthogonal in-phase (I) and quadrature (Q) components

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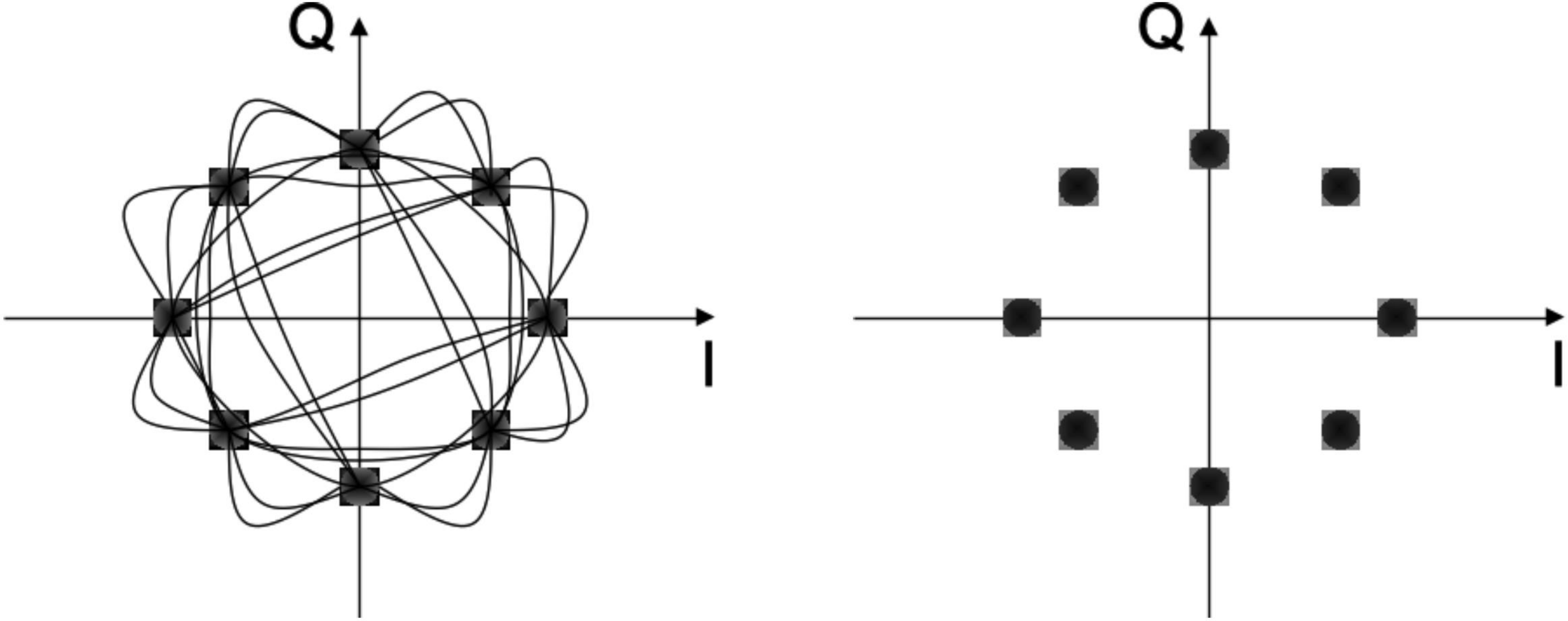
Simple phase and amplitude modulation analysis

Vector (I-Q) diagrams

- **Vector diagram**: the whole trajectory of the complex vector representing the modulating signal is presented in its evolution over time
- **Constellation diagram**: the diagram presents the value of the modulating signal only at decision time, that is, when I and Q components are sampled to determine the value of the measured (received) symbol

- Other measurements:
  - **Multilevel eye diagrams**
  - **Separate I and Q** components analysis

Vector (I-Q) diagrams



(a) vector diagram; (b) constellation diagram.

Vector diagram

- Displays the **whole vector trajectory** of the modulating signal, not only at decision times, but during the whole observation interval
- Analysis of the **circuit characteristics** of a transmission system
  - Transitions between symbols may correspond to variations of the signal power

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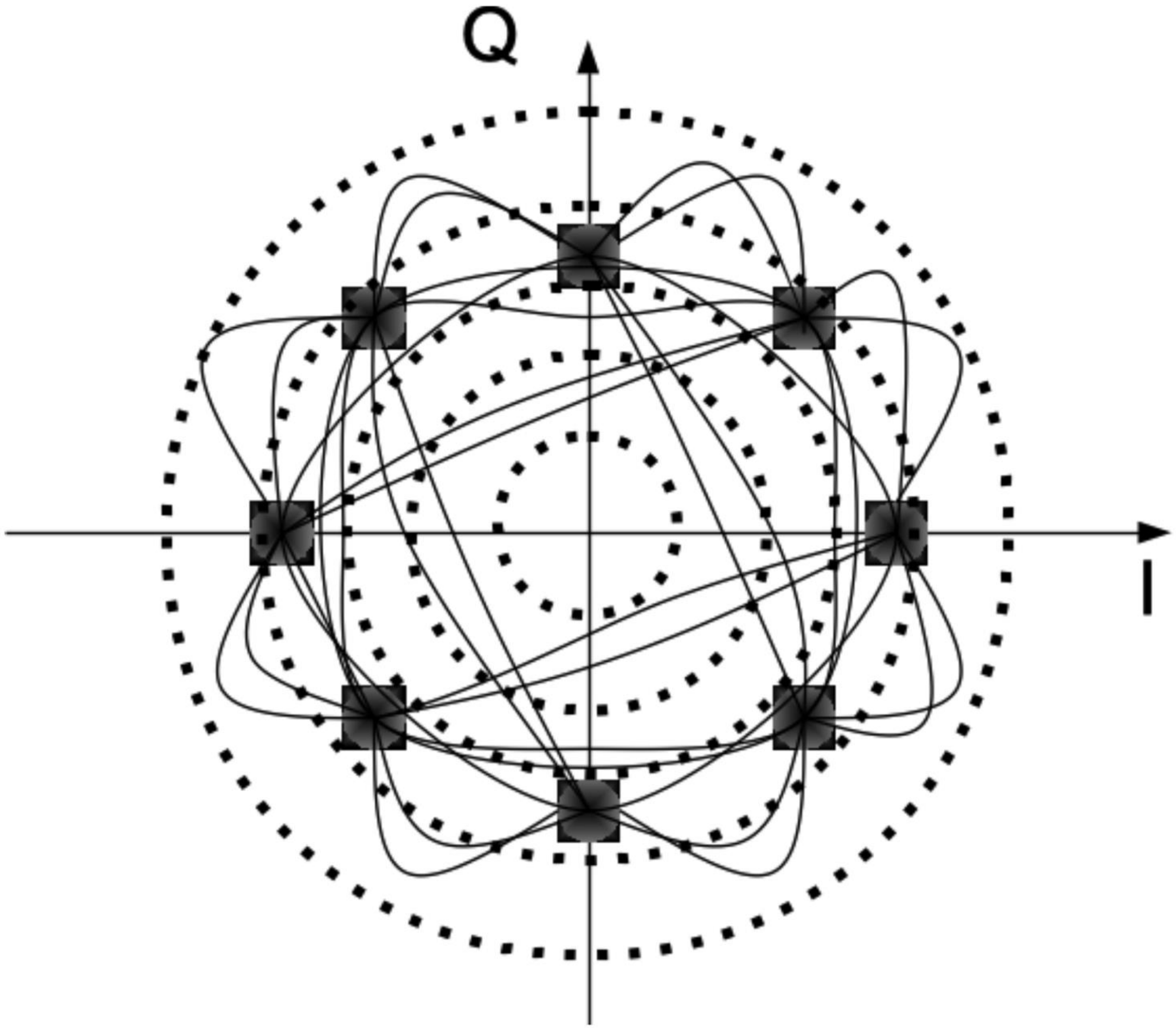
Detect malfunctions or improper behaviour (e.g., undesired power peaks during transients, low transitions…)

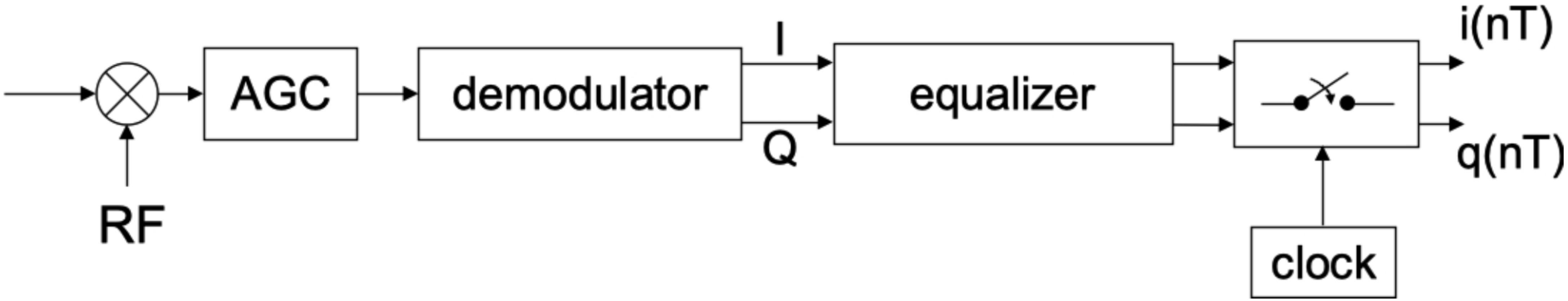
- Signal power is associated to **circumferences** on the I-Q plane
  - Overlayed on a vector diagram
  - Assessment of **minimum and maximum power**

Vector diagram



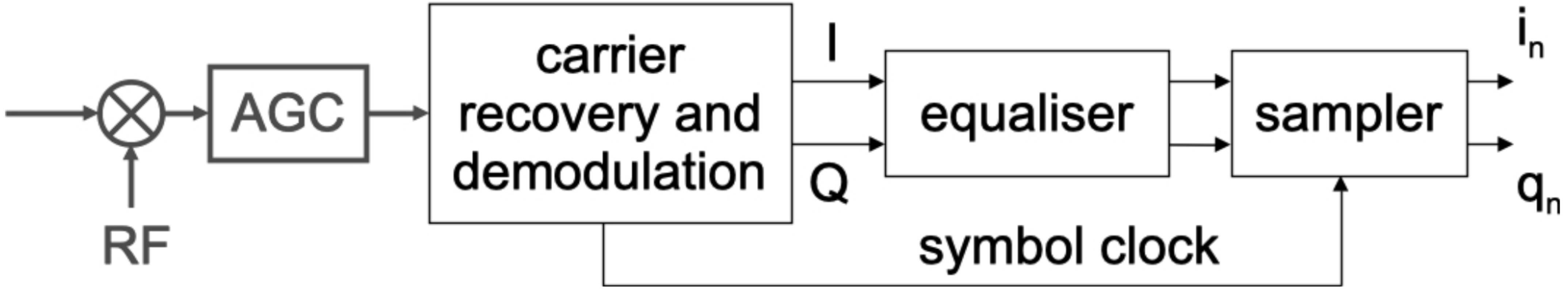
Receiver structure

- **Automatic gain control (AGC):** compensates the attenuation at the receiver input
- **Equalizer:** reproduces the reference behaviour of a receiver designed for the modulation format under analysis
  - Any deviation of the actual diagram from the expected one can be correctly attributed to some form of impairment in the transmitter/receiver system
- **Clock:** VSA internal sampling clock, at higher frequency and independent of the symbol clock employed in the communication system



Constellation analysis

- Constellation diagram: $i(t)$ and $q(t)$ have to be determined exactly at the communication system **decision times**
- The measuring system must be able to employ the **same symbol clock as the system under analysis**
  - **Supplied** as an independent input
  - **Recovered** from the analyzed signal, as a receiver would do



Constellation analysis

- Sampled sequences $i(nT_s)$ and $q(nT_s)$ are resampled at the lower symbol frequency
- Sampled baseband vector components at decision times → **Actual values**
- Compared to the **nominal values (references)**

- Presence of broadband noise
- Actual and nominal values **do not perfectly coincide**

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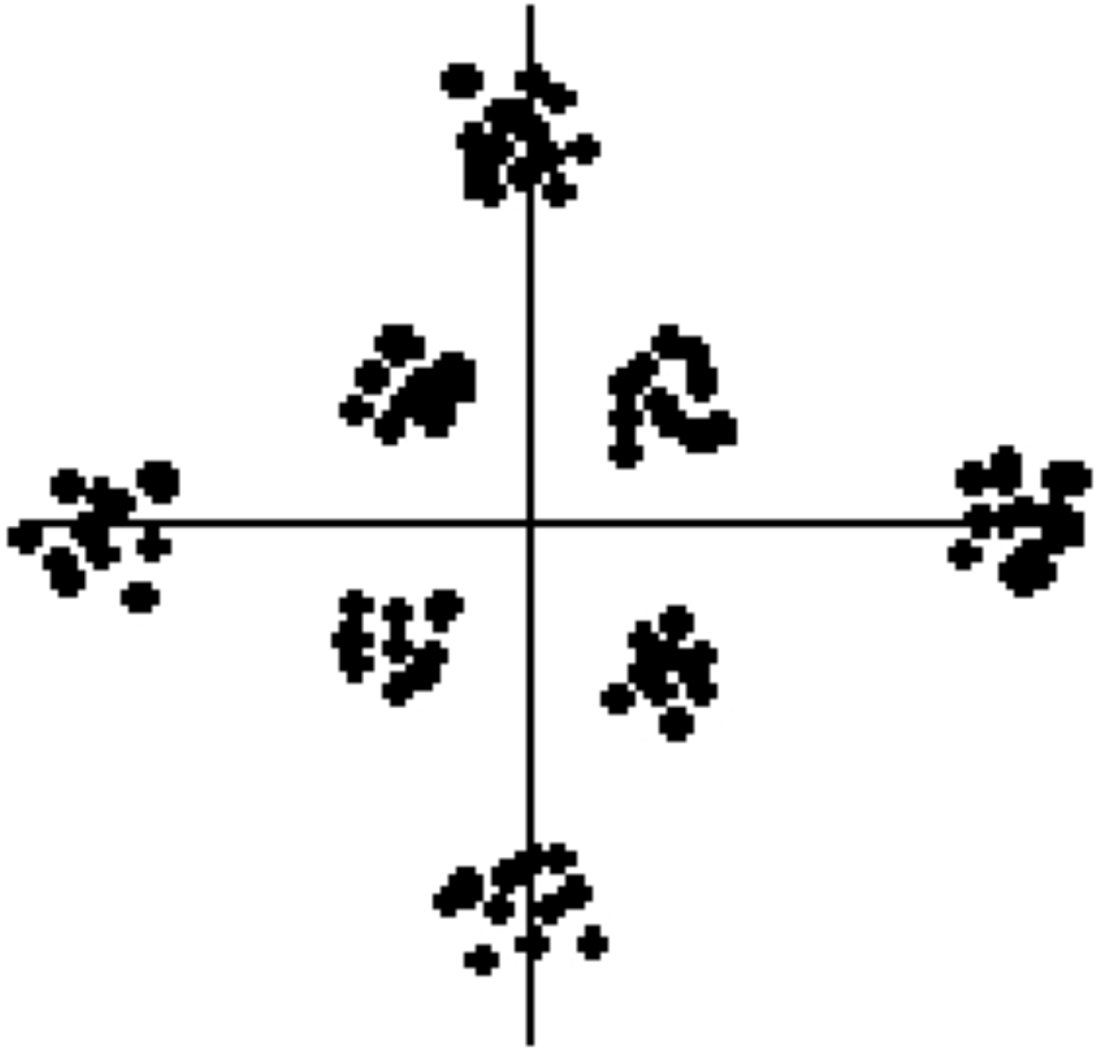
Creation of clusters

Constellation analysis

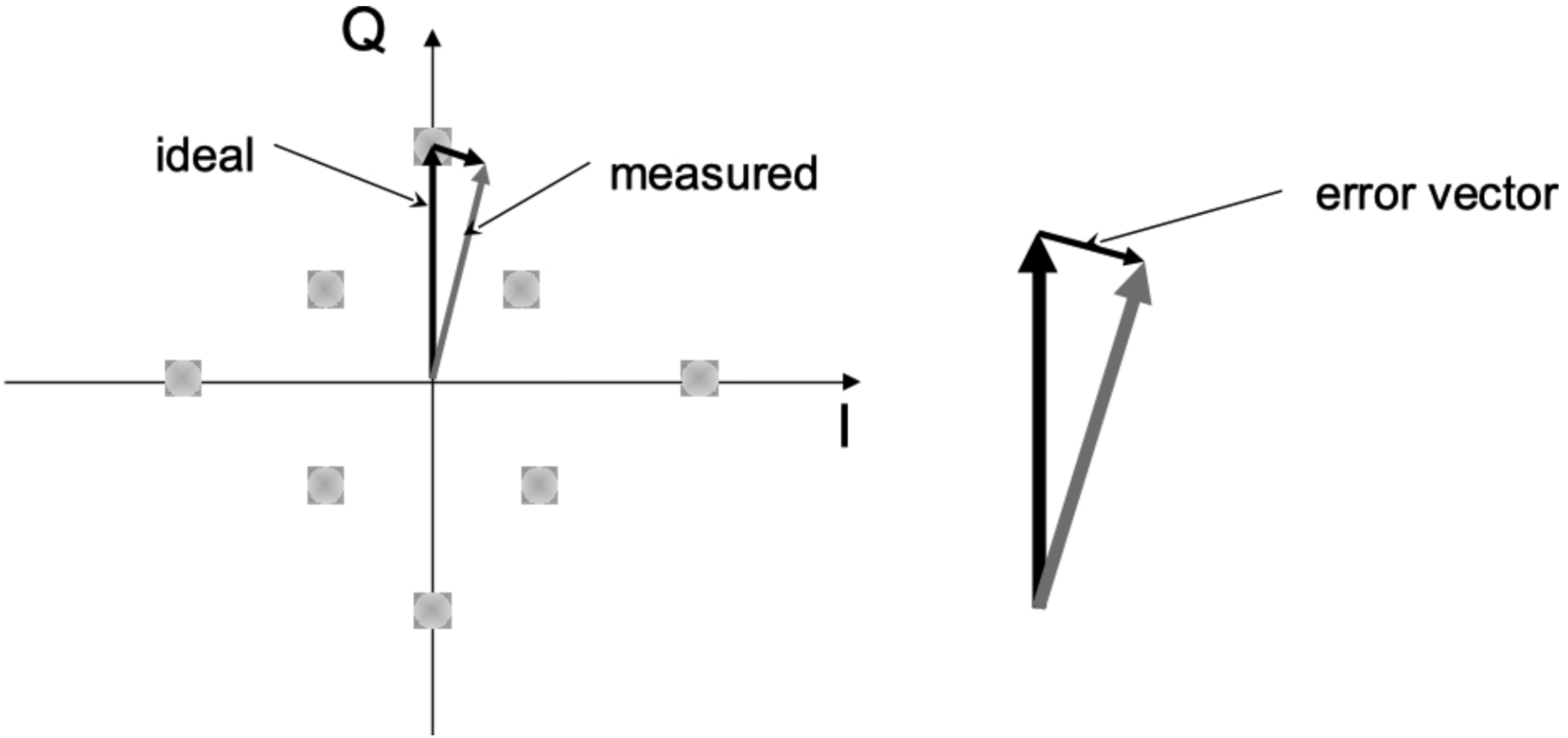


Constellation analysis

- Correct operation: the dispersion of measured points will only be due to the effect of noise on the measuring receiver
- **Noise power** estimation
- Assessment of **Signal-to-Noise Ratio (SNR)**

- Deviations from the nominal constellation points → **Error vector**
- **Difference in the I-Q plane** between the actual measured vector position and its ideal position in the nominal reference constellation

Constellation analysis



Constellation analysis

Error vector determination

- The measuring instrument associates the measured point to a specific constellation symbol
  - The measured coordinates i_m and q_m are sent to a decision element called **slicer**
  - The slicer **determines the region** of the I-Q plane where the measured point falls and **assigns the reference constellation symbol** accordingly

- The measured symbol $\underline{\hat{a}}_m = \hat{\imath}_m + j\hat{q}_m$ is then compared to the reference symbol $\underline{a}_{ref}$
- The error vector is calculated

$$\underline{e}_m = \underline{\hat{a}}_m - \underline{a}_{ref}$$

Constellation analysis

Parameters of interest

- **Noise power**:

$$\hat{\sigma}_e^2 = \frac{1}{M}\sum_{m=1}^{M}\left|\underline{e}_m\right|^2$$

  where M is the number of symbols acquired during the measurement interval

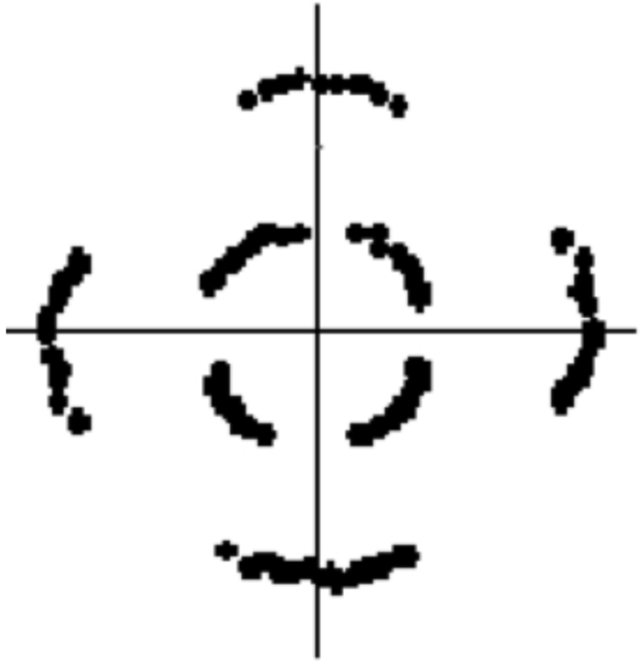
- **Analysis of an individual cluster C_a**:

$$\sigma_a = \sqrt{\frac{1}{M_a}\sum_{\underline{\hat{a}}_m \in C_a}\left|\underline{e}_m\right|^2}$$

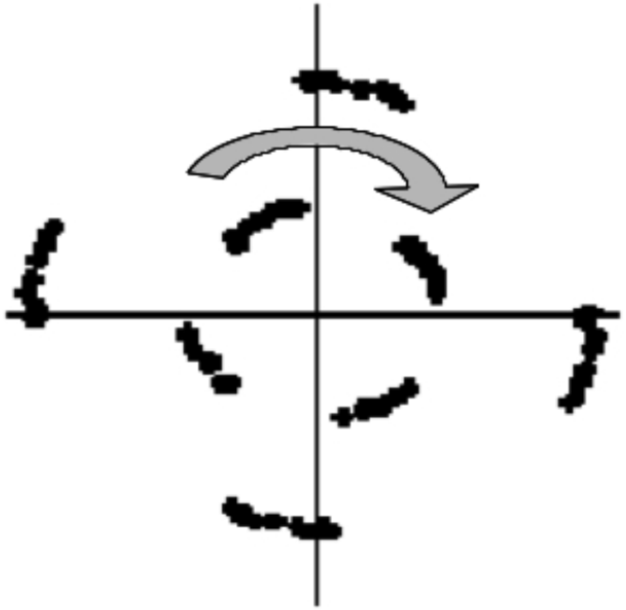
- Cluster **extension**
- "**Closure**" for a specific symbol → $\sigma_a/(d/2)$ where d is is the distance between contiguous symbols

Constellation analysis

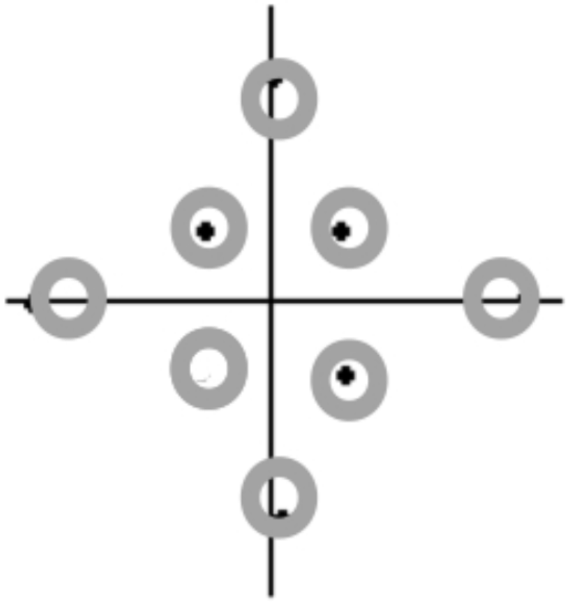
Direct evidence of some kinds of **system performance impairment**



(a) jitter: "vibration" around nominal position;



(b) frequency offset: "rotation" in the I-Q plane;



(c) sinusoidal interferer.

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