Wireless Transceiver Electronics (WTE)

Wireless Transmitter Architectures

Course # 3/9

EWI course 121150

Previous and next lecture

Last course: RF specification and system design

- Gain, noise and (non-)linearity of crucial importance for Front-ends
- Noise Figure NF = SNR degradation
- Several Power Gain definition (matching matters!)
- IIP2 and IIP3 convenient characterization of non-linearity
- Non-Linearity is the cause of limited SFDR (IM3, IM2 components), densitization/blocking and cross-modulation.

Next course: RF Receiver Architectures

This course: RF Transmitter Architectures

Content lecture # 3/10

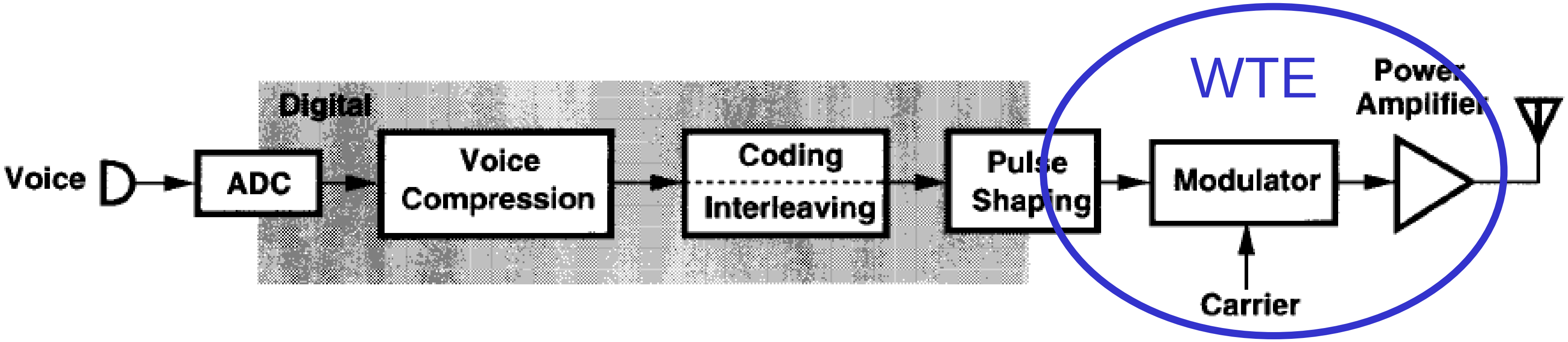
- Transmitter Functions: What needed & why?
  - Power Amplifier and Antenna interface
  - Modulation considerations: I/Q or AM/PM/FM
- TX specifications
- Functions Blocks
  - Mixer
  - Tuning system (frequency synthesizer)
  - Quadrature Generation
- TX Architectures
  - Direct-conversion transmitters
  - Direct-conversion transmitters with offset LO
  - Two-step transmitter architecture
  - Offset PLL architecture
- Recent developments
  - Linearisation techniques
  - Digital transmitter concept example
  - Multi-path PolyPhase Concept for Software Radio

Transmitter Function Overview

Why Transmit at RF?

- Share spectrum by many users
- Antenna size & RF propagation properties

What needed: typical TX chain (mobile telephone):



Aim: convert a baseband information signal to a modulated RF signal at a specific channel and deliver specified power level that can drive the antenna.

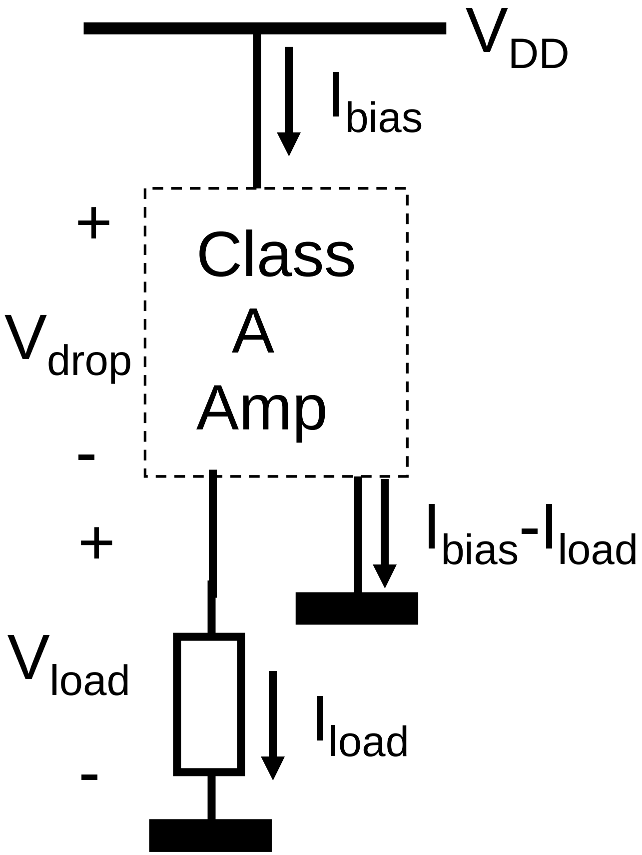
Antenna Interface Consideration

Power Amplifier

Duplexer

Matching Network

Power Amplifier: Efficiency wanted!



Class-A:

☺ Linear (always on, $I_{load}<I_{bias}$)

☹ power inefficient because:

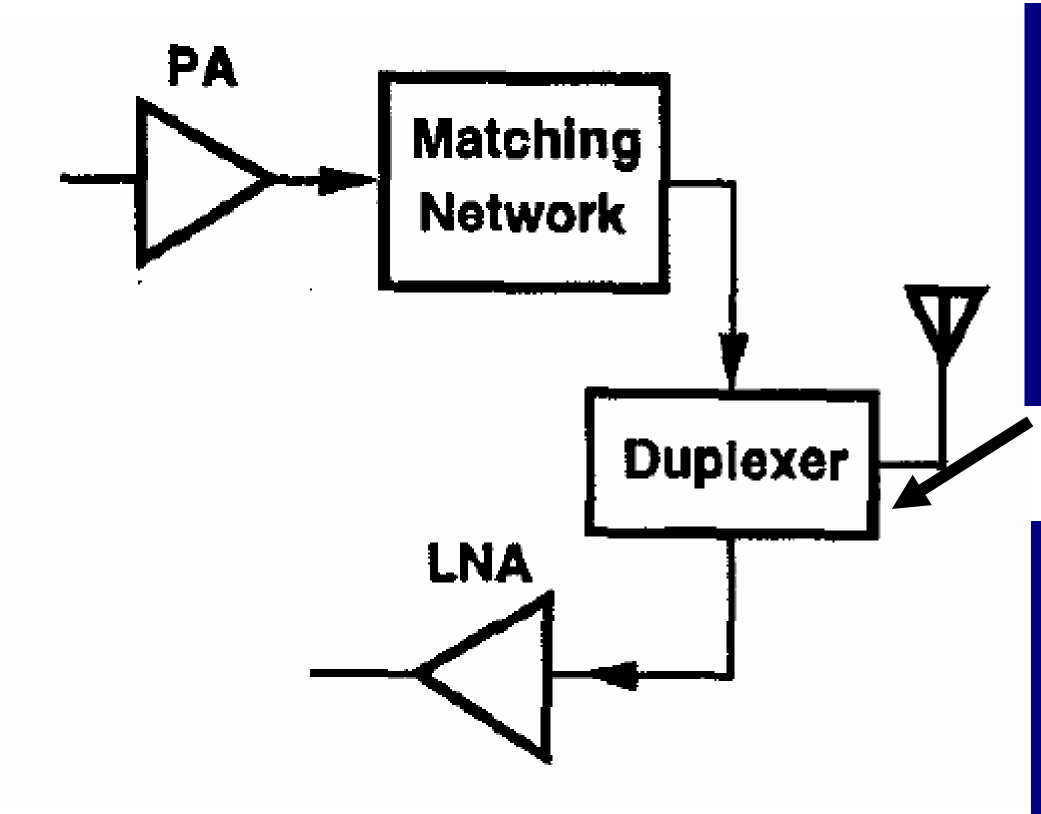
- $P_{dis}=V_{drop}I_{bias}$ (“useless”)
- $P_{load}= V_{load}I_{load}$ (wanted)
- but: $V_{load}<< V_{DD}$, $I_{load} < I_{bias}$ so efficiency << 100%
- (typically a 5-10%)

☺ Class-C, D, E, F: increase efficiency by reducing on-time and/or simultaneous presence of large Vdrop and current

☹ Amplitude dependent distortion (harmonics, intermodulation)

PA-antenna interface: Duplexer

Deliver power via Power Amplifier (PA)



Separates the RX frequency and the TX frequency in case of FDD.

The duplexer is replaced by an RF switch in case of TDD

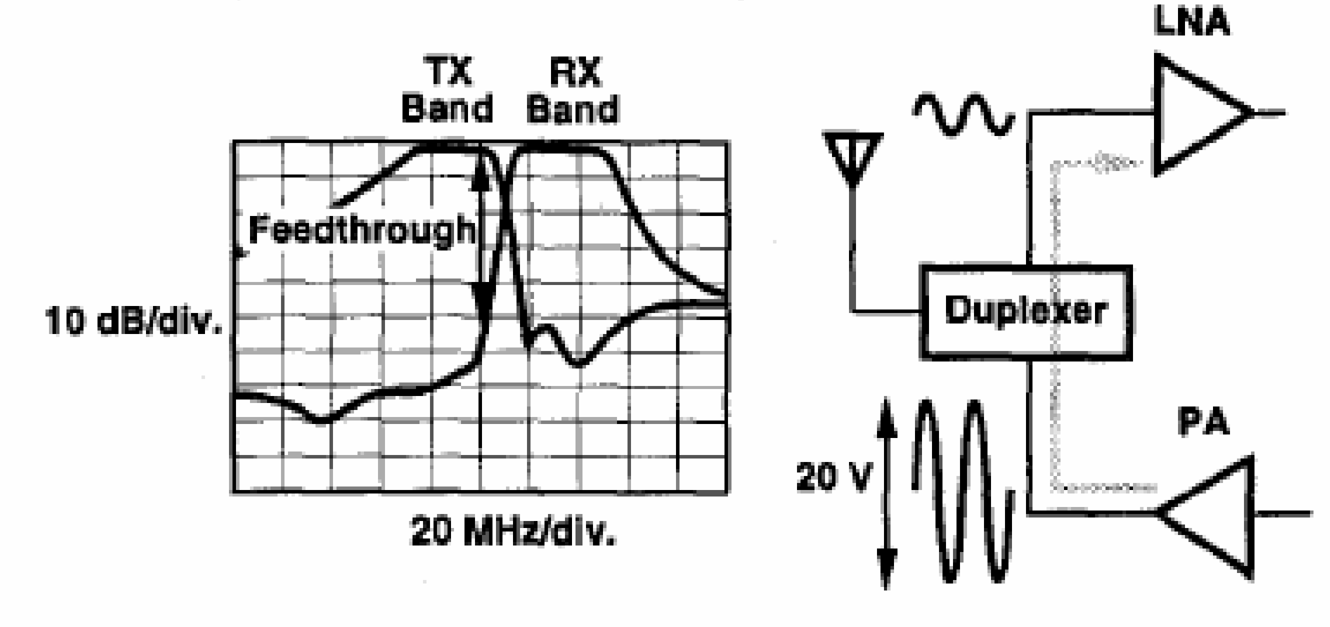
FDD = Frequency Division Duplex

Image: B. Razavi

TDD = Time Division Duplex

But: Duplexer only offers finite isolation

Feed-through from TX to RX path



Duplexer may have 2-3 dB insertion loss. Solution (used in GSM) for feed-through is to use non-overlapping time slots for RX and TX.

Image: B. Razavi

What and why of matching network

Why matching network?

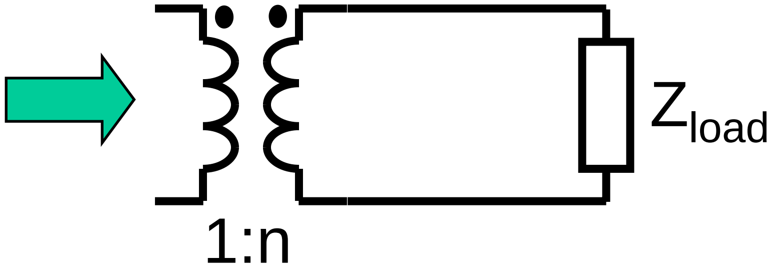
- Maximum power: impedance match wanted
- Adapt high load voltage to low IC technology voltage

(e.g. 1Watt in 50ohm => $V = \sqrt{P_{out} R_{load}} = \sqrt{1 \cdot 50} = 7.1 V_{rms}$!)

How? transformer-like device:

- Transfer power (at low loss) to other voltage/current:

$$\boxed{\begin{aligned} V &= V_{load} / n \\ I &= n I_{load} \\ Z &= Z_{load} / n^2 \end{aligned}}$$



How? Transformer or (narrowband) L-C network

(see later lecture on LNA input matching)

Modulation Considerations

Arguments for
Constant Envelope
versus
Non-constant Envelope

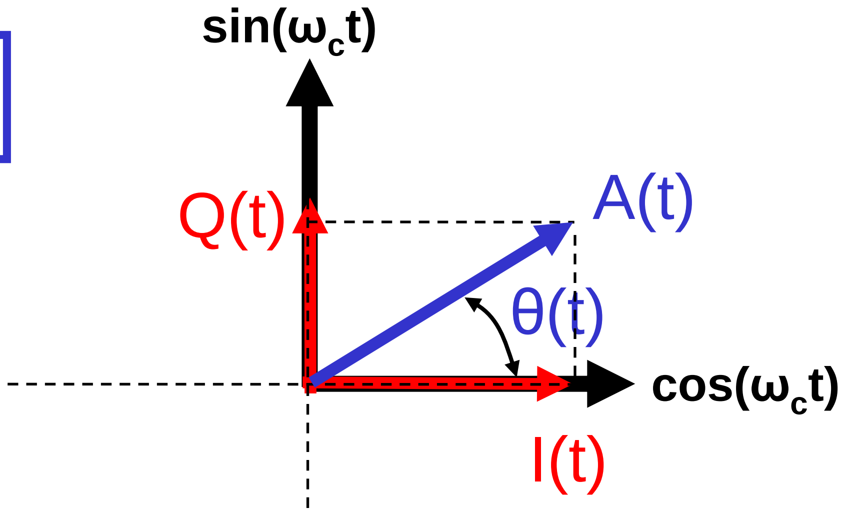
Basic Modulation Options

Two orthogonal modulation dimensions:

A (AM) and θ Phase (PM)

$$\boxed{s(t) = A(t)\cos(\omega_c t + \phi(t))}$$

Requires Amplitude and Phase modulator



or

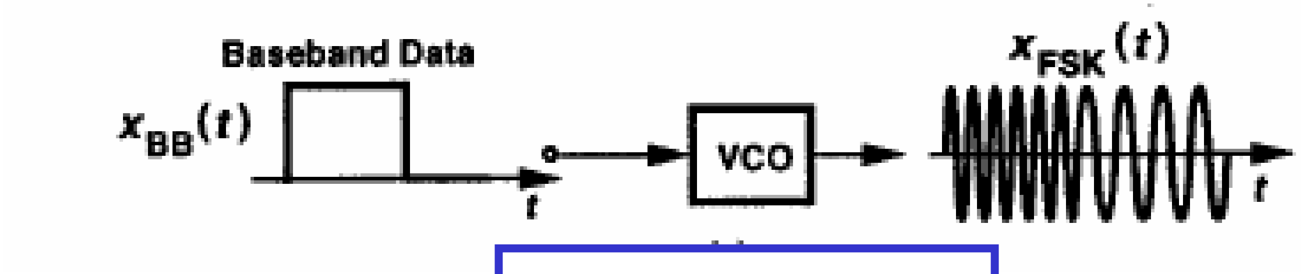
I and Q component

$$\begin{aligned} s(t) &= A(t)\cos(\phi(t))\cos(\omega_c t) - A(t)\sin(\phi(t))\sin(\omega_c t) \\ &= I(t)\cos(\omega_c t) - Q(t)\sin(\omega_c t) \end{aligned}$$

2 multipliers needed

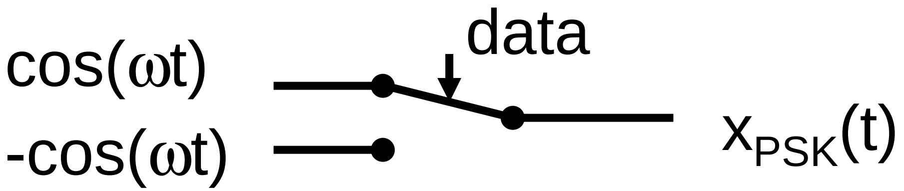
Simple FM or PM means Constant envelope

Frequency Shift Keying (FSK) is easily implemented via a VCO (Voltage Controlled Oscillator)



$$\boxed{f_{VCO} = K_{VCO} V_{in}}$$

Binary Phase Shift Keying (BPSK) also simple:

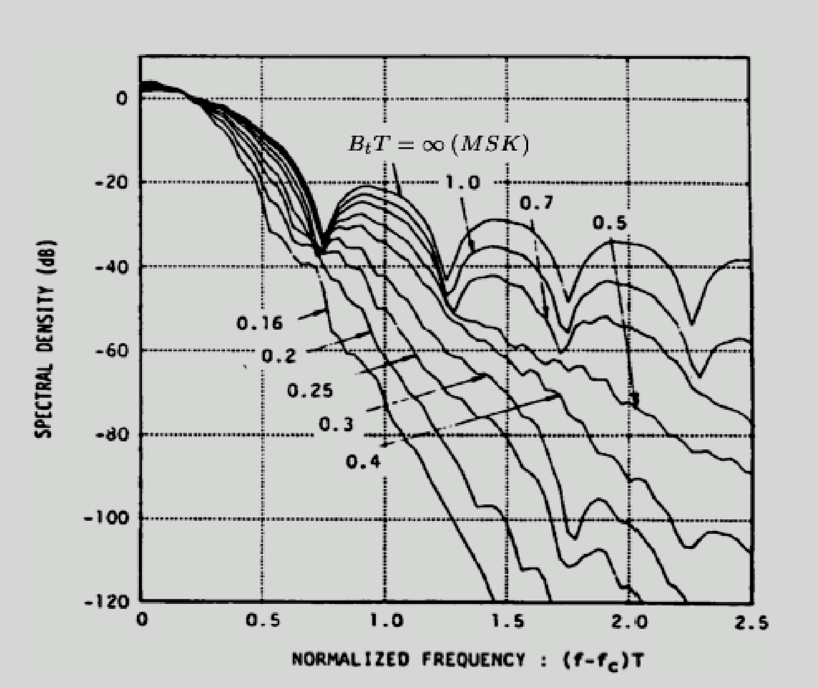


☺ The amplitude of the baseband modulated signal <u>does not vary in time</u>, but only info in the phase/frequency.

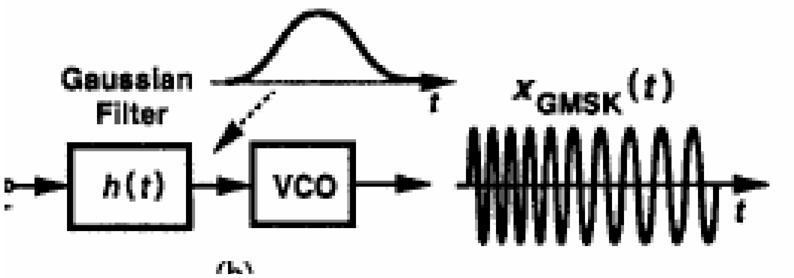
☺ Allows switching and non-linear (limiting) power amplifier (next slide)

Pulse shaping: limit spectral content

Simple BPSK (Binary Phase Shift Keying) occupies a relatively large spectrum.



GMSK (Gaussian Minimum Shift Keying) uses pulse shaping via Gaussian filter to limit the spectral content.



$$h_G(t) = B_t \frac{2\pi}{\ln 2} e^{-\frac{2\pi^2 B_t^2}{\ln 2} t^2}$$

3 dB bandwidth of Gaussian LPF filter.

Note: Gaussian filter shape is good compromise between spectral purity and step response (minimum t_{step}BW)

Gaussian minimum shift keying widely used

Examples of standards

- Digital European Cordless Telephone (DECT)
- GSM
- Hyper-lan
- Frequency hopping part of IEEE 802.11

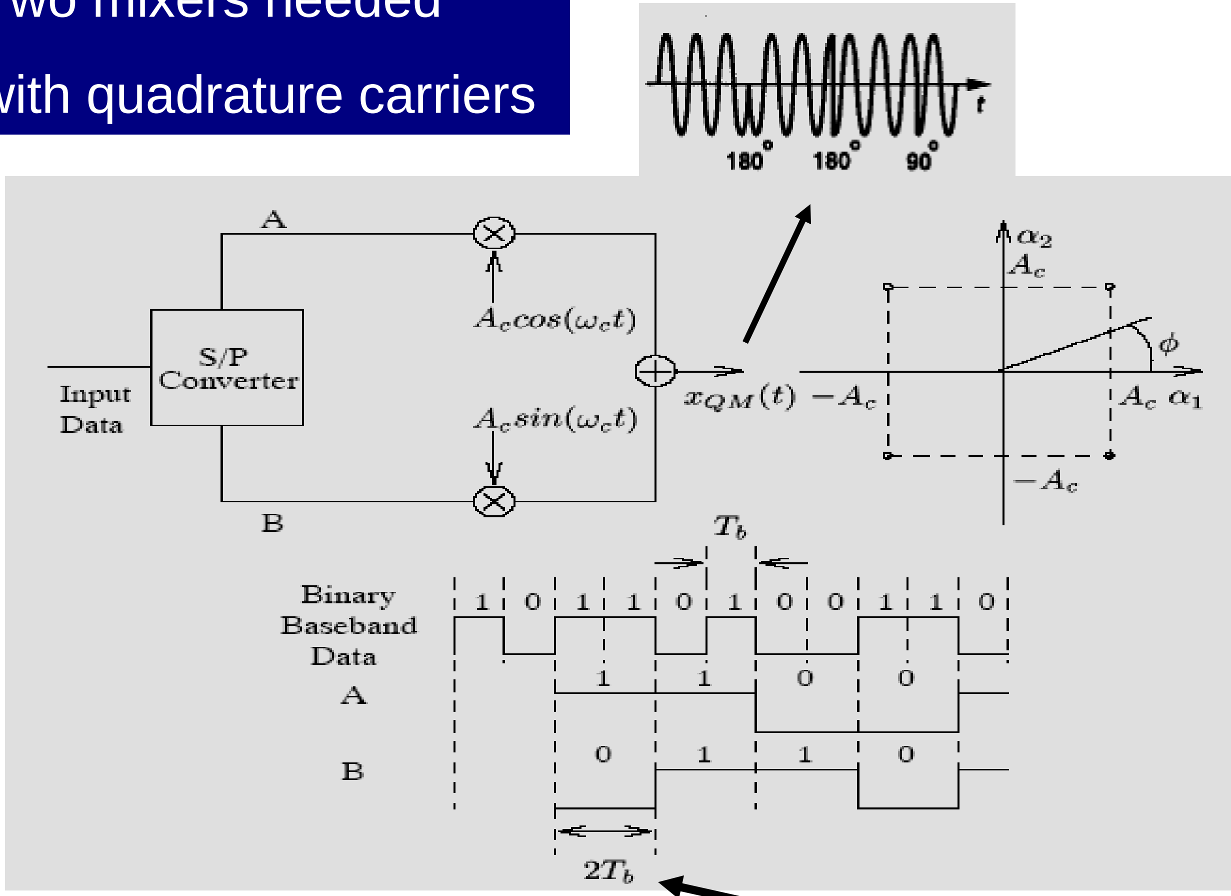
☺ GSMK allows the use of a non-linear, efficient power amplifier while occupying a moderate part of the spectrum.

☹ Pulse shaping causes inter-symbol interference (ISI). Using Matched filters in RX and TX helps to minimize ISI.

More spectral efficiency: QPSK modulation

Two mixers needed

with quadrature carriers

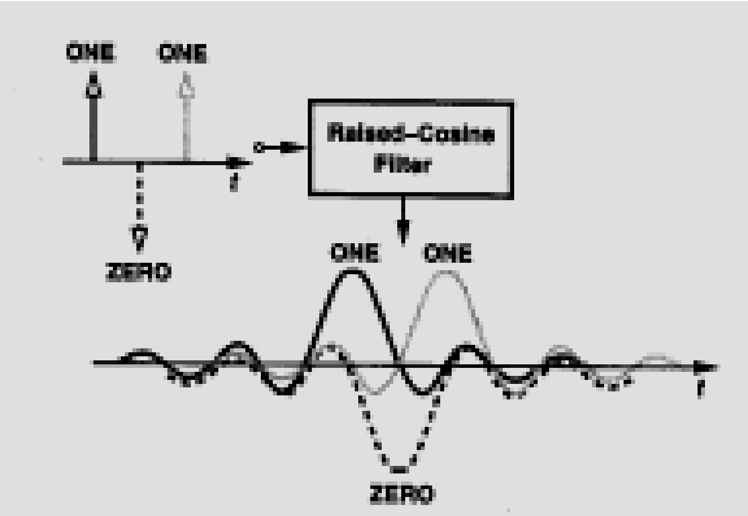


Half rate

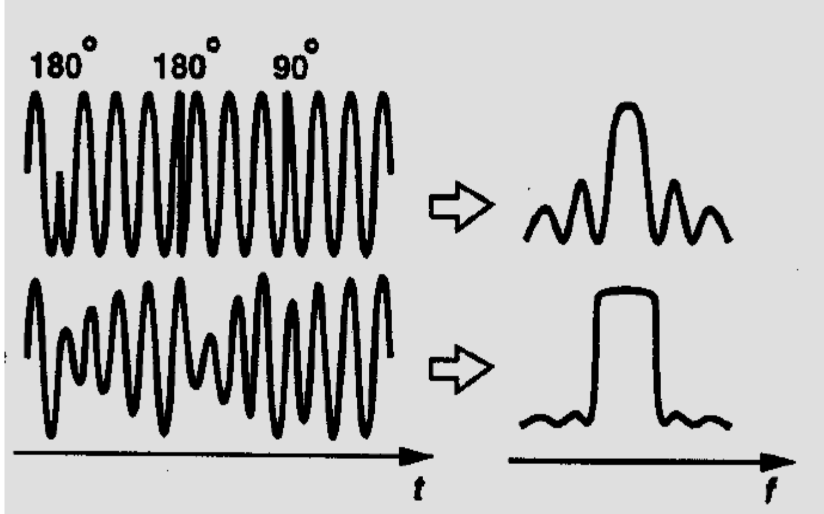
☺ less BW needed!!

QPSK with pulse shaping gives a high spectral efficiency at the cost of a non-constant envelope

Is used in standards like IS-94, IS95 and the spread-spectrum variant of IEEE 802.11



Each bit is represented by a sinc-function.



This yields a block-like spectrum in the frequency domain.

Image: B. Razavi

New standards: even more efficiency

QAM = Quadrature Amplitude Modulation

serveral AM levels: 4-QAM (=QPSK), 8QAM, 16QAM ... 1024QAM

Clear trend to more spectral efficiency in new standards

This requires non-constant envelope signals and ask for new TX architecture exploiting efficient Power Amplifier amplifier concepts

Summary modulation options

Constant Envelope (FM/PM):

☺ Highly efficient Power Amplifiers

☺ Easy implementation via switch or VCO

☹ Moderate or low spectral efficiency

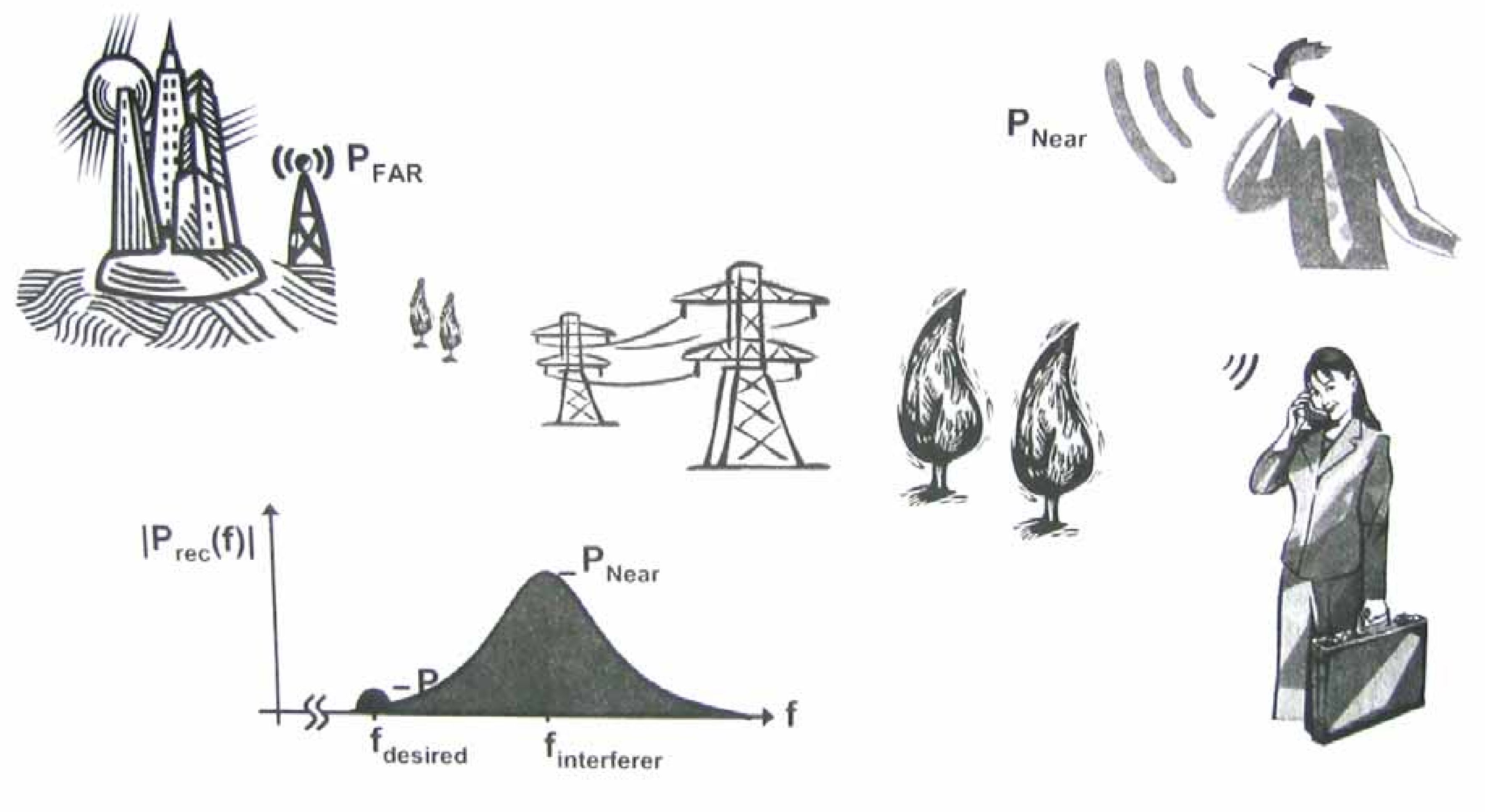
Non-constant envelope (QPSK,xxQAM, etc):

☺ Spectral efficiency

☹ Moderate or low spectral efficiency

TX specifications

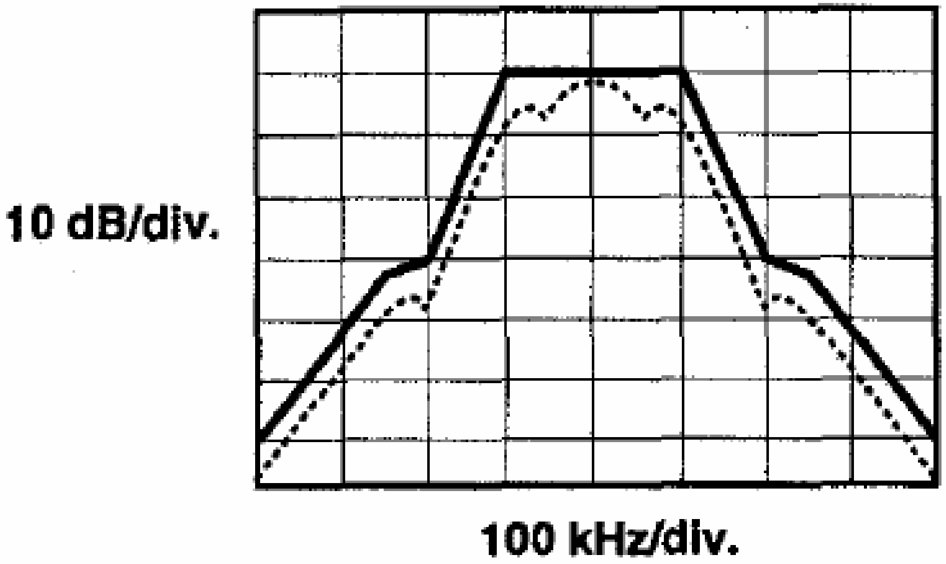
Problem: Interfering with Other Users



Transmitter should only transmit power in narrow band

(=> spectral purity wanted, low power in adjacent channels)

Quantify: TX Spectral Emission Mask

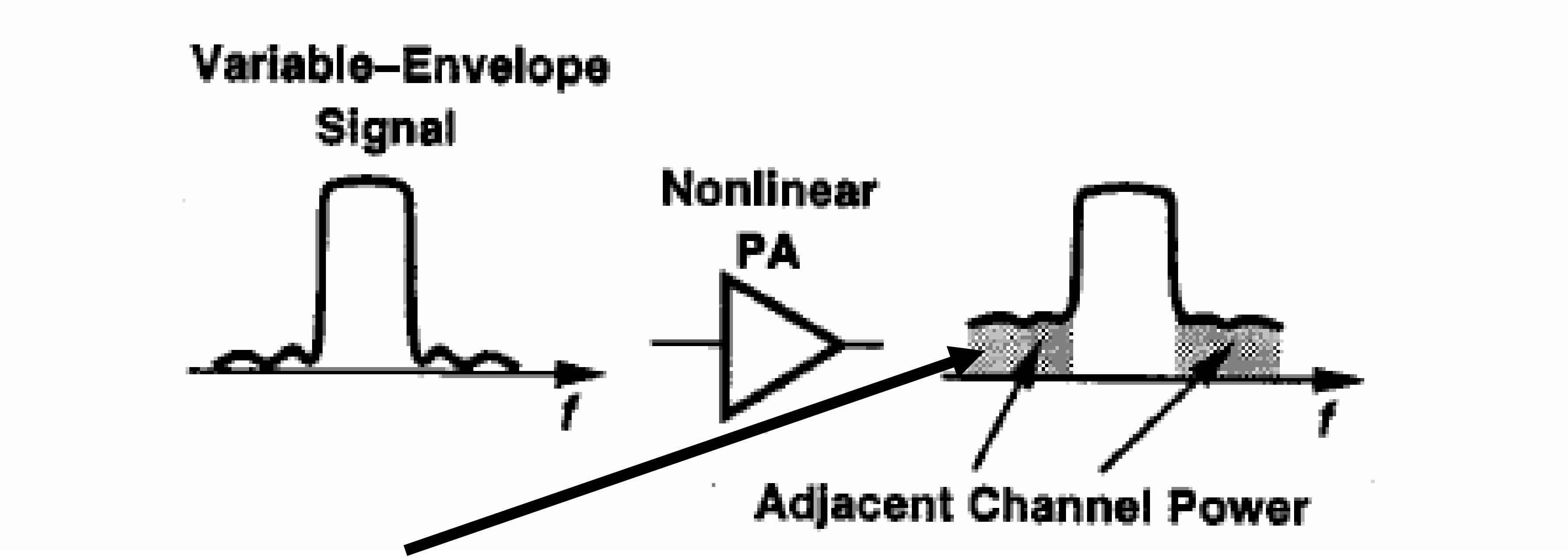


TX spectral content is specified by TX emission masks.

(example shows an emission mask for GSM).

Image: B. Razavi

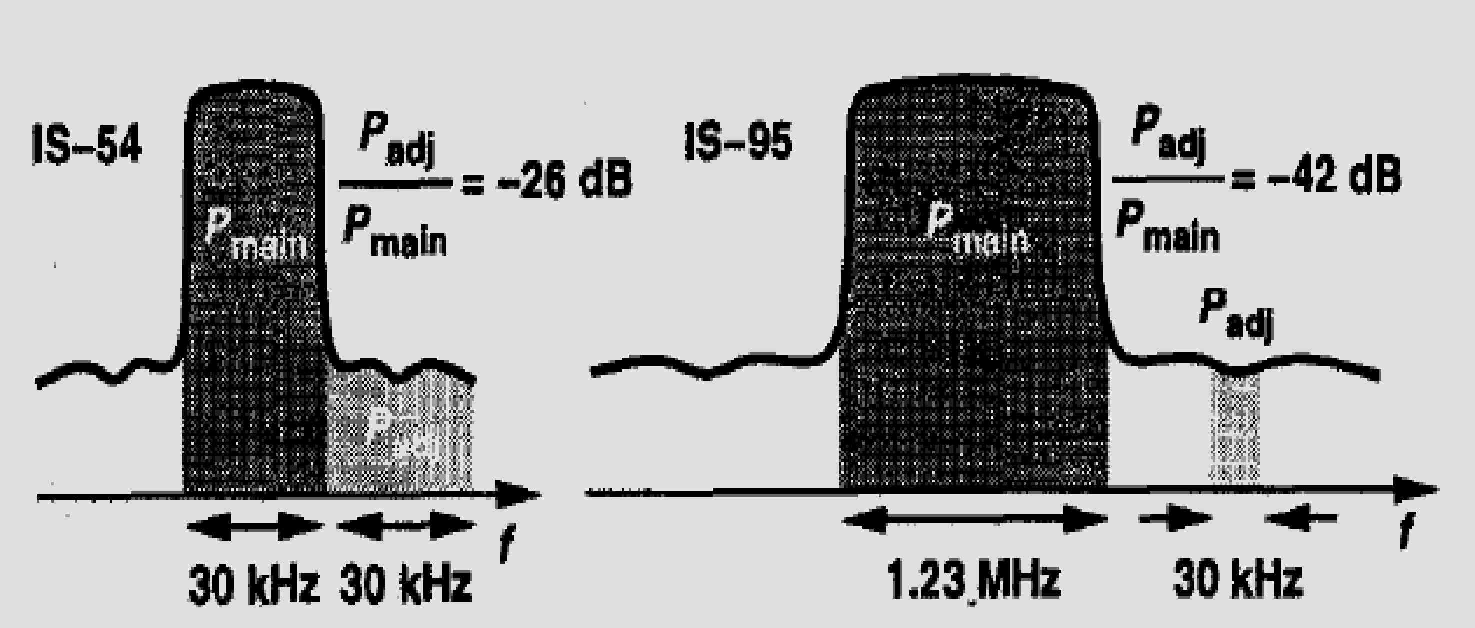
Quantify? Adjaced Channel Power Ratio



ACPR: Adjacent Channel Power Ratio, sometimes referred to as ACLR, Adjacent Channel Leakage Ratio. If the ACPR is too high: an adjacent channel sees a high interfering signal.

Image: B. Razavi

Non-constant envelope modulation: ACPR



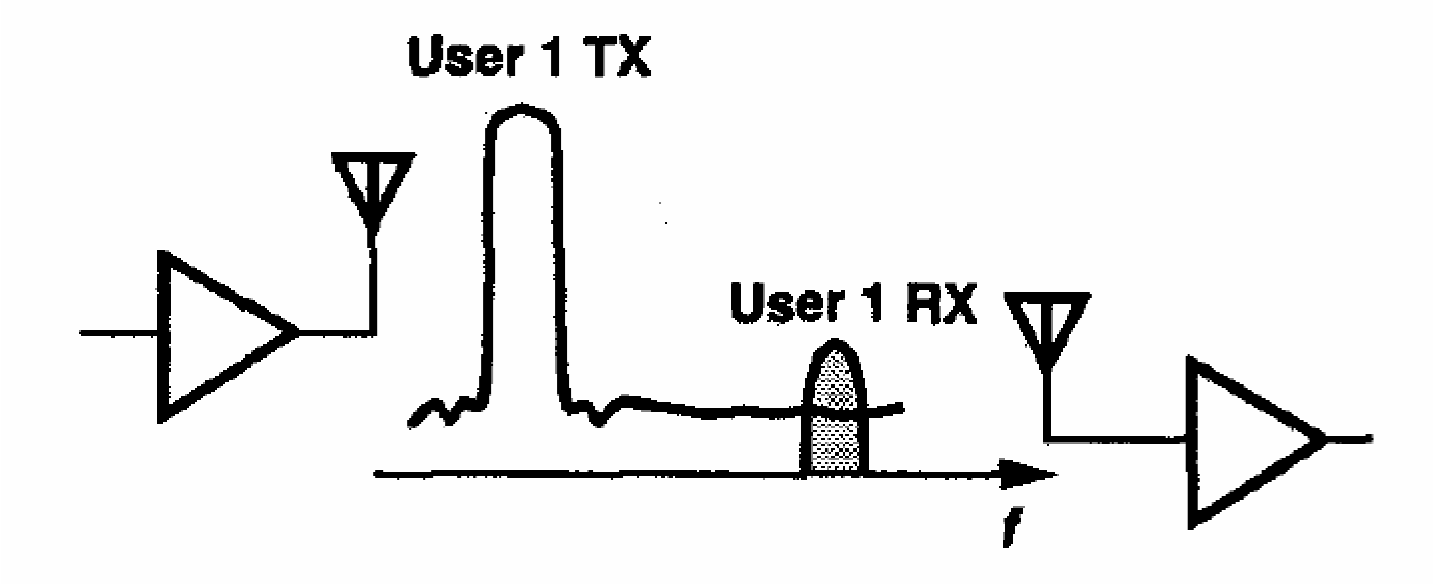
IS-94 standard (USA)

IS-95 standard (USA)

The ACPR spec. enforces sufficient linearity in up-conversion mixers and power amplifiers of the TX.

Image: B. Razavi

Transmitted noise (frequency duplex systems)



The transmitter noise interfers the RX band signal

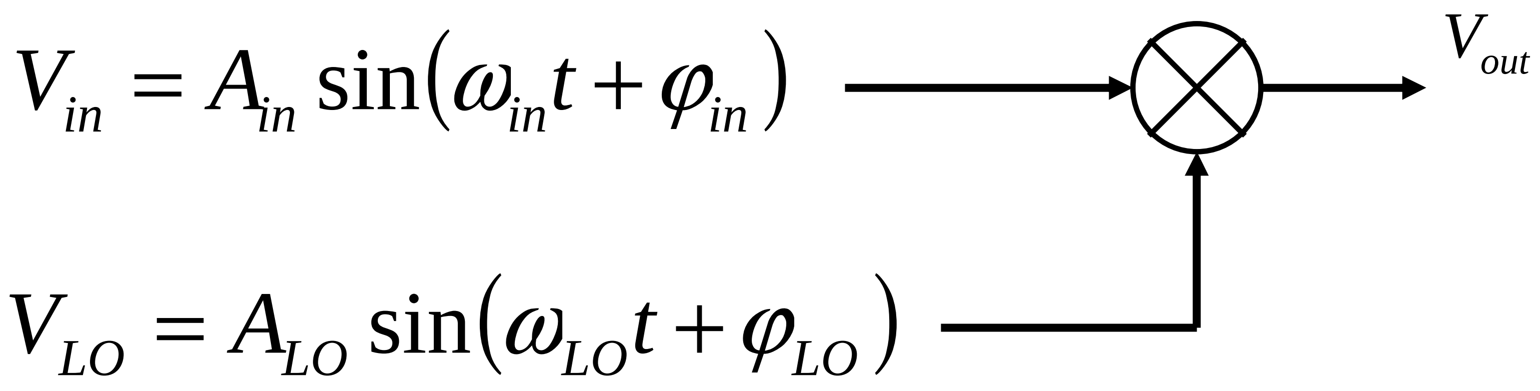
Especially for frequency multiplex system (simultaneous RX/TX)

Image: B. Razavi

Functional Blocks I

Mixer

Multiply with Local Oscillator signal



$$V_{in} = A_{in}\sin\left(\omega_{in}t + \varphi_{in}\right)$$

$$V_{LO} = A_{LO}\sin\left(\omega_{LO}t + \varphi_{LO}\right)$$

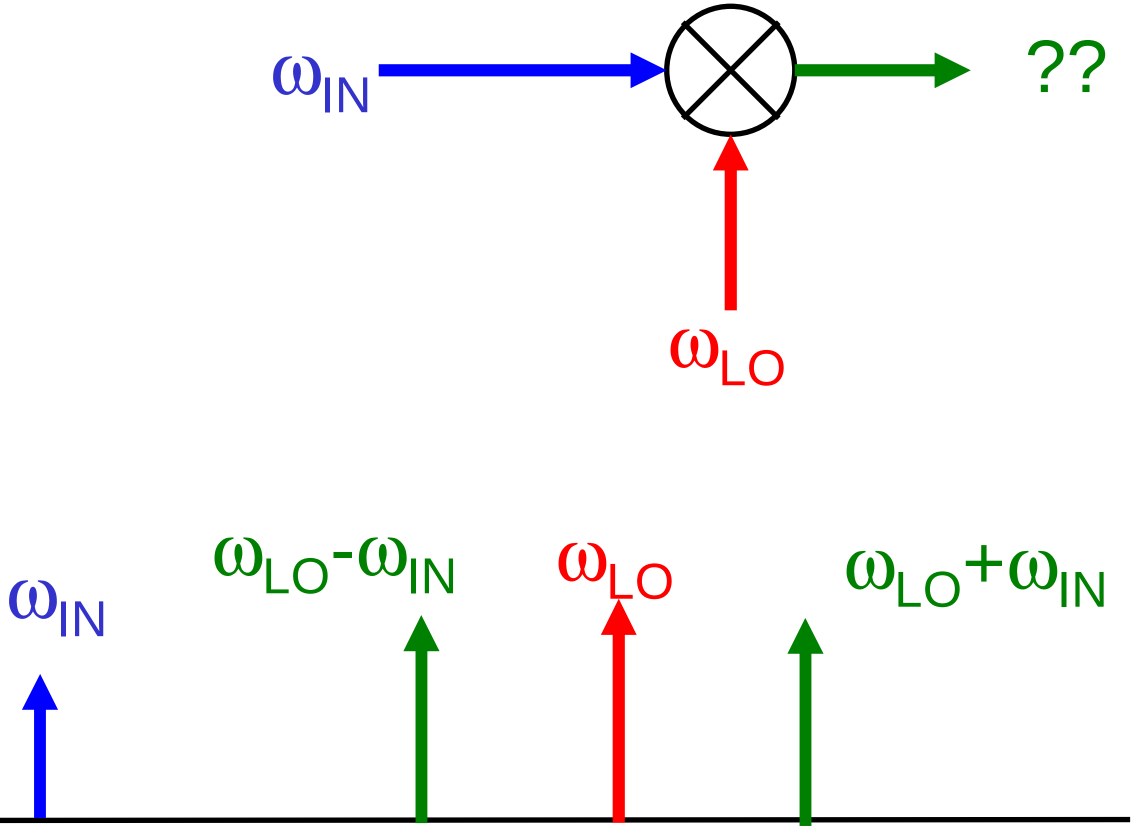
$$V_{out} = V_{in}\cdot V_{LO} = \tfrac{1}{2}A_{in}A_{LO}\sin\left[\overbrace{\left(\omega_{LO}-\omega_{in}\right)}^{\text{Lower Sideband}}t + \left(\varphi_{LO}-\varphi_{in}\right)\right]$$

$$+\tfrac{1}{2}A_{in}A_{LO}\sin\left[\underbrace{\left(\omega_{LO}+\omega_{in}\right)}_{\text{Upper Sideband}}t + \left(\varphi_{LO}+\varphi_{in}\right)\right]$$

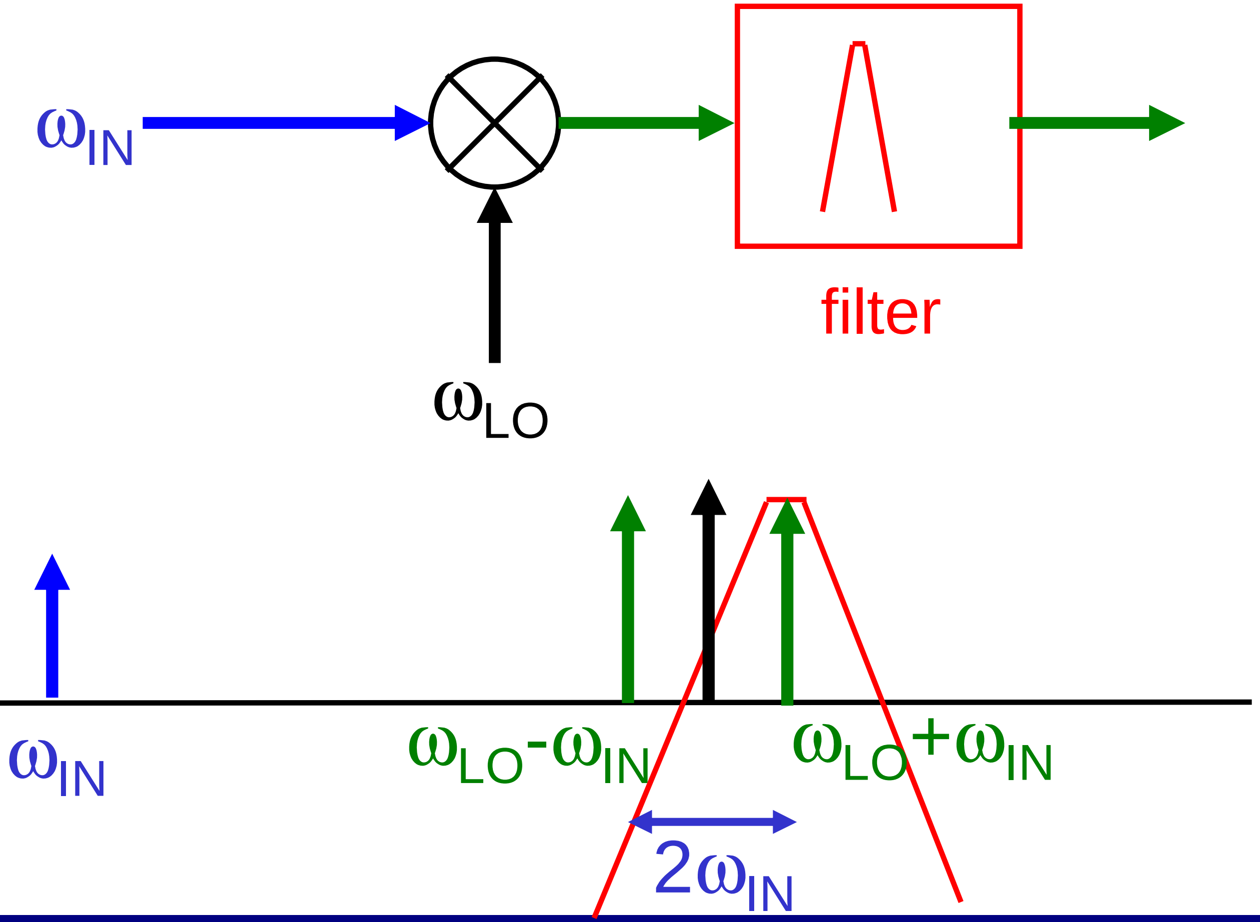
TRANSPARANT for Amplitude and Phase information!!

=> Modulation information available at another Frequency

Spectrum at output of multiplier



Select desired sideband via bandpass filter

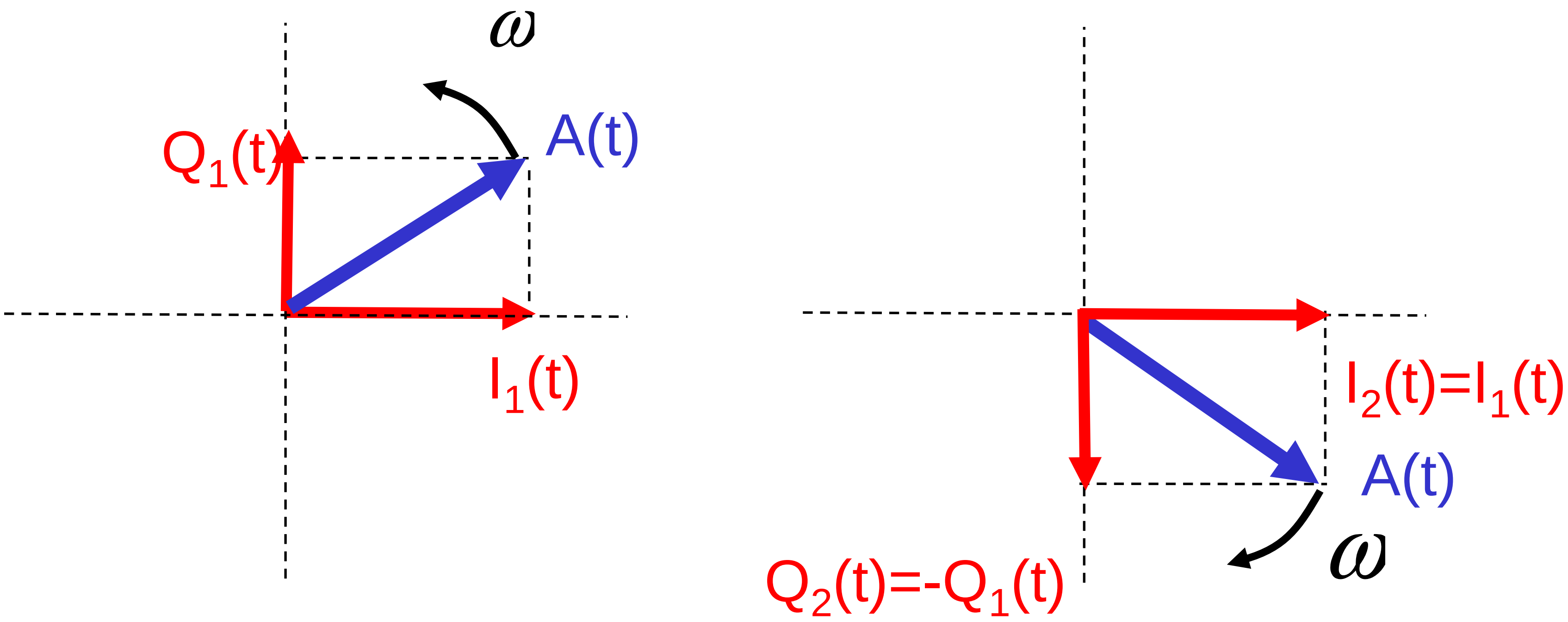


High selectivity filter needed if ωin is low!

Other techniques desired, e.g. cancelling one sideband

Distinguish upper and lower sideband?

If equal modulation but opposite frequency:

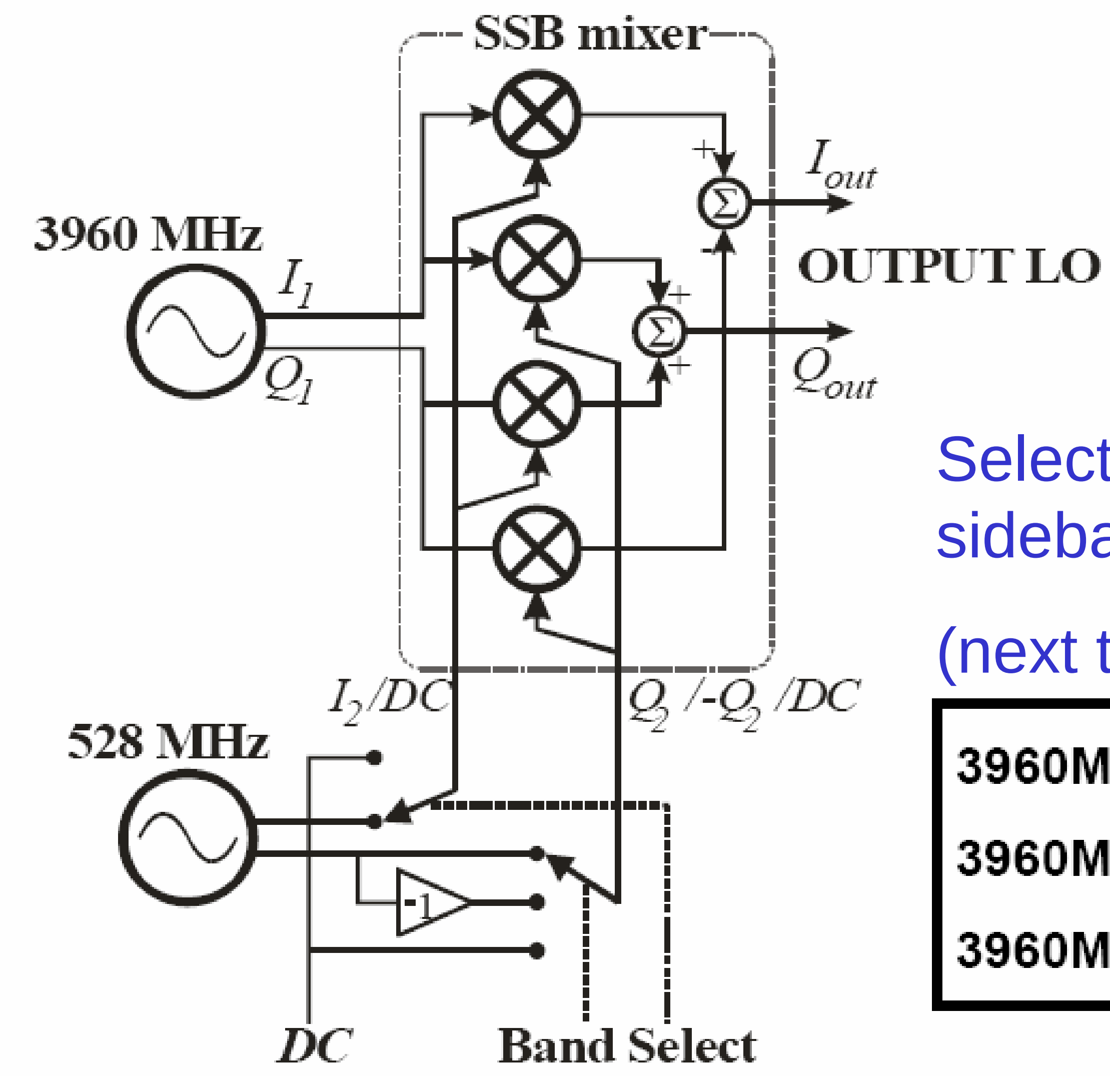


Observing I or Q alone: no rotation direction info

Use both I & Q to get “single-sideband mixer” (SSB)

More details next time (image reject mixers)

Single sideband mixer example



$$I_{out} = I_1 I_2 - Q_1 Q_2$$
$$Q_{out} = I_1 Q_2 + Q_1 I_2$$

Select upper of lower sideband or no shift (DC)

(next time more details)

3960MHz – 528MHz = 3432MHz

3960MHz + 0MHz = 3960MHz

3960MHz + 528MHz = 4488MHz

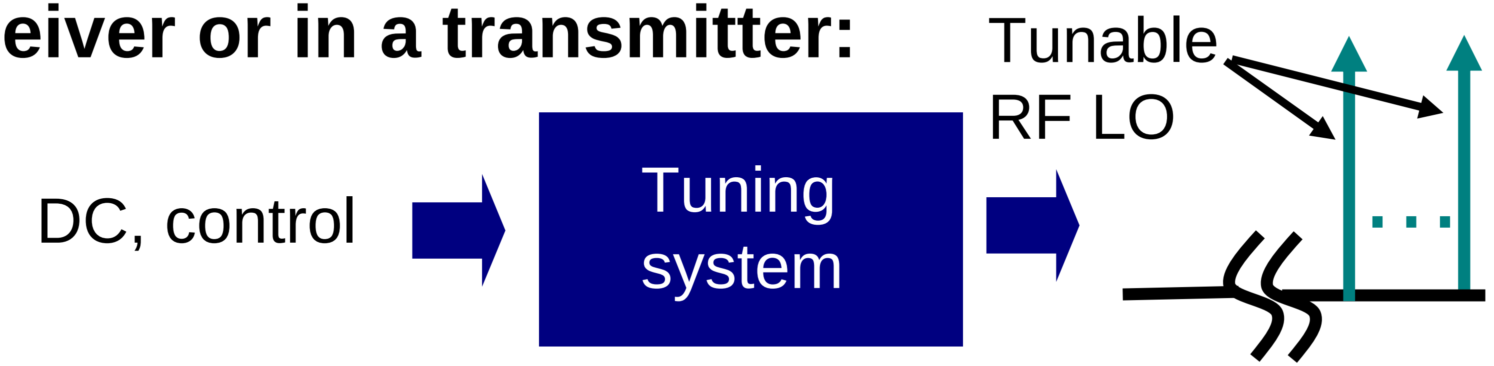
Function Blocks II

Tuning system

How to generate the RF carrier?

Basic function of a tuning system

What do we want of a tuning system in a receiver or in a transmitter:



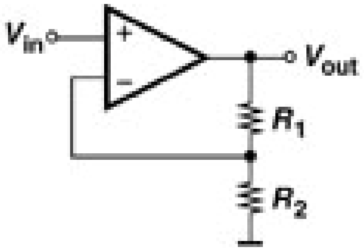
The tuning system in a transceiver generates the required tunable Local Oscillator (LO) signal. The signal should be accurate in terms of absolute frequency and stable (have a high spectral purity).

Single-loop PLL

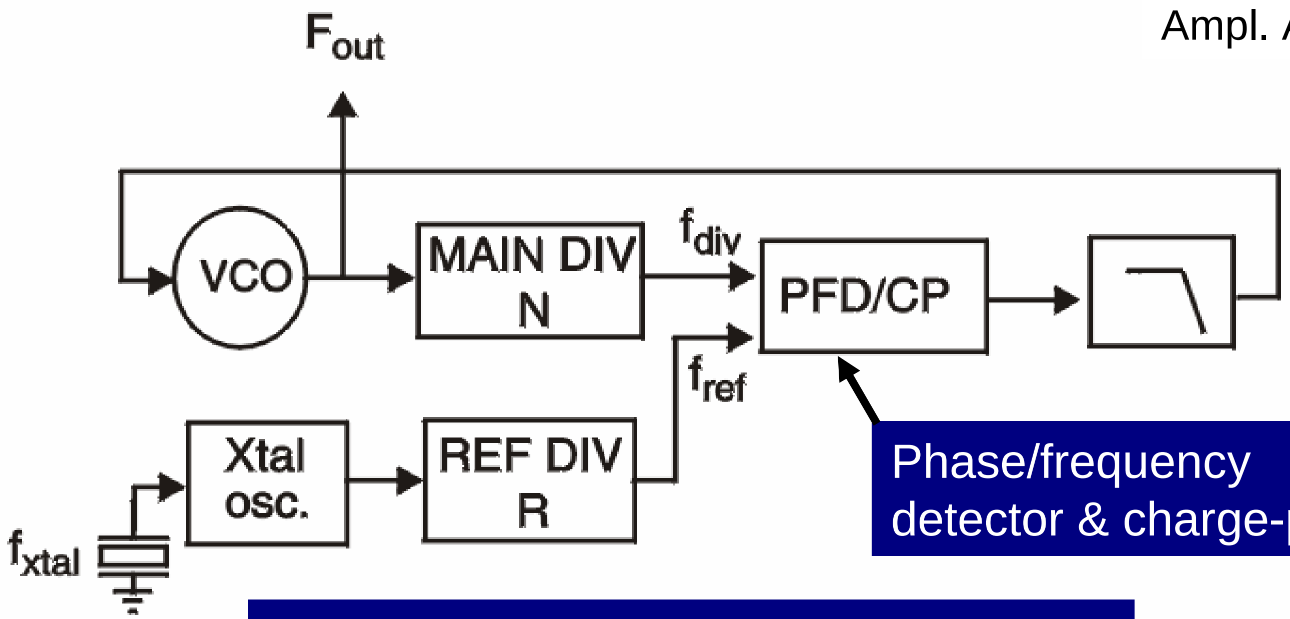
Phase Lock Loop (PLL):

Phase of divider and ref signal equal

(and hence also frequency)



Ampl. Analogy $V_{in}=V_{out}/n$



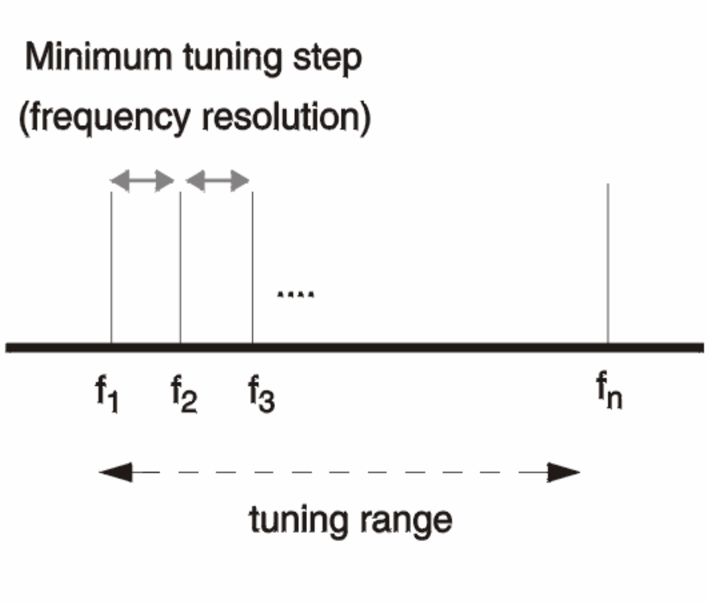
Phase/frequency detector & charge-pump

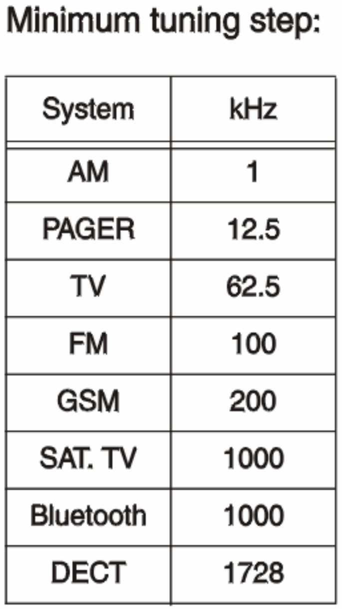
$$F_{out} = N * f_{ref} = N * \frac{f_{xtal}}{R}$$

Tuning system specifications (I)

Tuning range: which RF input or TX frequencies need to be covered

Step-size related to f_{ref}:



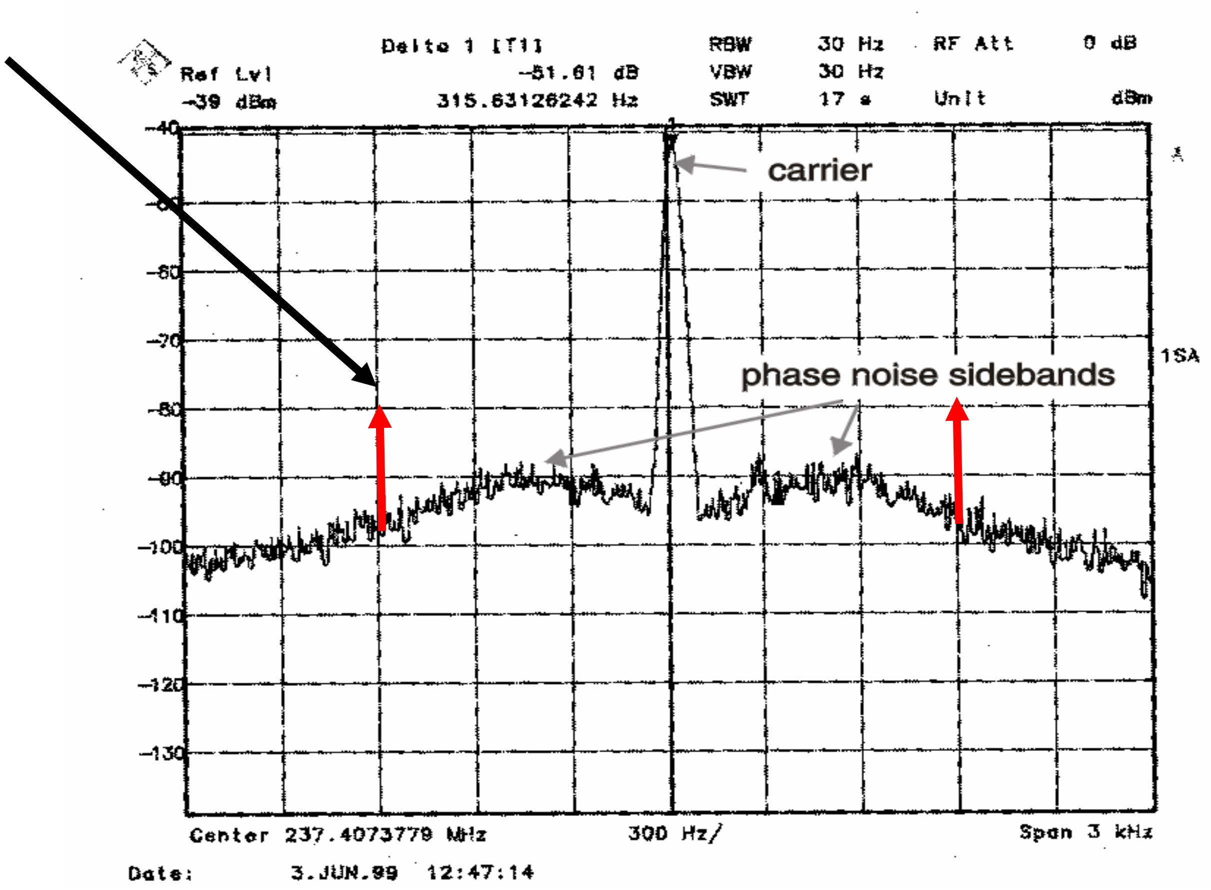

Minimum tuning step:

System	kHz
AM	1
PAGER	12.5
TV	62.5
FM	100
GSM	200
SAT. TV	1000
Bluetooth	1000
DECT	1728

Settling time (after a frequency jump) is also related to f_{ref} (loopfilter bandwidth $<0.1*f_{ref}$ for stability)

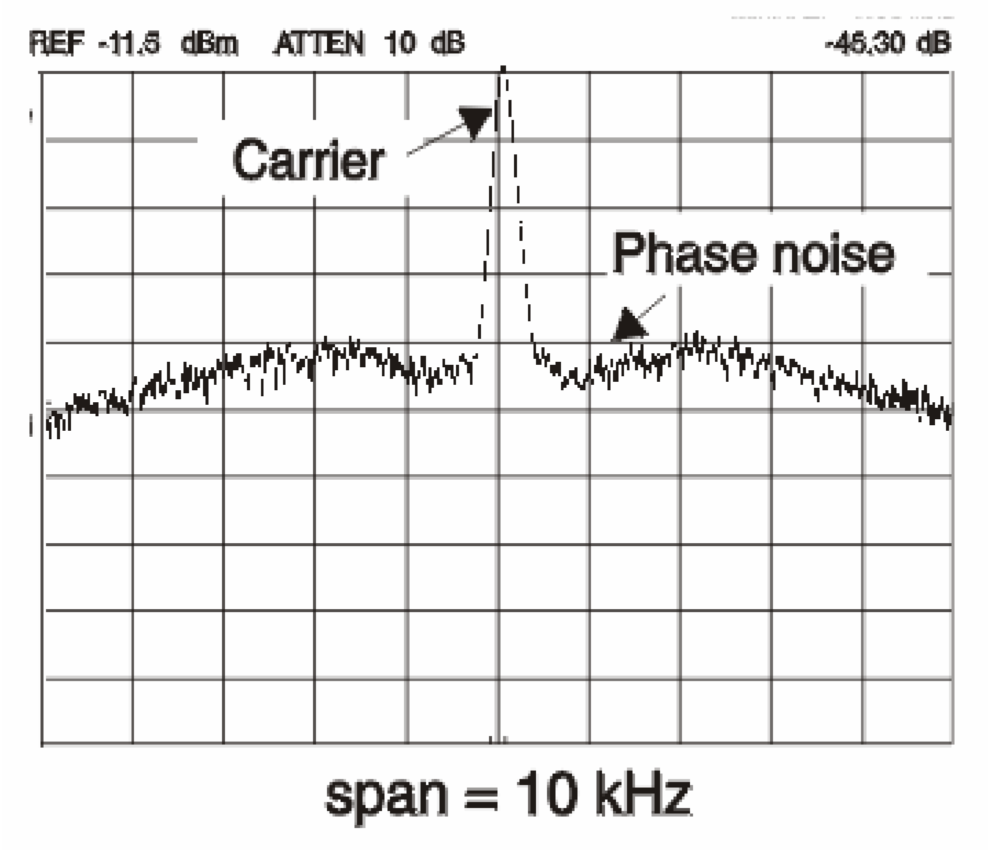
Tuning system specifications (II)

Spurious signals (deterministic)

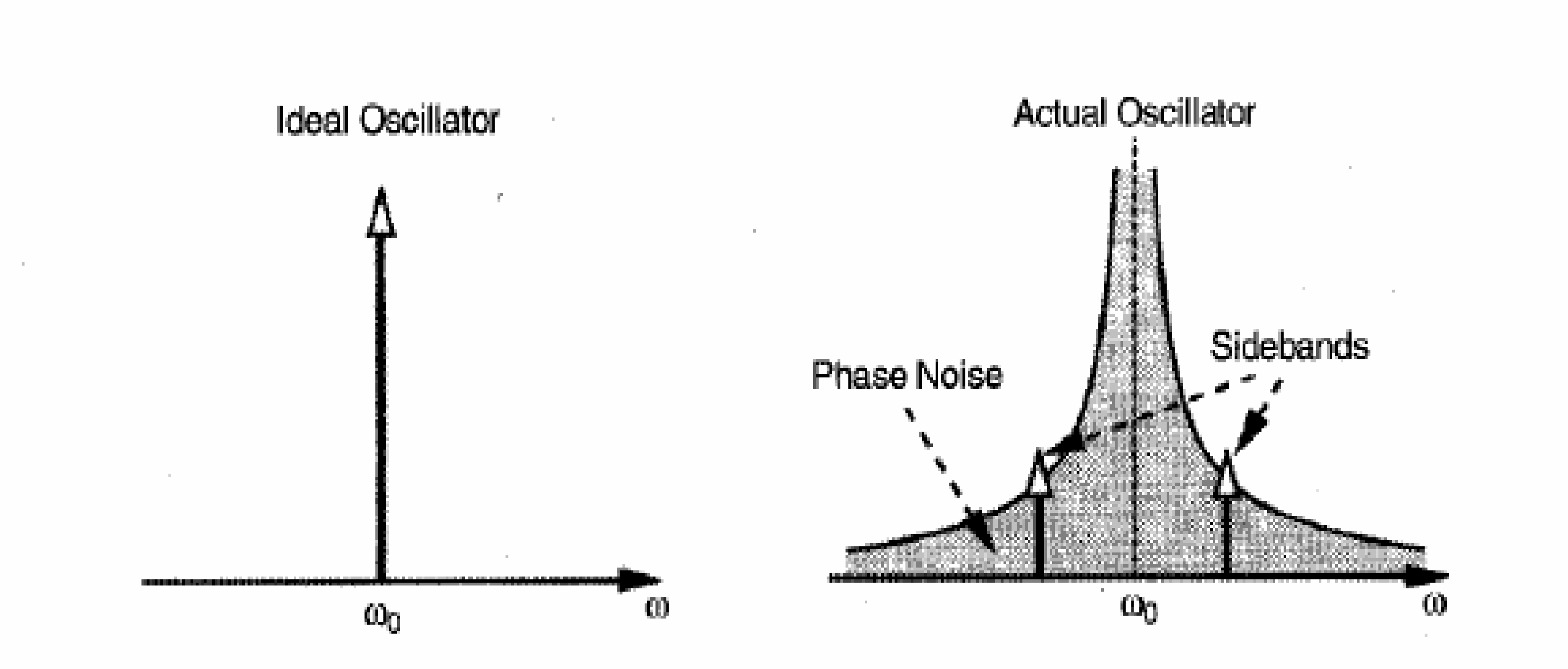


Tuning system specifications (III)

Phase noise sidebands (stochastic)



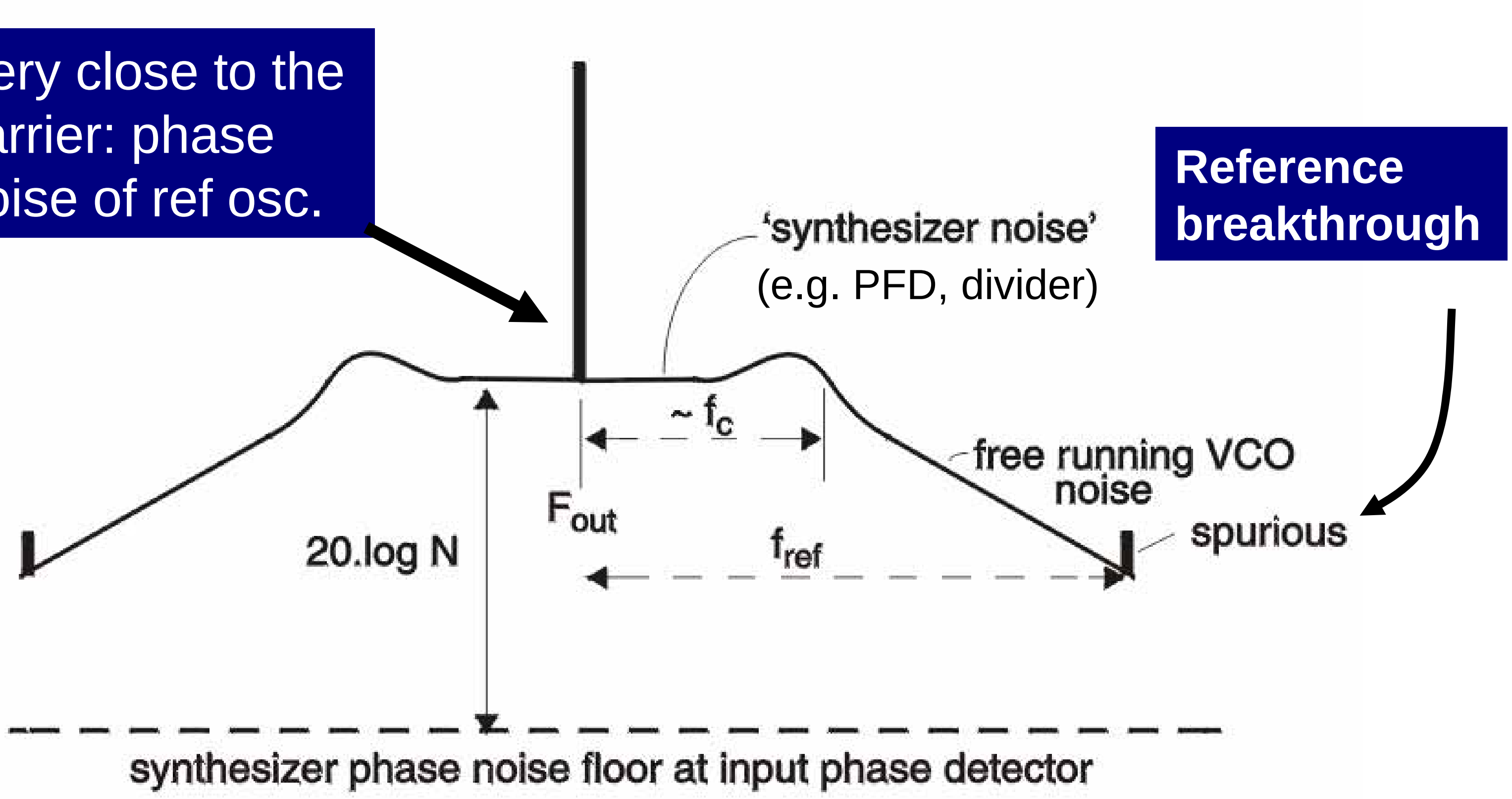
Ideal versus practical oscillator



More on oscillator phase noise in course #6/10 on oscillators.

Image: B. Razavi

Typical synthesizer spectrum



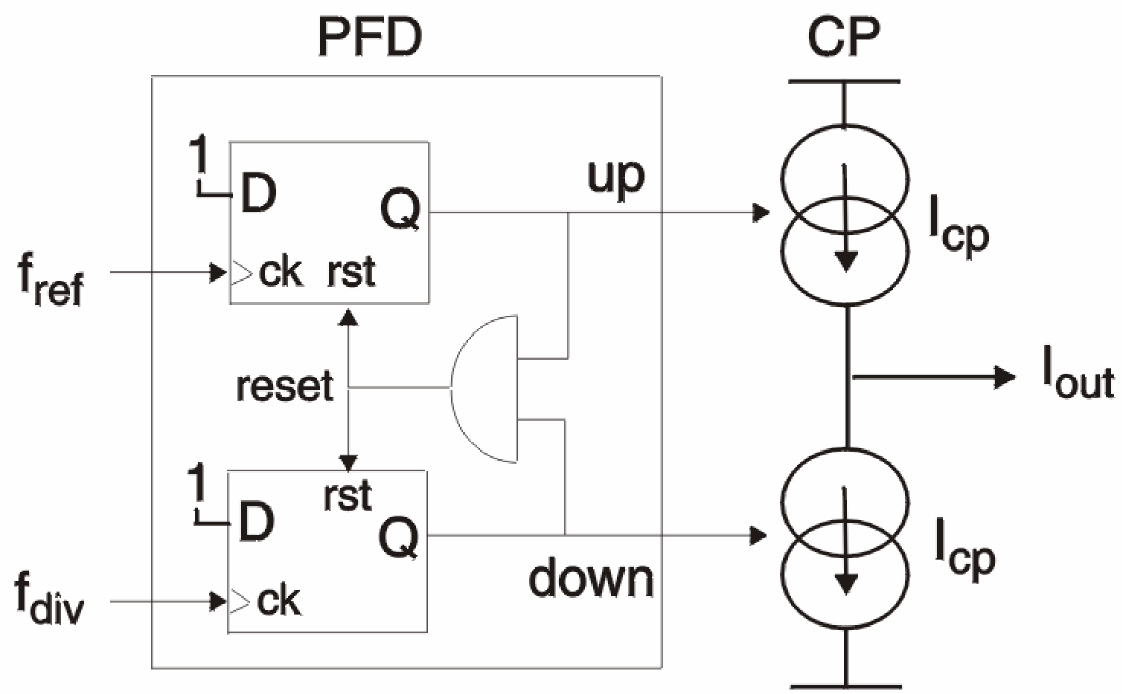
Very close to the carrier: phase noise of ref osc.

Reference breakthrough

Example of a “PFD/CP”

PDF = Phase Frequency Detector

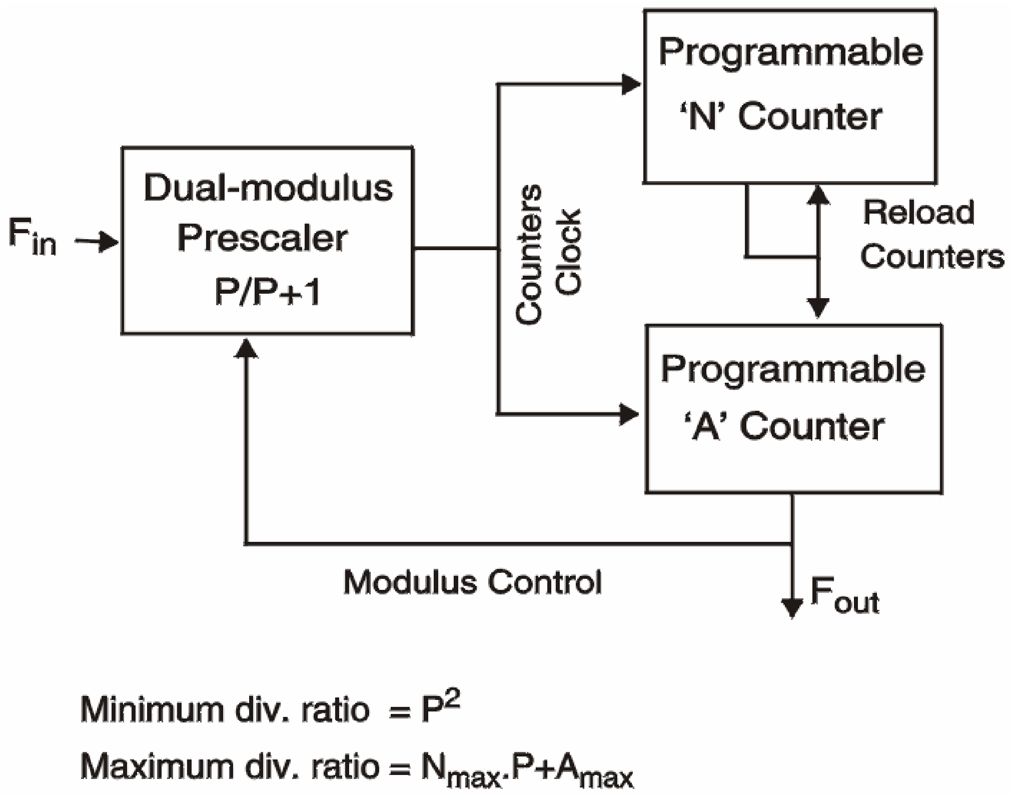
CP = Charge Pump



“Sequential PFD”: detect first rising edge (fref or fdiv?)

Charge pump provides current during time between edges

Example of divider architecture



Minimum div. ratio $= P^2$

Maximum div. ratio $= N_{max}.P+A_{max}$

The Prescaler drives counters N and A. When N=0 it generates a reload signal for N and A.

Then the counters start to count down again.

There are much more modular architectures: see course book

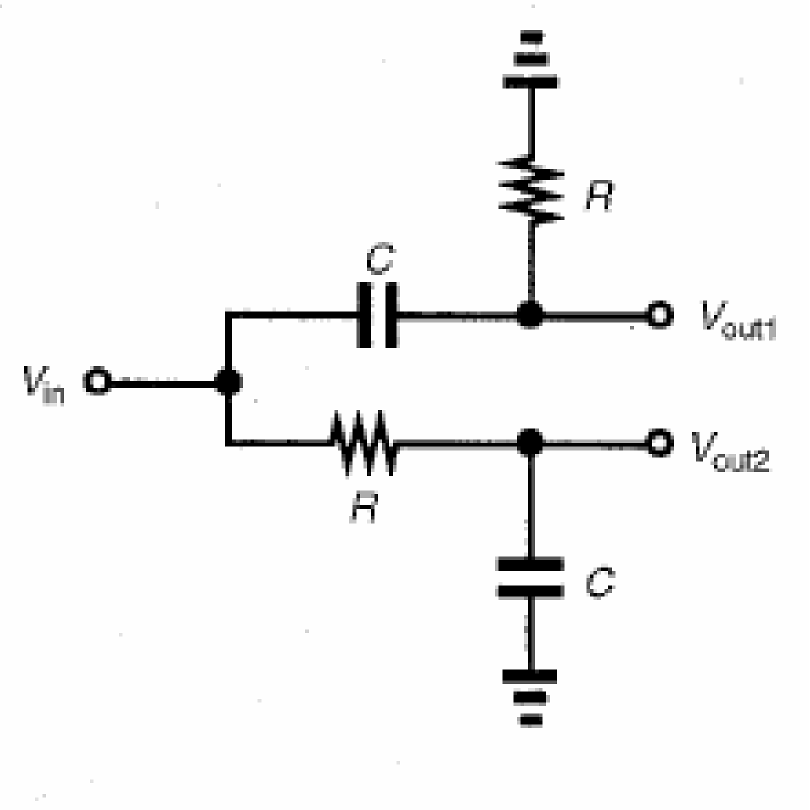
Function Blocks III

Quadrature generation

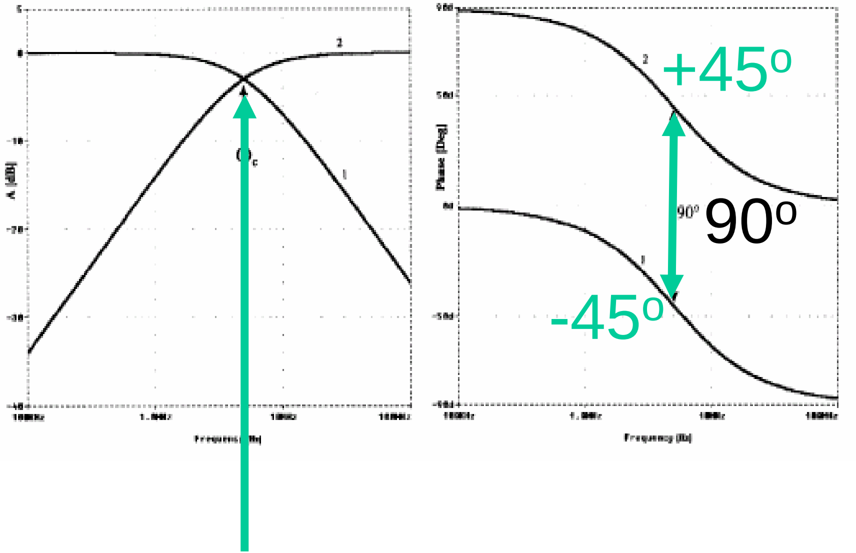
(90 degrees out of phase)

Quadrature signal generation: RC network (1)

RC-CR network



Amplitude(ω) & Phase(ω):



ω=1/(RC).

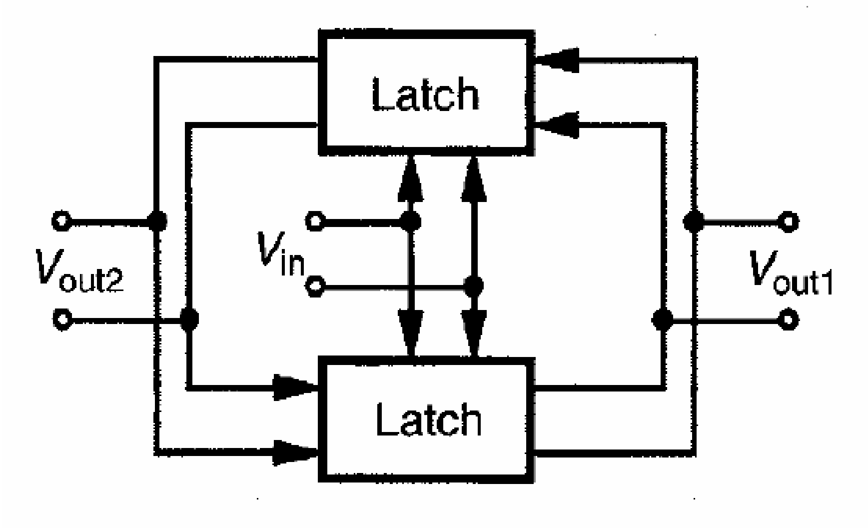
Phase-difference Vout1 and Vout2 always 90 degrees.

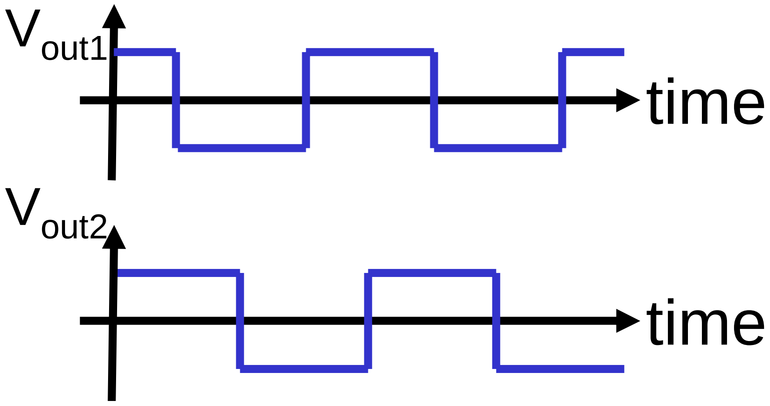
Only equal amplitude at ω=1/RC, but clipping (limiter) may be used (LO)

Image: B. Razavi

I/Q generation: divider (2)

Using a divider-by-two and input clock at 2 f_{osc}





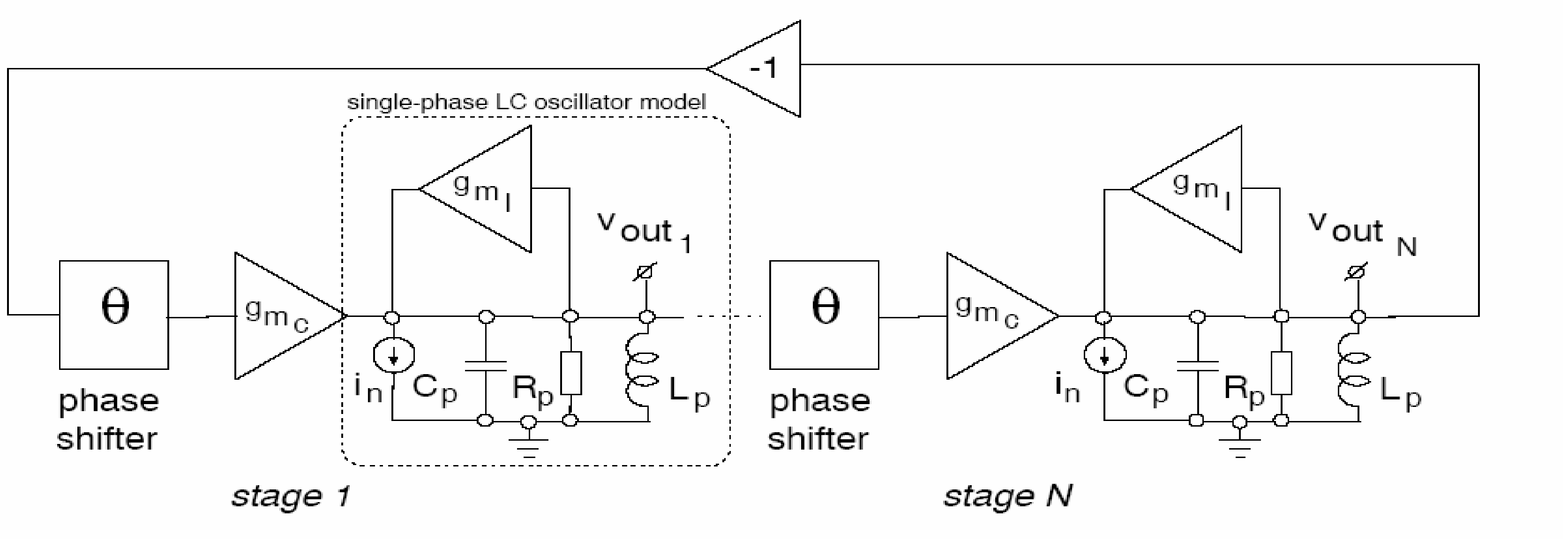
Outputs in quadrature if input signal has a duty cycle of 50%.

Cascade of two dividers can be used to improve the I/Q matching if V_{in} has no 50% duty-cycle (but input signal must then be at 4 f_{osc})

Image: B. Razavi

I/Q generation: multi-stage Oscillator (3)

Even number of stages multi-phase LC oscillator can generate multiple signals with desired phase-difference



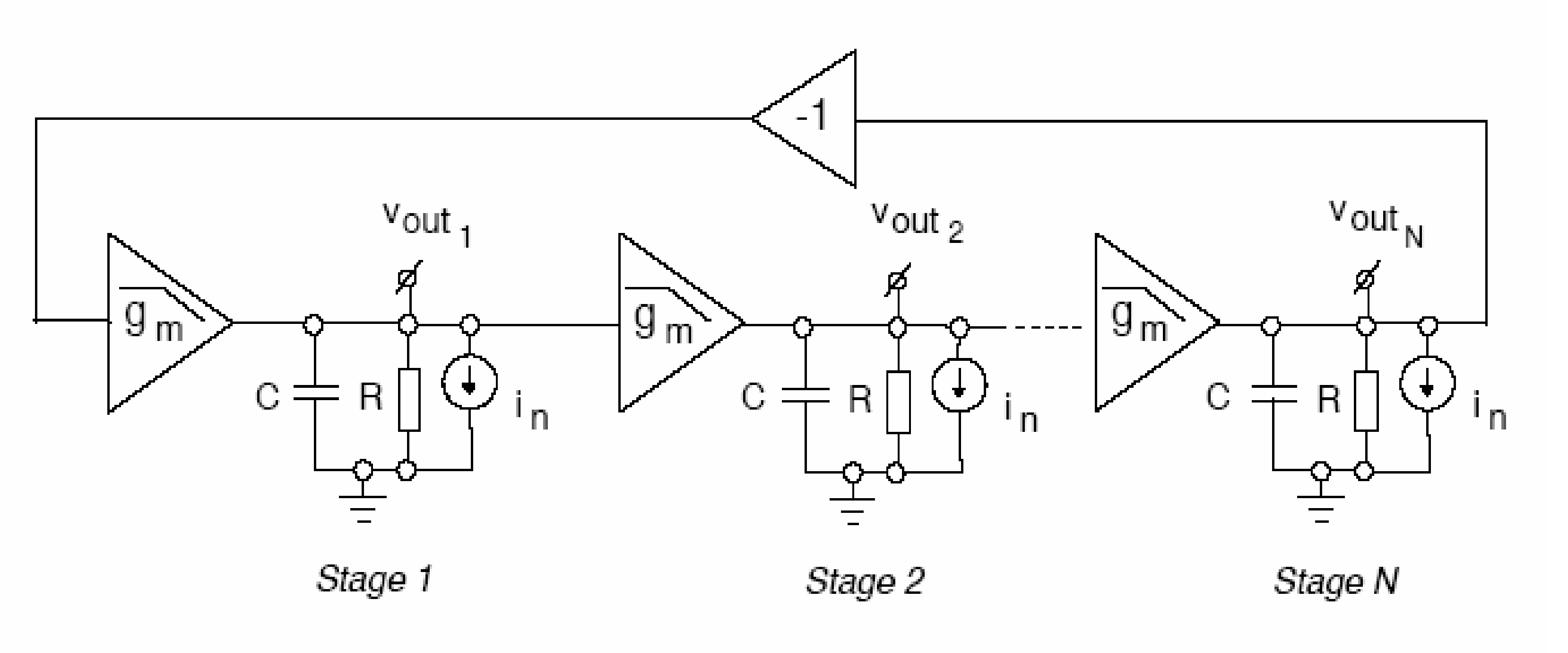
☺ No higher frequency needed

☹ Inductors (2, balanced or 4 single) may require a lot chip area.

Power should be compared to other solutions.

I/Q generation (4)

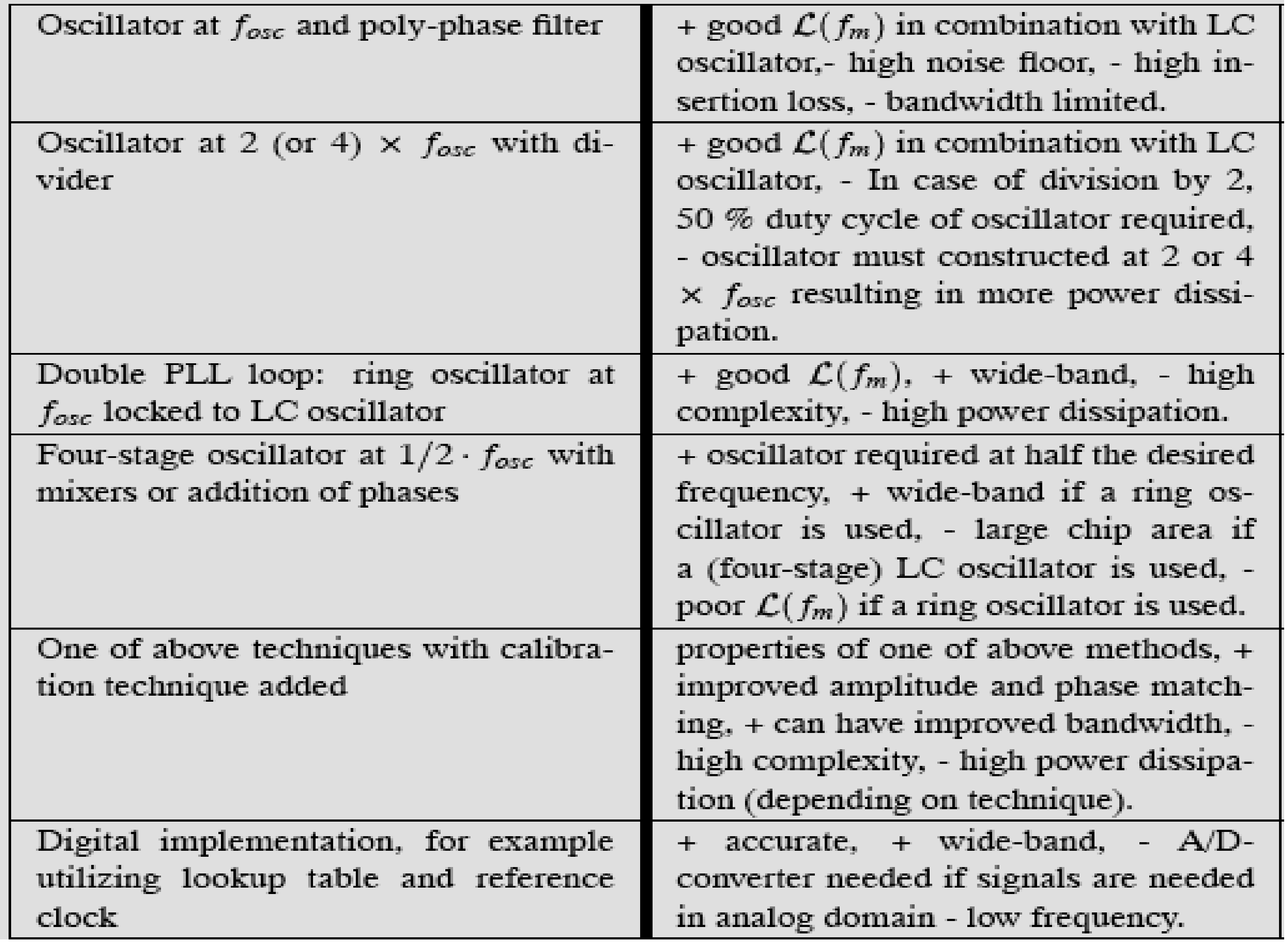
Even-number N-stage ring oscillators oscillators:



☺ No higher frequency needed

☹ Ring oscillators much more noisy compared to LC oscillators given the same power budget.

Some other I/Q generation methods

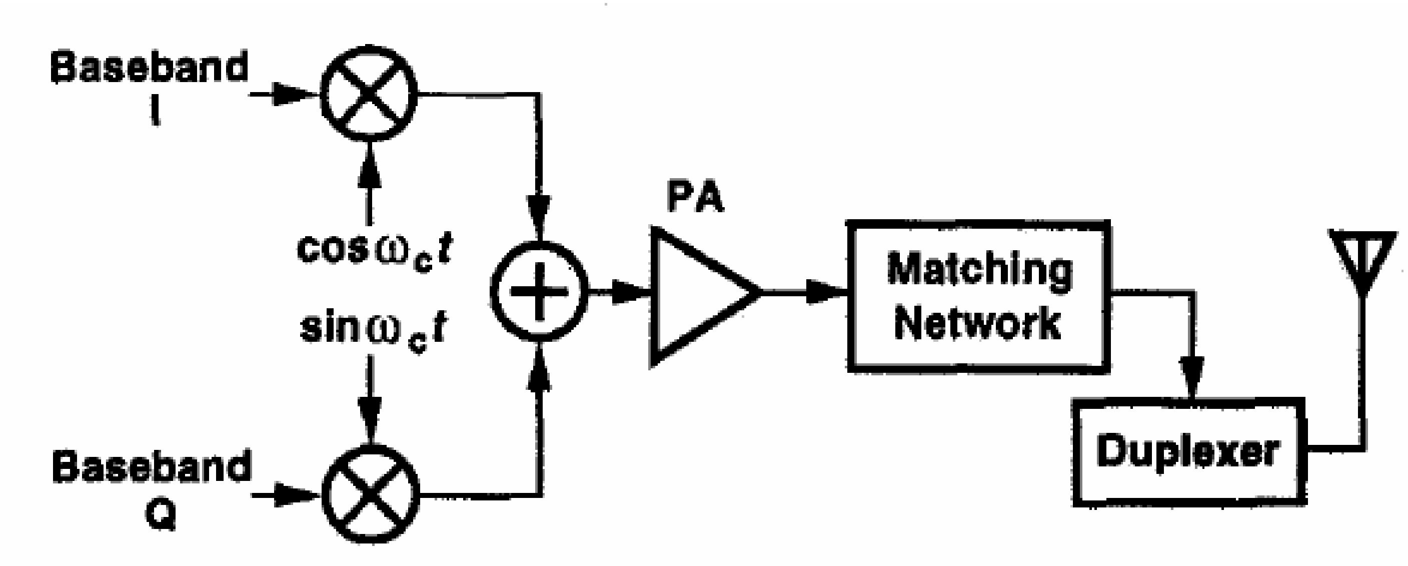


Oscillator at f_{osc} and poly-phase filter	+ good $\mathcal{L}(f_m)$ in combination with LC oscillator,- high noise floor, - high insertion loss, - bandwidth limited.
Oscillator at 2 (or 4) × f_{osc} with divider	+ good $\mathcal{L}(f_m)$ in combination with LC oscillator, - In case of division by 2, 50 % duty cycle of oscillator required, - oscillator must constructed at 2 or 4 × f_{osc} resulting in more power dissipation.
Double PLL loop: ring oscillator at f_{osc} locked to LC oscillator	+ good $\mathcal{L}(f_m)$, + wide-band, - high complexity, - high power dissipation.
Four-stage oscillator at $1/2 \cdot f_{osc}$ with mixers or addition of phases	+ oscillator required at half the desired frequency, + wide-band if a ring oscillator is used, - large chip area if a (four-stage) LC oscillator is used, - poor $\mathcal{L}(f_m)$ if a ring oscillator is used.
One of above techniques with calibration technique added	properties of one of above methods, + improved amplitude and phase matching, + can have improved bandwidth, - high complexity, - high power dissipation (depending on technique).
Digital implementation, for example utilizing lookup table and reference clock	+ accurate, + wide-band, - A/D-converter needed if signals are needed in analog domain - low frequency.

Transmitter Architectures

Direct- conversion transmitters

Direct-conversion TX



☺ Simple architecture: Up-conversion and quadrature modulation in the same mixer circuit)

So: LO frequency is the same as the output frequency

Image: B. Razavi

Key disadvantage direct-conversion TX

Very strong output signal of PA modulates local oscillator: "LO pulling"

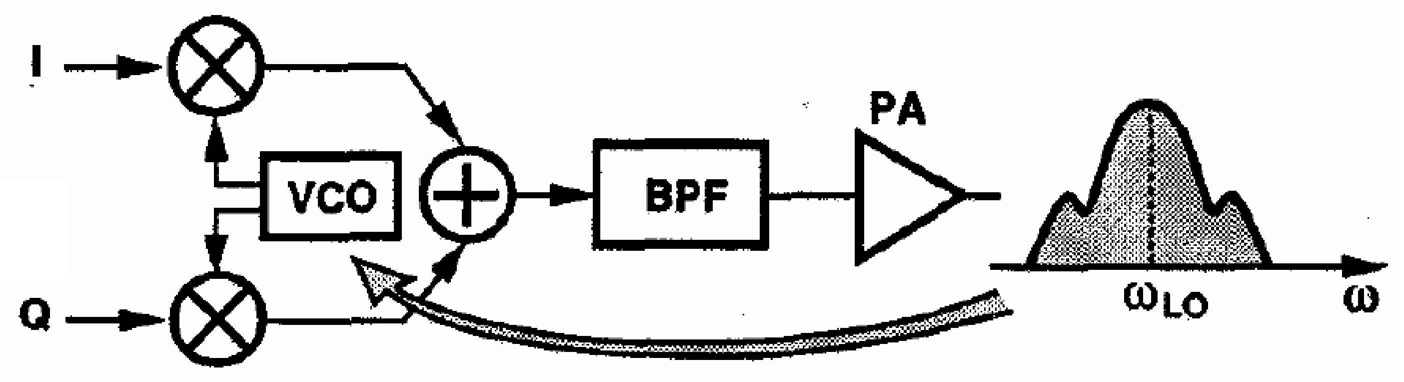


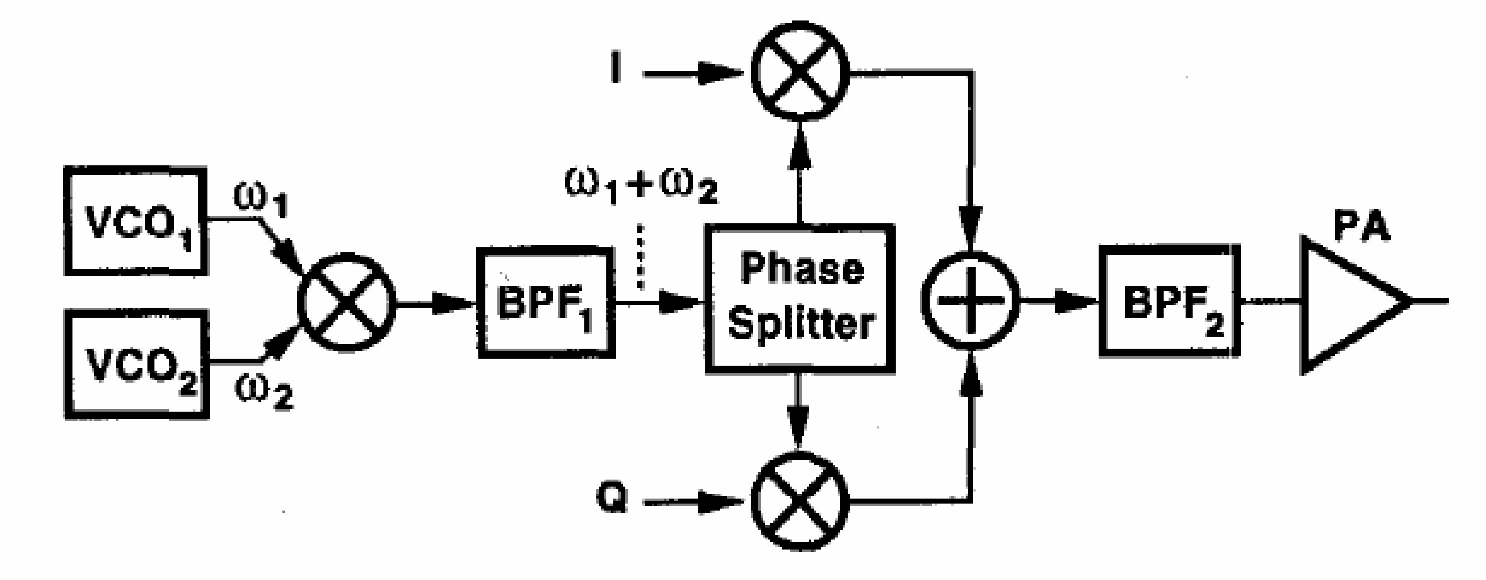
Image: B. Razavi

Strong PA signals injected into the oscillator may modulate the oscillator in a noisy fashion or even "pull" it away from its intended frequency (note the PA output is modulated!).

Note: oscillator are especially sensitive to pulling close to their oscillation frequency (where loop gain is close to 1)

Direct-conversion transmitters with offset LO

Direct-conversion with offset LO



☺ None of the VCOs runs at the output frequency => less pulling issues

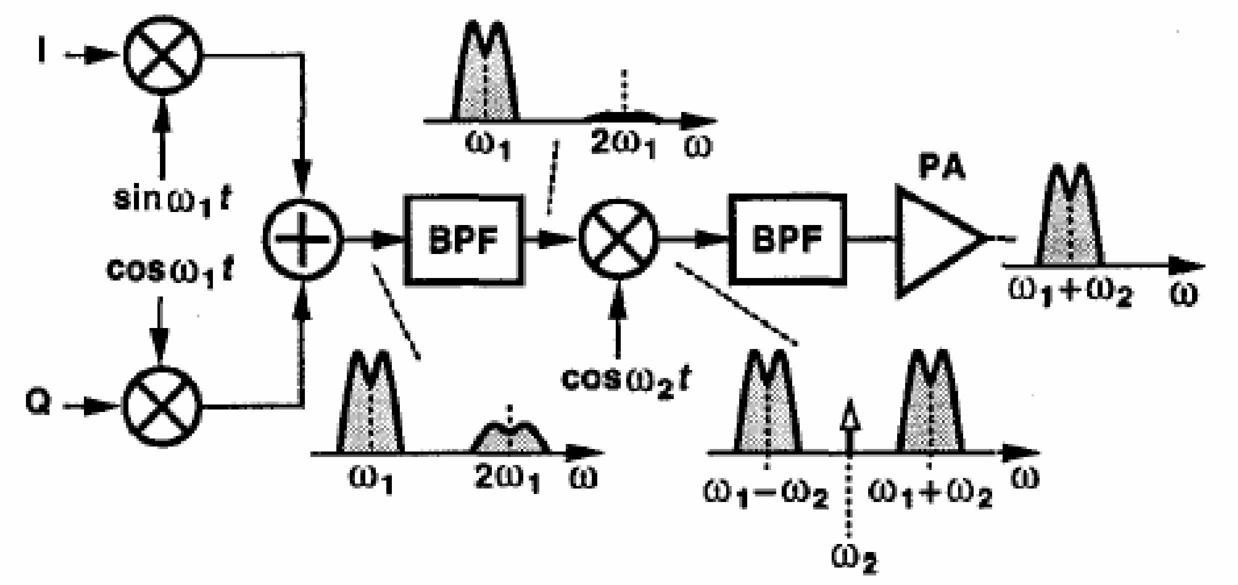
☹ BPF must suppress all unwanted mixing products sufficiently

Image: B. Razavi

Two-step transmitter architecture

Or: Two-step transmitter architecture

Two up-conversions to remove LO pulling problem



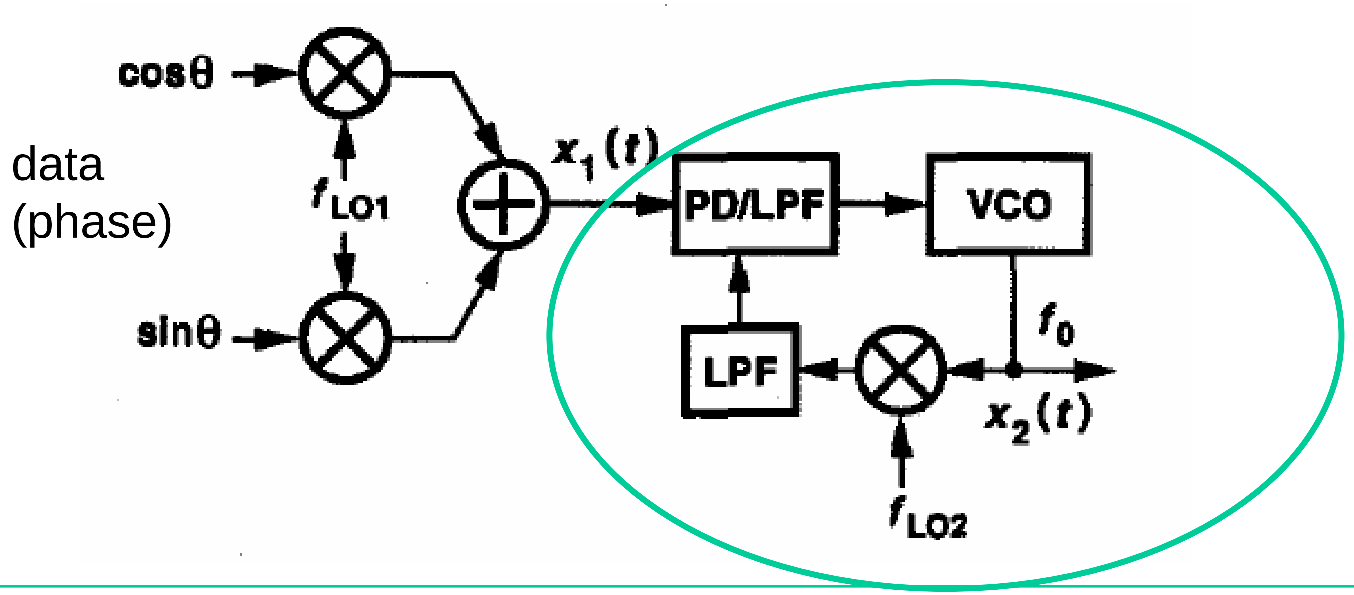
☺ Only one high frequency mixer, no quadrature needed there

☹ Bandpass filters are difficult to make on-chip and may require 50-60 dB suppression of unwanted conversion product.

“Offset-PLL” transmitter architecture

Offset PLL architectures:

Only for PM systems (“constant envelope”)



PLL: 1) Upconverter; 2) Phase modulator; 3) Narrow filter

$f_o = f_{LO1} + f_{LO2}$ (f_{LO2} is the “Offset frequency”)

f_{LO2} reduces the input frequency of phase detector (PD) to f_0-f_{LO2}

Excellent out-of-band noise performance (PLL loop)

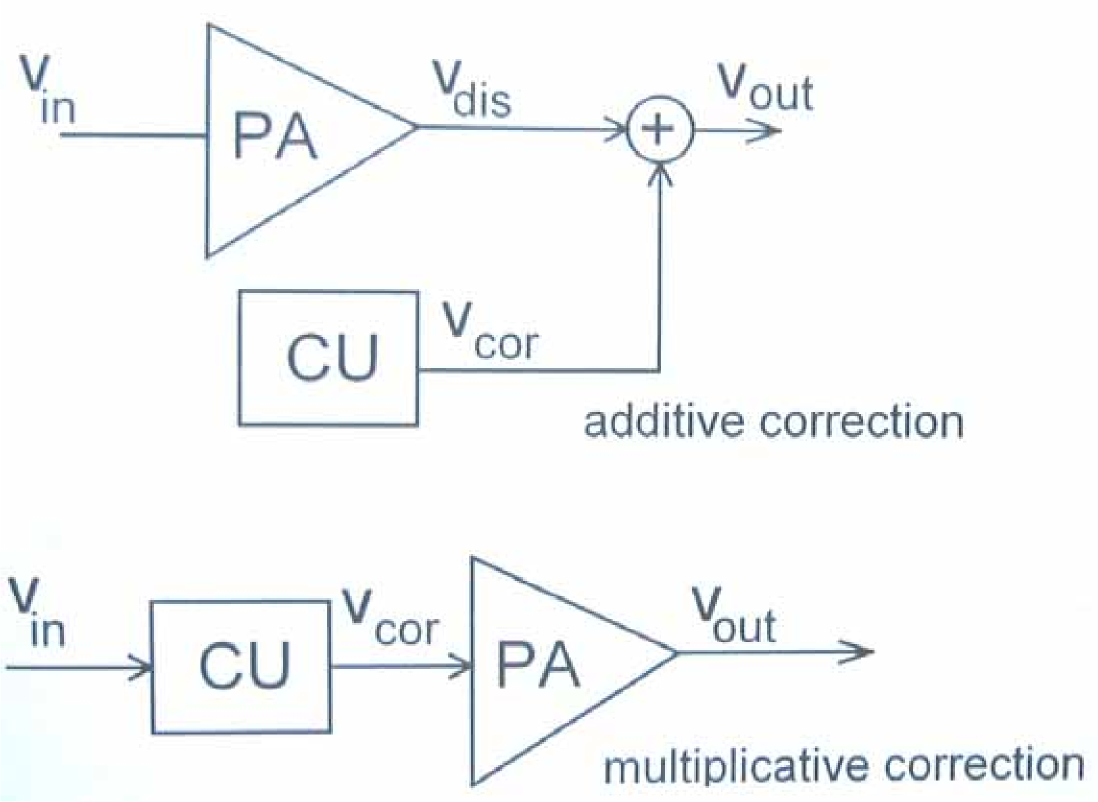
Image: B. Razavi

Recent Developments

Linearisation Techniques for PAs (non-constant envelope modulation)

More digital: Software Defined Radio

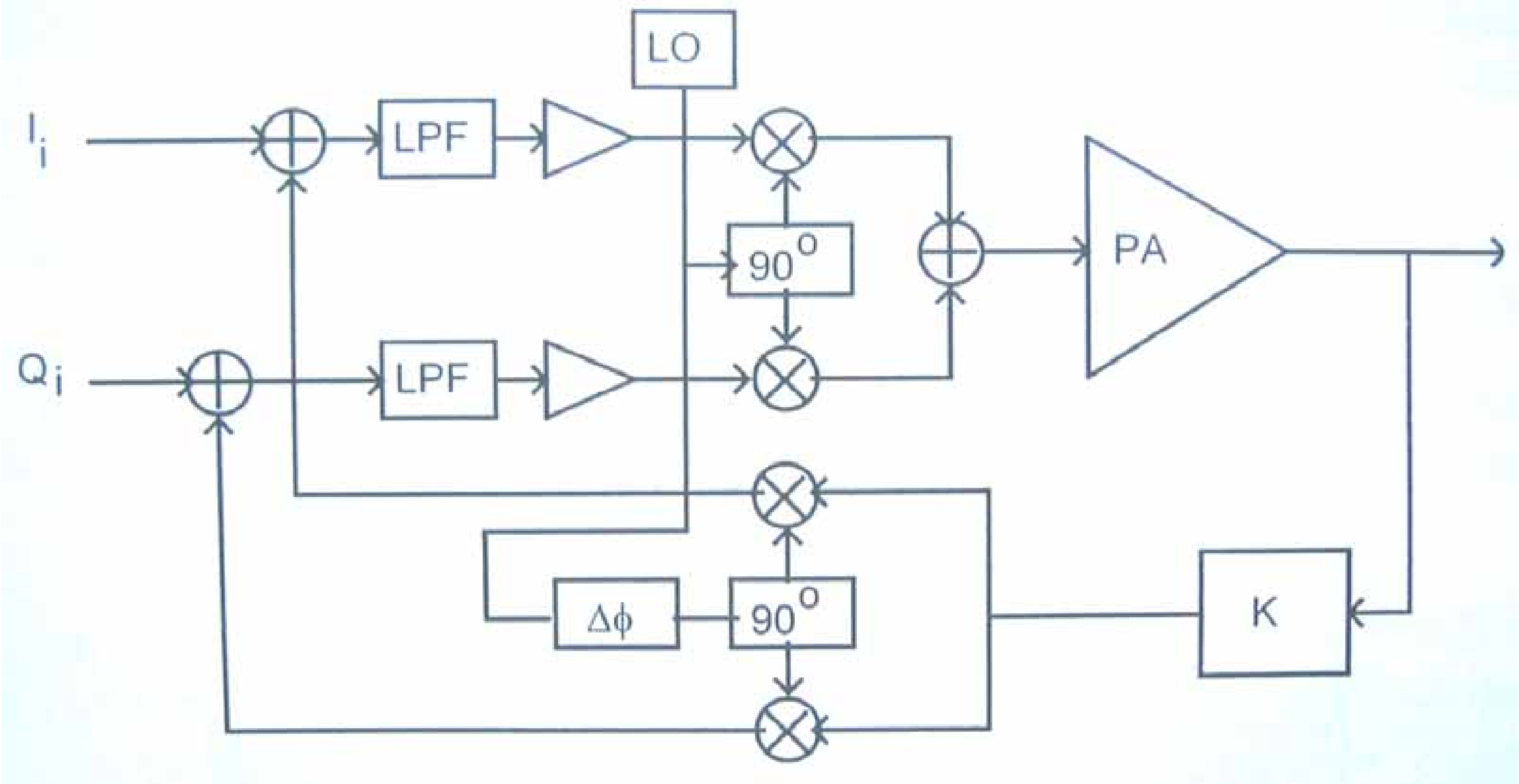
Predistortion (Compensation)



☺ Correct the non-linearity in the PA => higher output power at same distortion possible => better efficiency

☹ Knowledge of PA nonlinearity needed

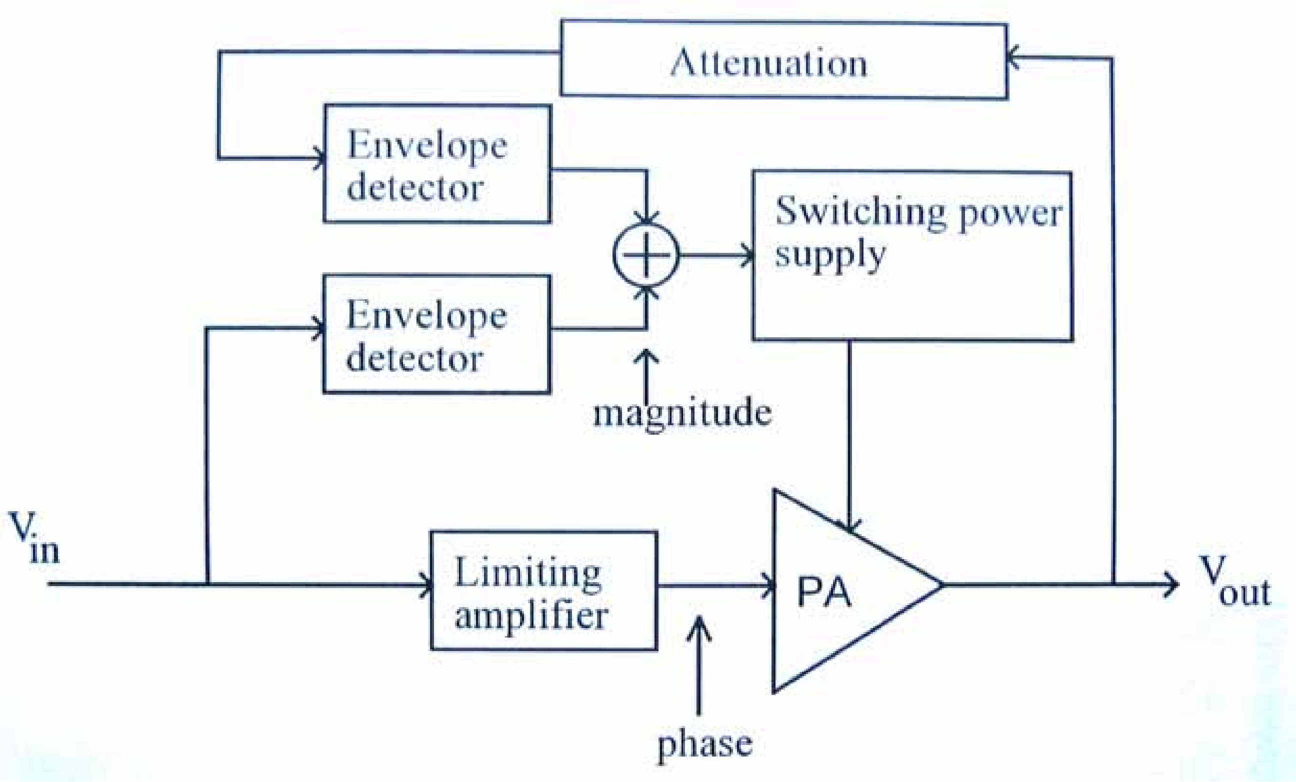
“Cartesian Feedback”



☺ Detect the I and Q component of PA output signal and correct it via comparison with input signal (feedback)

☹ Delay in loop set maximum to modulation speed

Envelope Elimination and Restoration



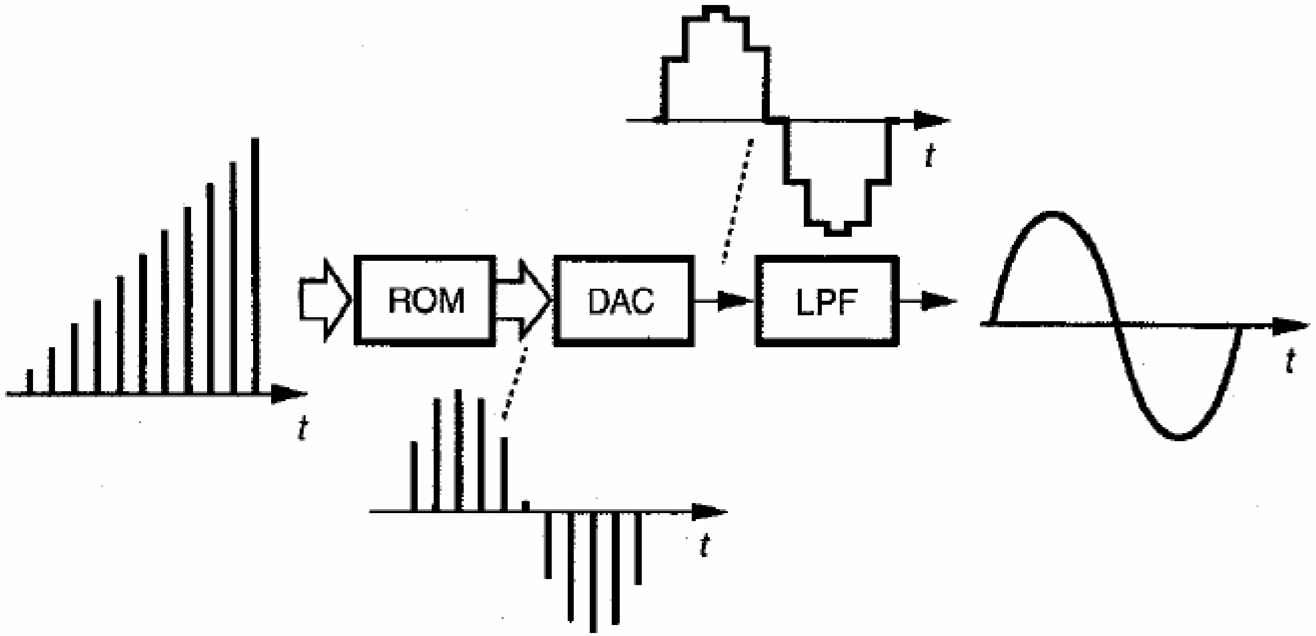
☺ Limiting amplifier removes AM “envelope” => constant envelope PA input signal => high efficiency PA possible

☺ Modulate a switching power supply to restore AM

☹ Equality of delay in different signal paths challenging

Digital signal generation

Direct digital synthesizer (DDS)



Very flexible waveform generation via ROM

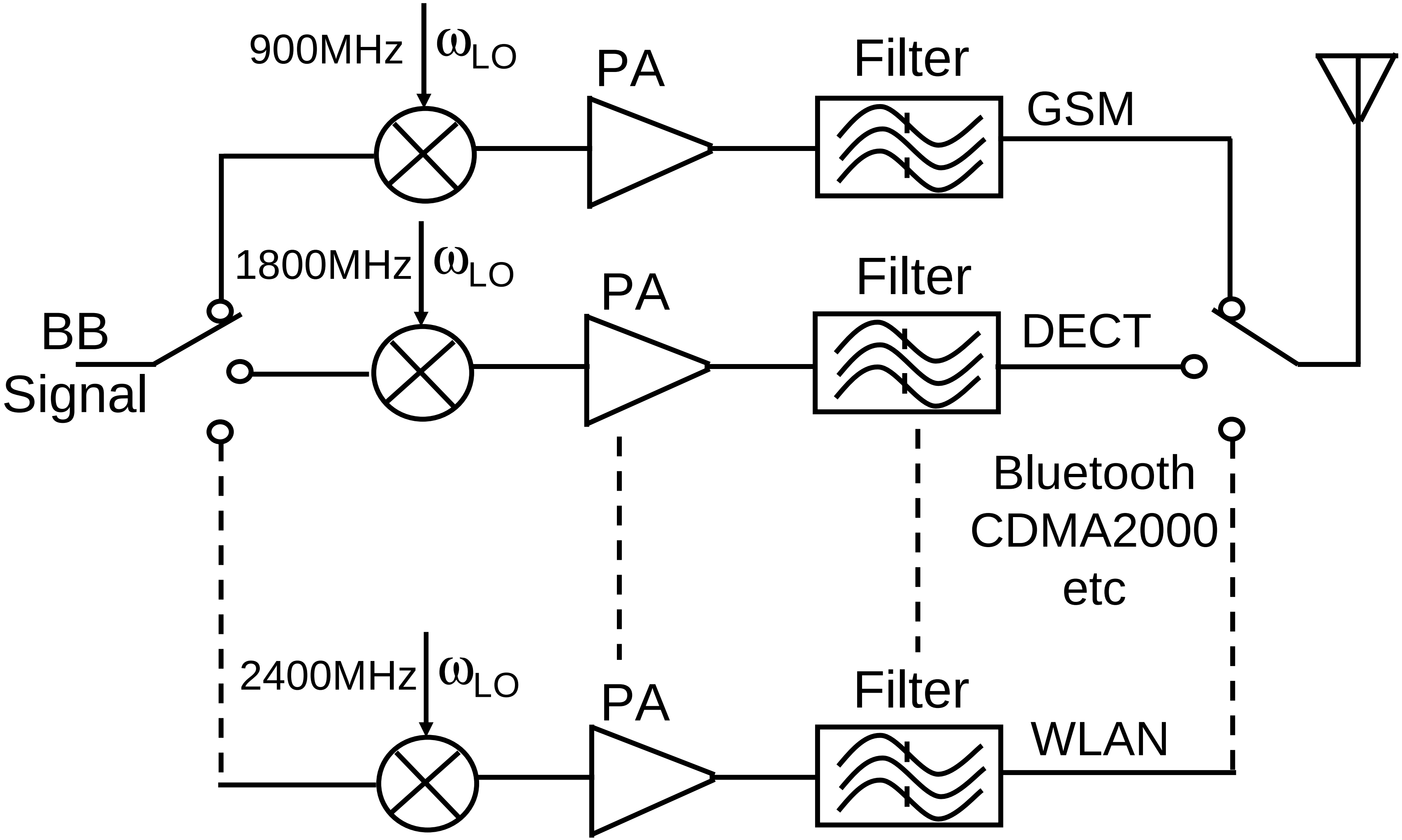
Relatively complex and power hungry

Typically not yet practical above 1GHz (100nm CMOS)

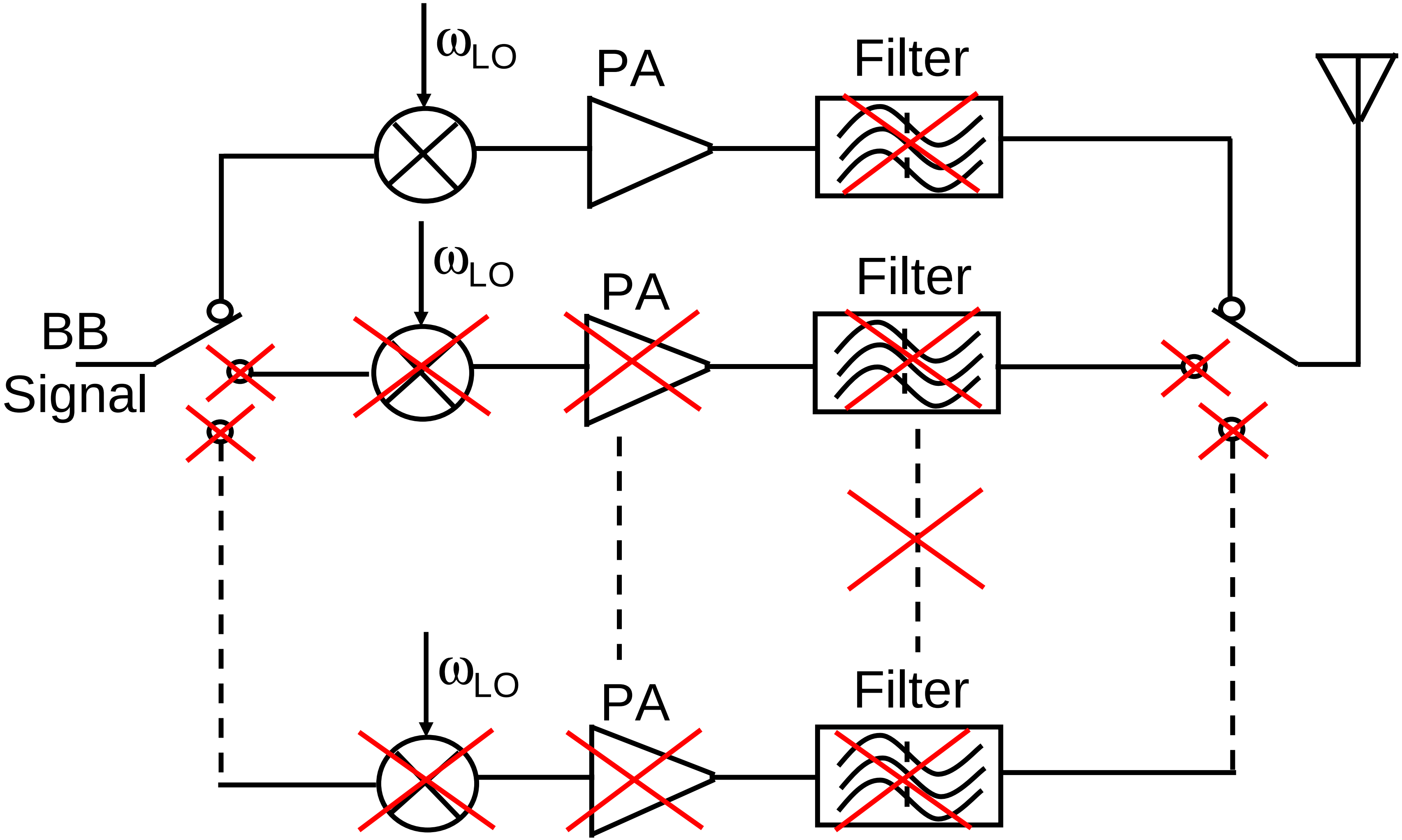
Image: B. Razavi

Polyphase Multipath Technique

Trend: Multi-standard Transmitter Architecture

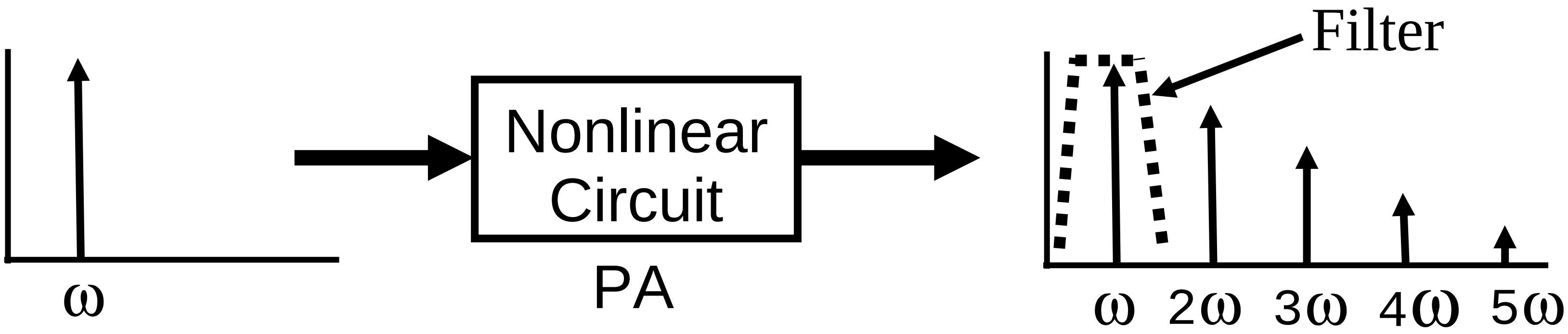


Software Defined Radio Transmitter Dream



Why do we need a *filter?*

To remove unwanted harmonics!



But: dedicated filter for each standard

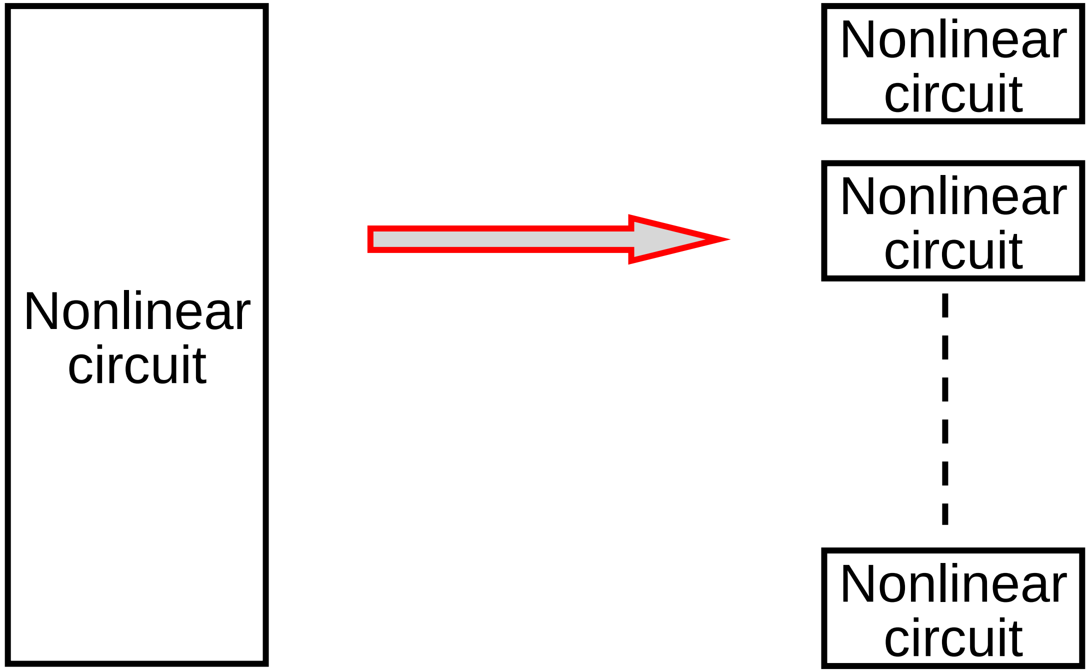
New concept for a flexible solution for software defined radio:

Multi-path Polyphase Technique for Power Upconverters

[Shresta, Mensink, Klumperink, Nauta, ISSCC 2006]

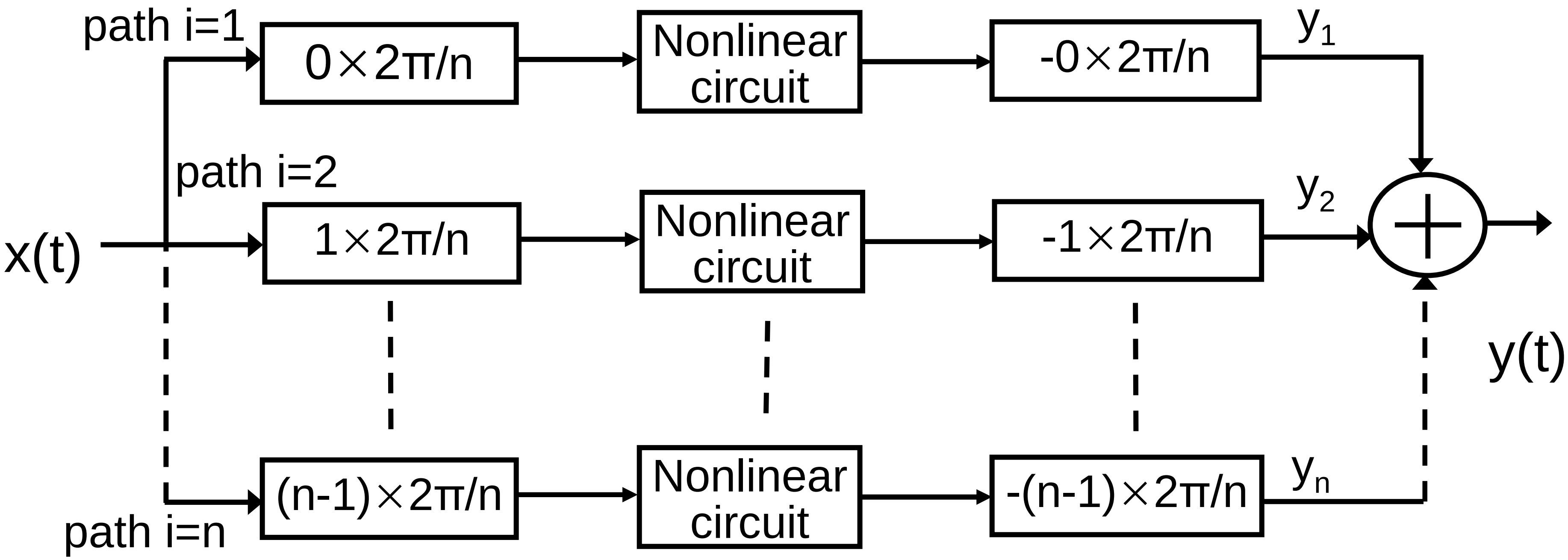
Theory of Polyphase Multipath (1)

Divide the nonlinear circuit into ‘n’ equal smaller pieces



Theory of Polyphase Multipath (2)

Add equal but *opposite* phase shift before and after

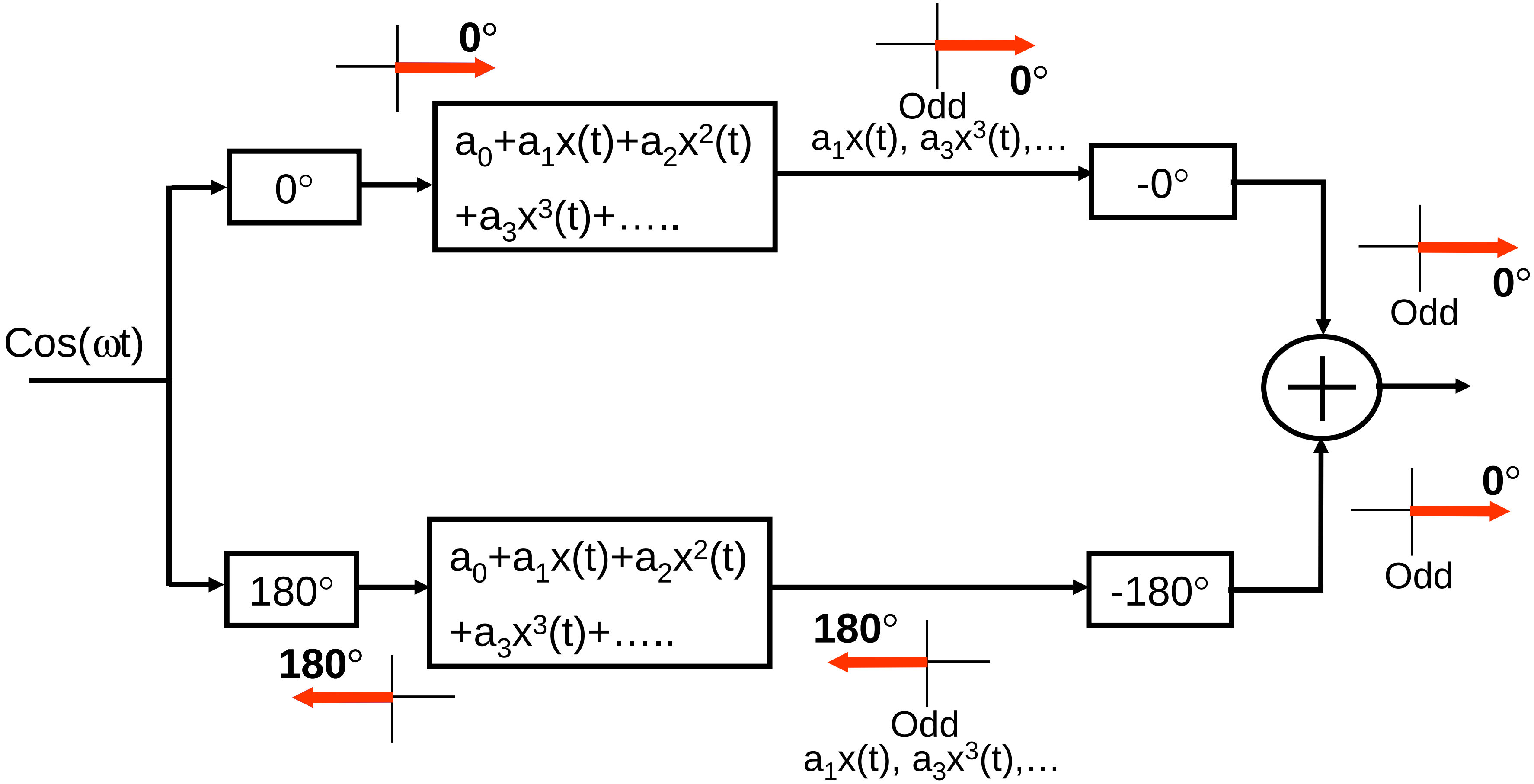


Exploit difference in phase between wanted 1st harmonic and (undesired) nth harmonic:

$$\boxed{\left(e^{j\omega t+\phi}\right)^n = e^{jn\omega t}e^{jn\phi}}$$

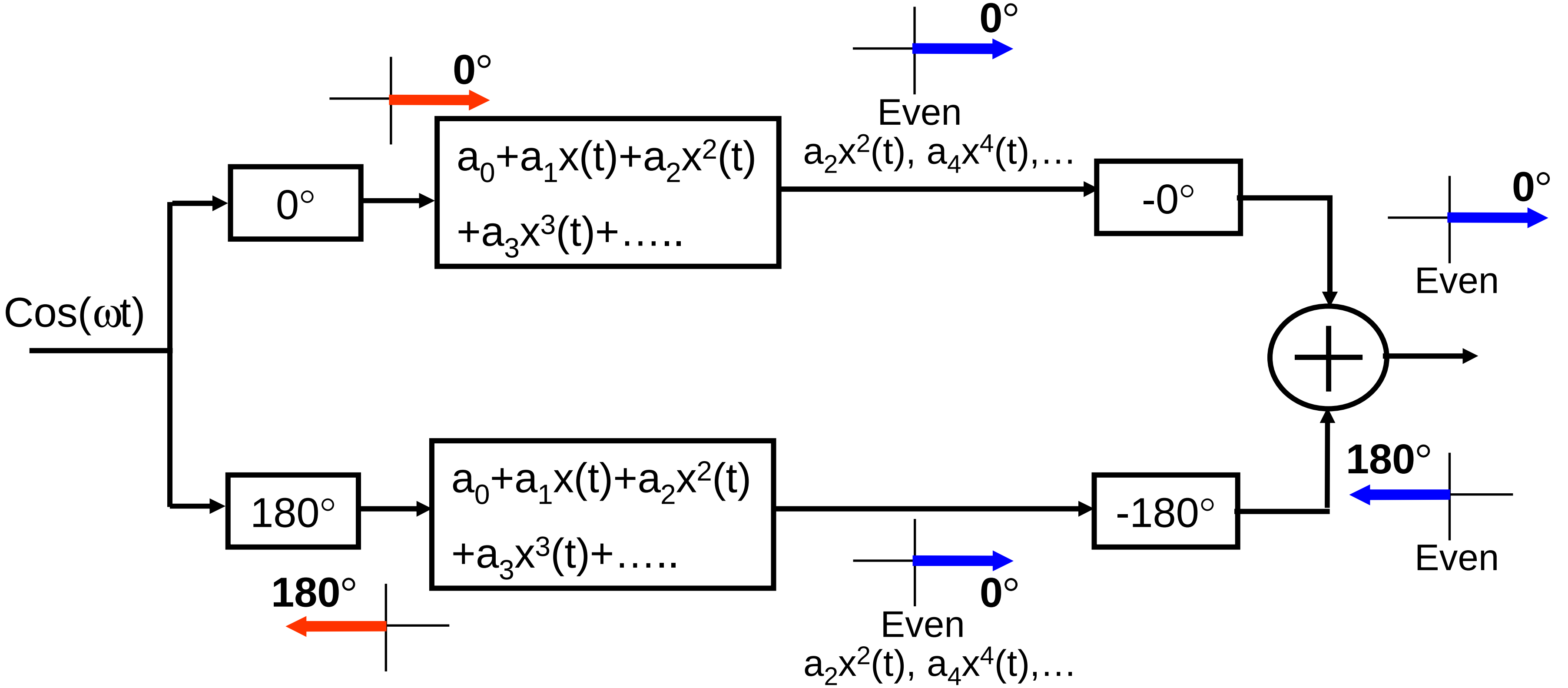
Example 2-Path Circuit: odd terms add in phase

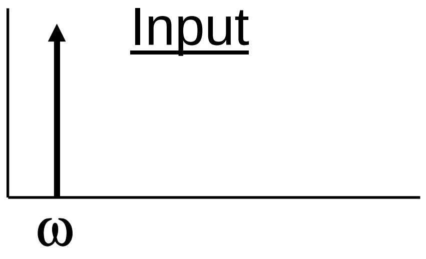
Differential Circuit:



2-Path Circuit: even terms cancel (anti-phase)

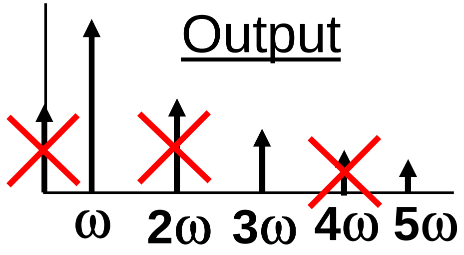
Differential Circuit:



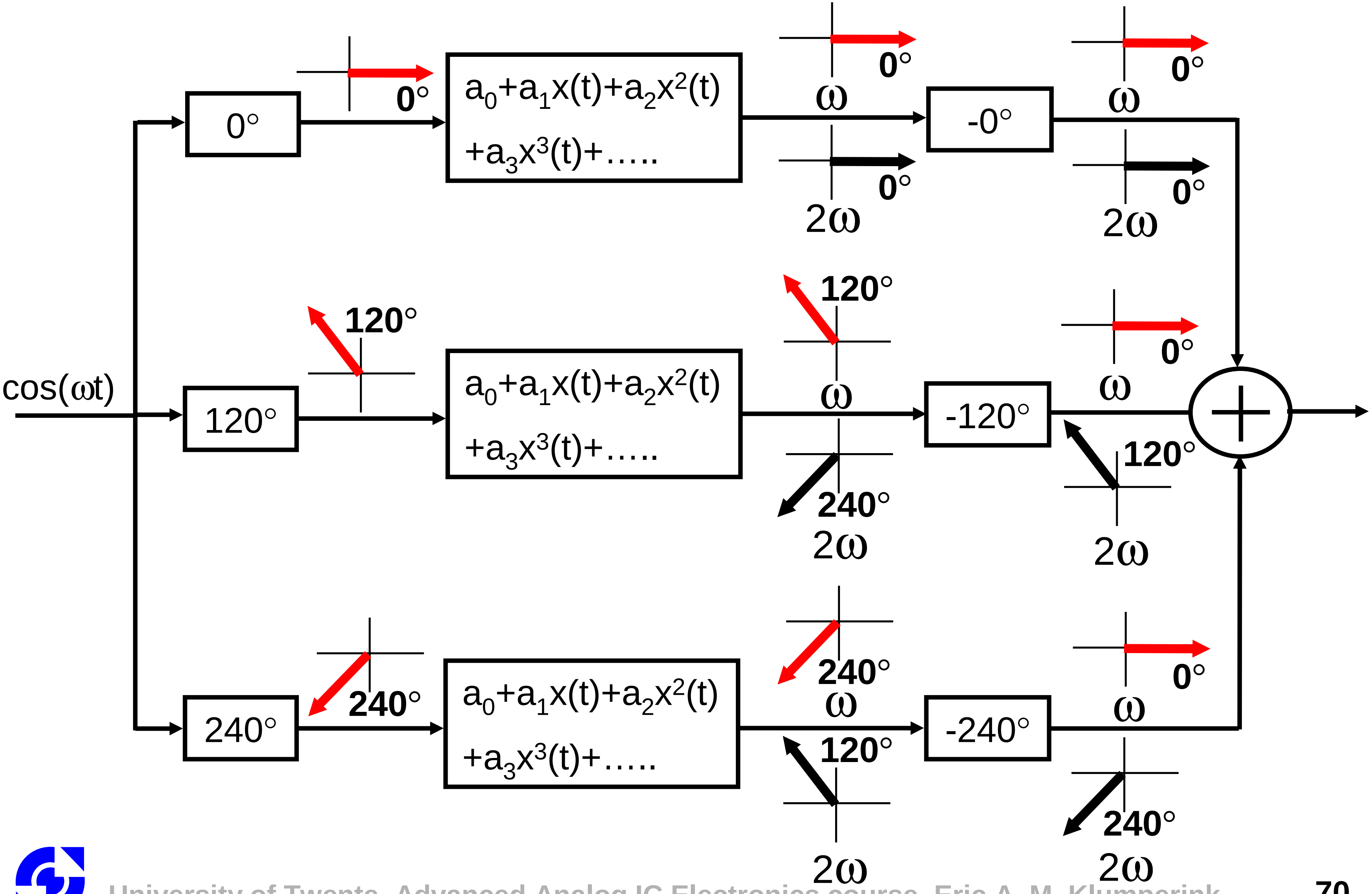


Even order at:

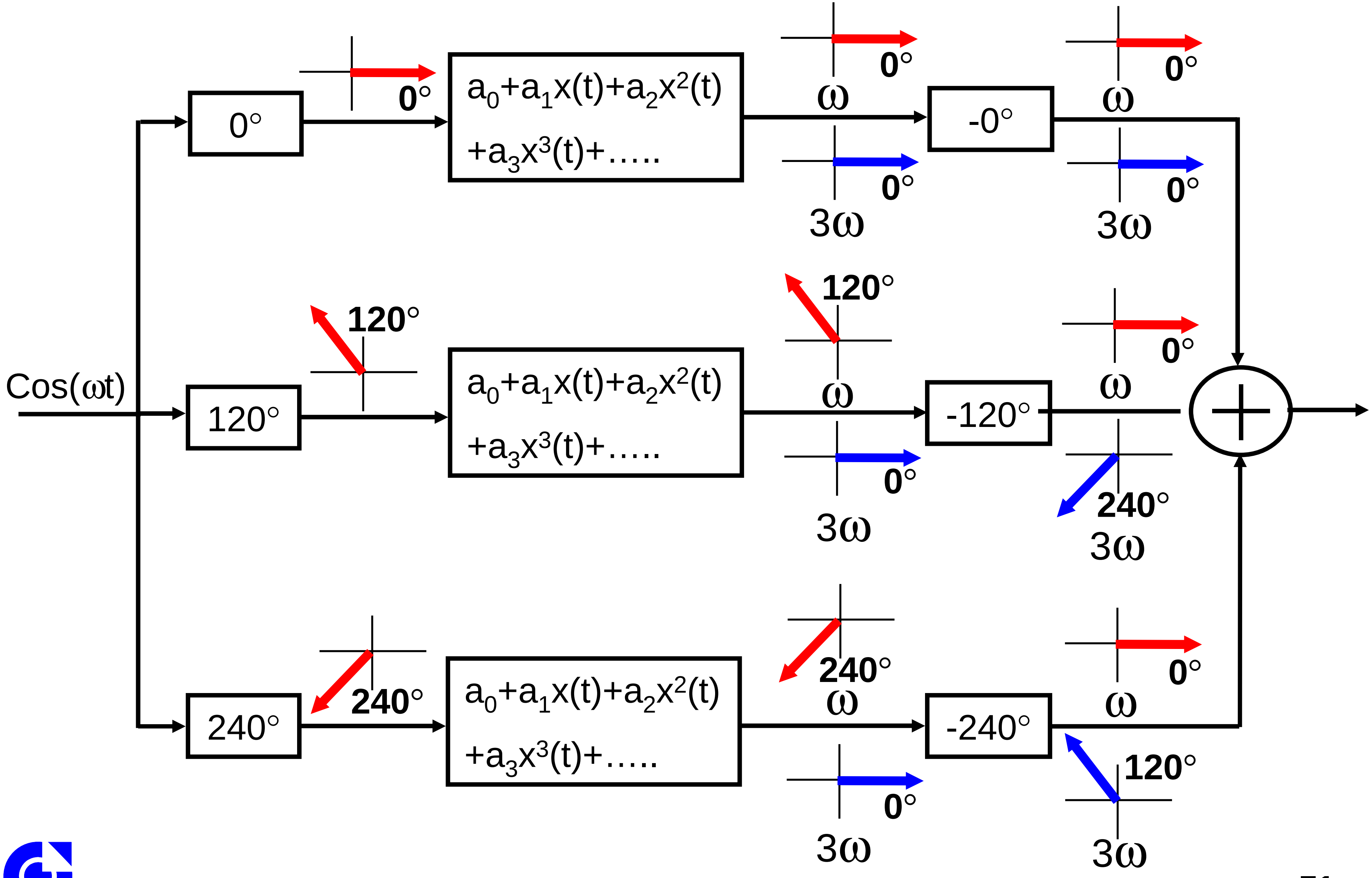
DC, 2ω, 4ω, ..



3-Paths: 2ω terms cancel (doubled phase)

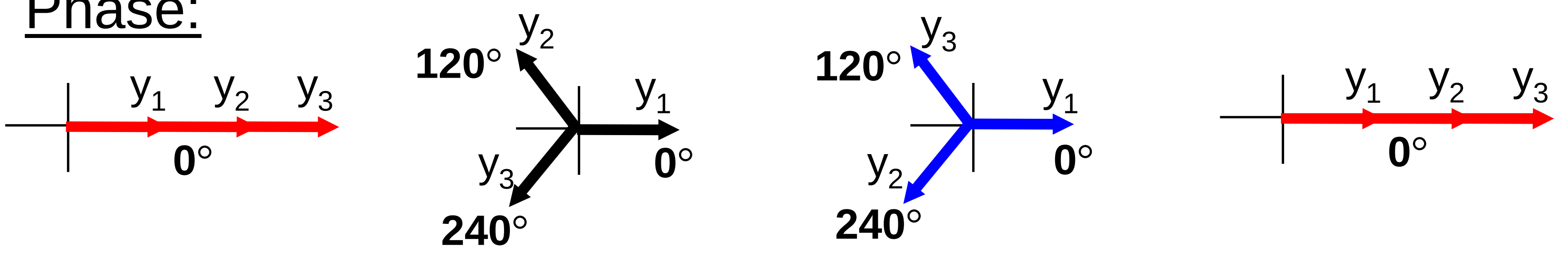


3-Path Circuit: 3ω terms cancel (trippled phase)



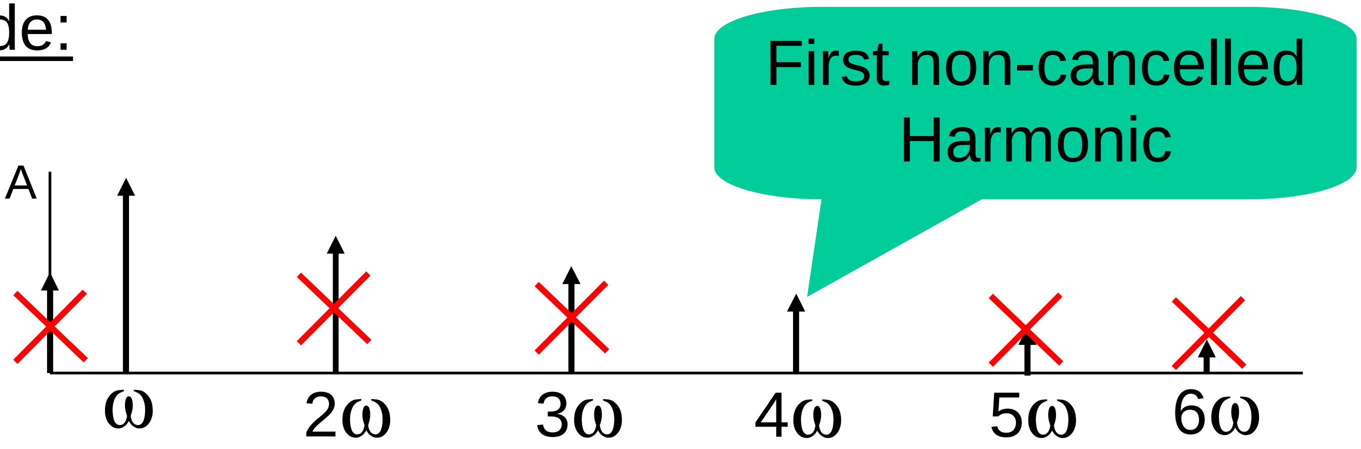
Output: Polyphase 3-Path

Phase:



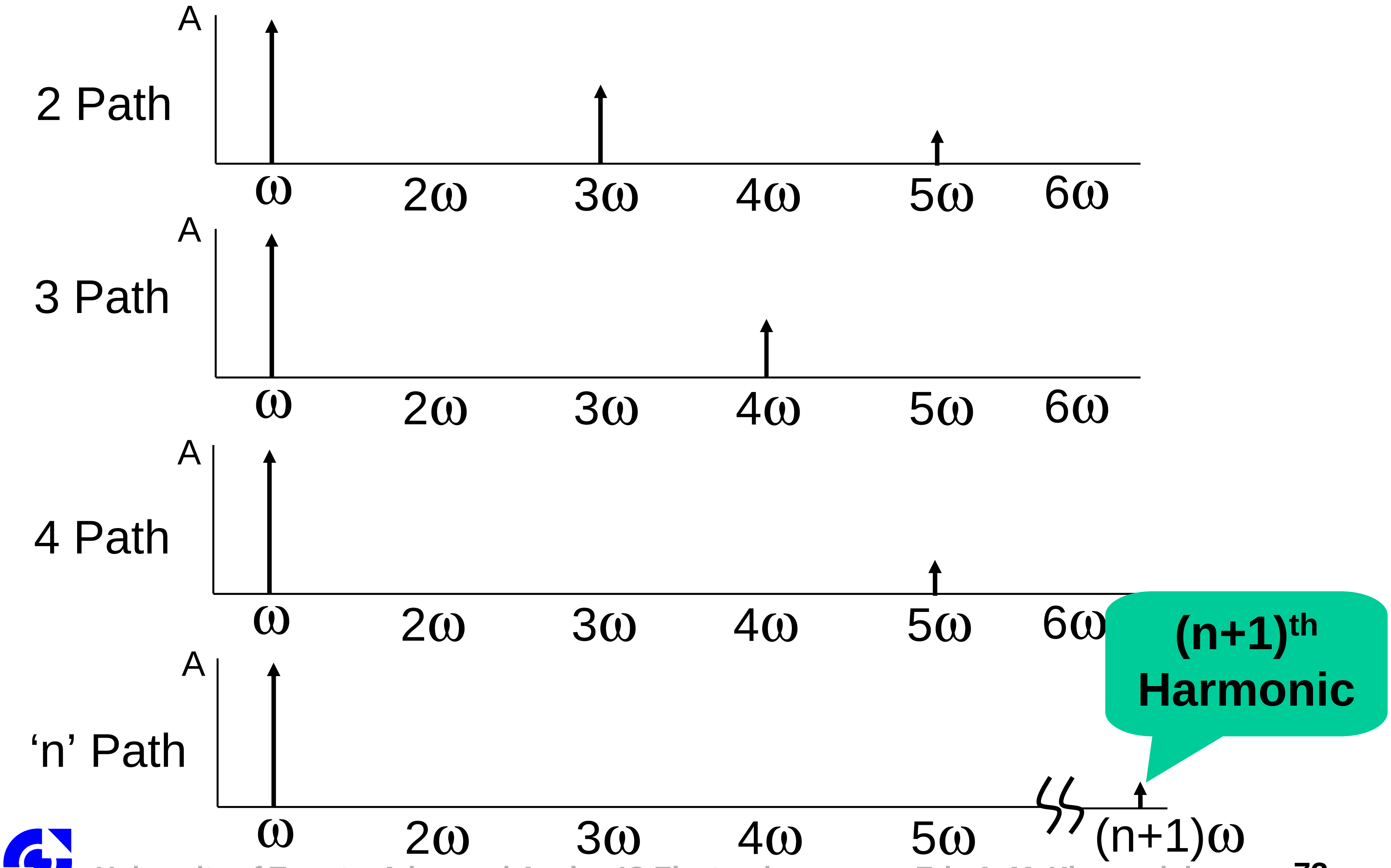
Fundamental **2nd Harmonic** **3rd Harmonic** **4th Harmonic**

Magnitude:



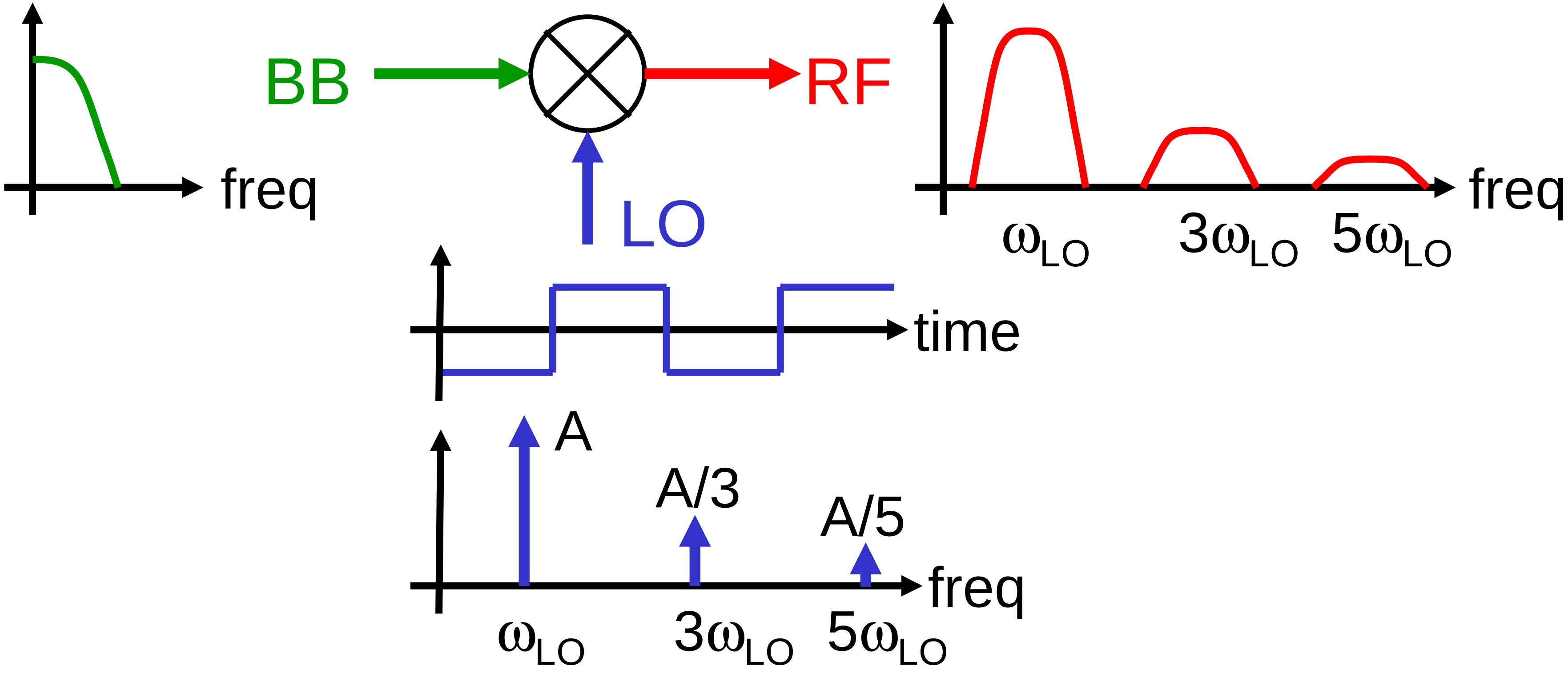
First non-cancelled Harmonic

n paths: first non-cancelled harmonic (n+1)



(n+1)th Harmonic

Also mixer problem with LO-Harmonics



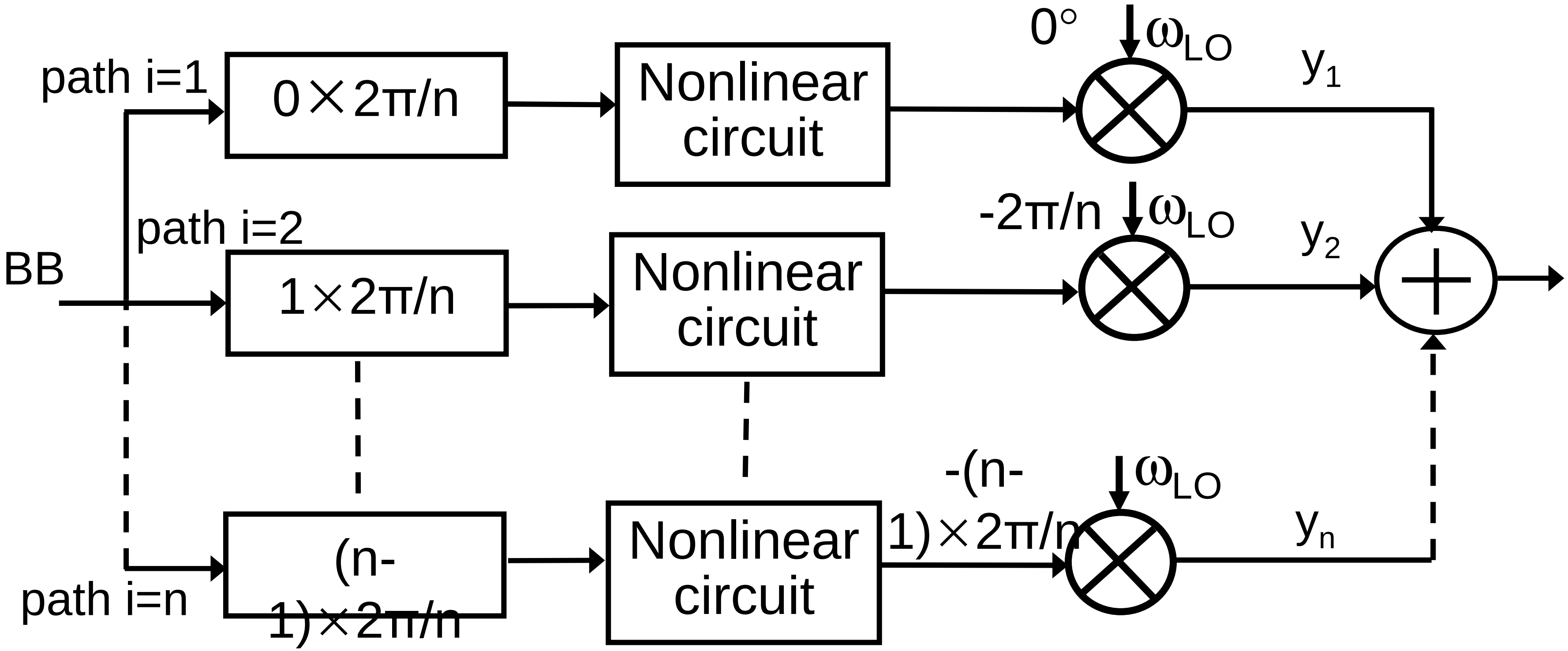
Ideal switching mixer also upconverts to odd harmonics!

“Harmonic Rejection Mixer” wanted!

Polyphase multipath technique also reject LO-harmonics!

Problem: Bandwidth of Phase Shifter

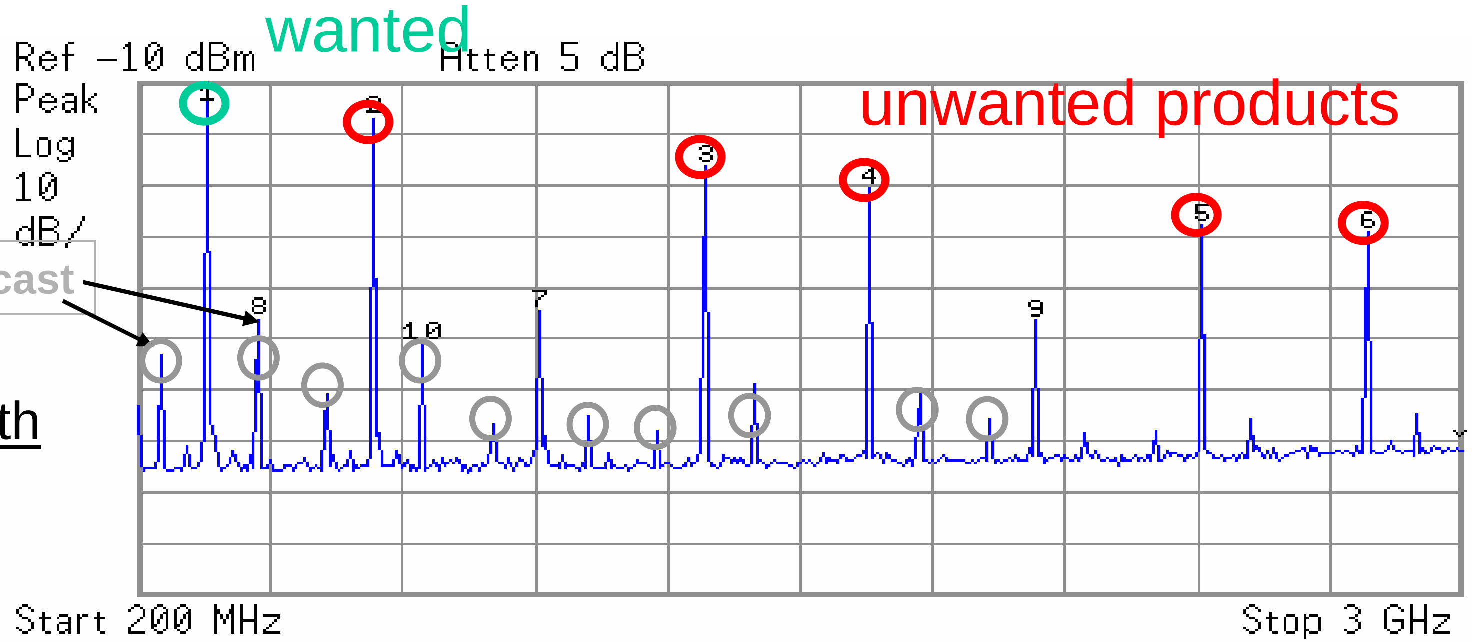
<u>Solution</u>: Mixer (transparent for LO Phase)



Mixer: Wideband band phase shift but also upconversion

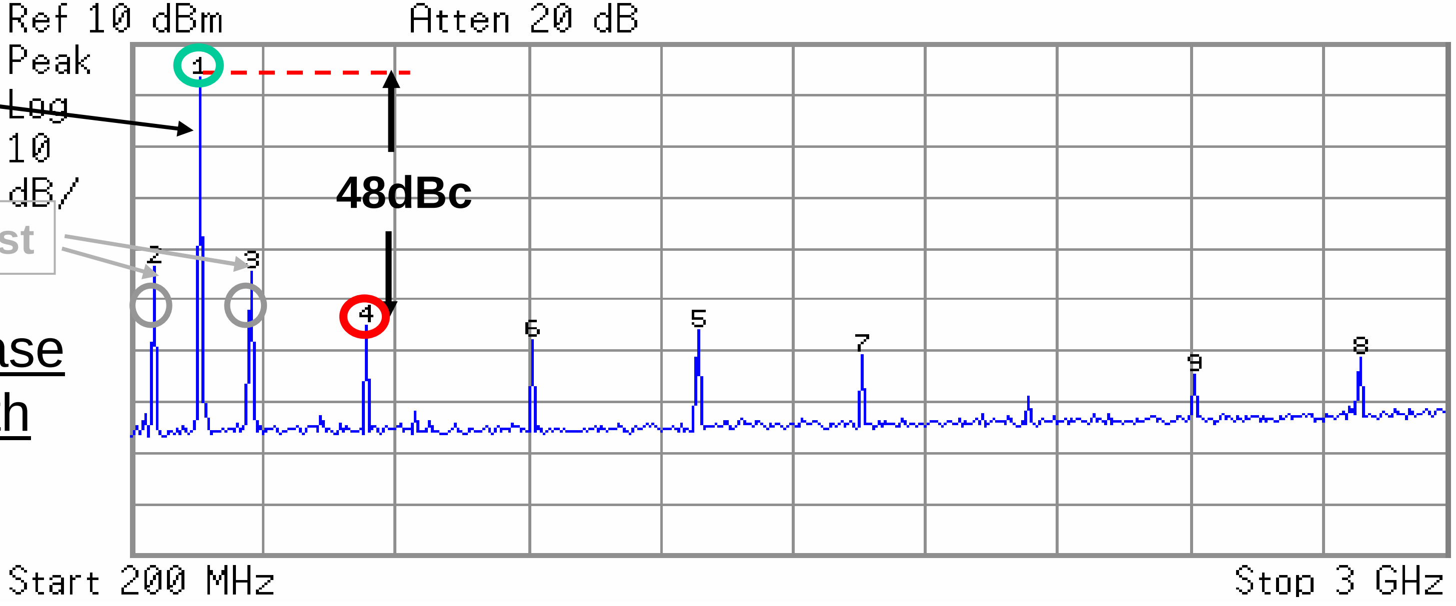
First phase shifters to be implemented in DSP + DAC

Measurement Results



FM broadcast

1-path



$\omega_{LO}+\omega_{BB}$

48dBc

FM broadcast

Polyphase
18-path

Summary (clues to remember)

Choice of TX architecture mainly defined by:

- PA efficiency => constant envelope desired (only FM or PM)
- Spectral efficiency => non-constant envelope signals
- Spectral purity (spectral mask, ACPR requirements)

Key functions: PA, mixer, quadrature generation

Quadrature mixing for (at least) two reasons:

- Orthogonal I/Q modulation (2 data streams, 2 mixers)
- Image rejection (reject sum or difference frequency)

Transmitter Architectures:

- Direct upconversion (but: LO-pulling problem)
- Offset-upconversion or Two-step architecture to avoid it
- Phase modulation via Offset-PLL modulators

Non-constant envelope PA techniques:

- Predistortion
- Cartesian feedback
- Envelope Elimination and Restoration (EER)

Software Defined Transmitter: Multi-path polyphase

Corresponding Course book pages

Read and study:

- **Chapter 7**
  (tuning system)

- **Papers:**

(**Look-up with IEEExplore**)

- B. Razavi: Architectures and circuits for RF CMOS receivers.
- B. Razavi: RF transmitters circuits and architectures.

Circuit Design for RF Transceivers

D. Leenaerts,
J. Van der Tang
C. Vaucher

Kluwer

ISBN 0-7923-7551-3

Useful Equations

$$\exp(j\omega t) = \cos(\omega t) + j\sin(\omega t)$$

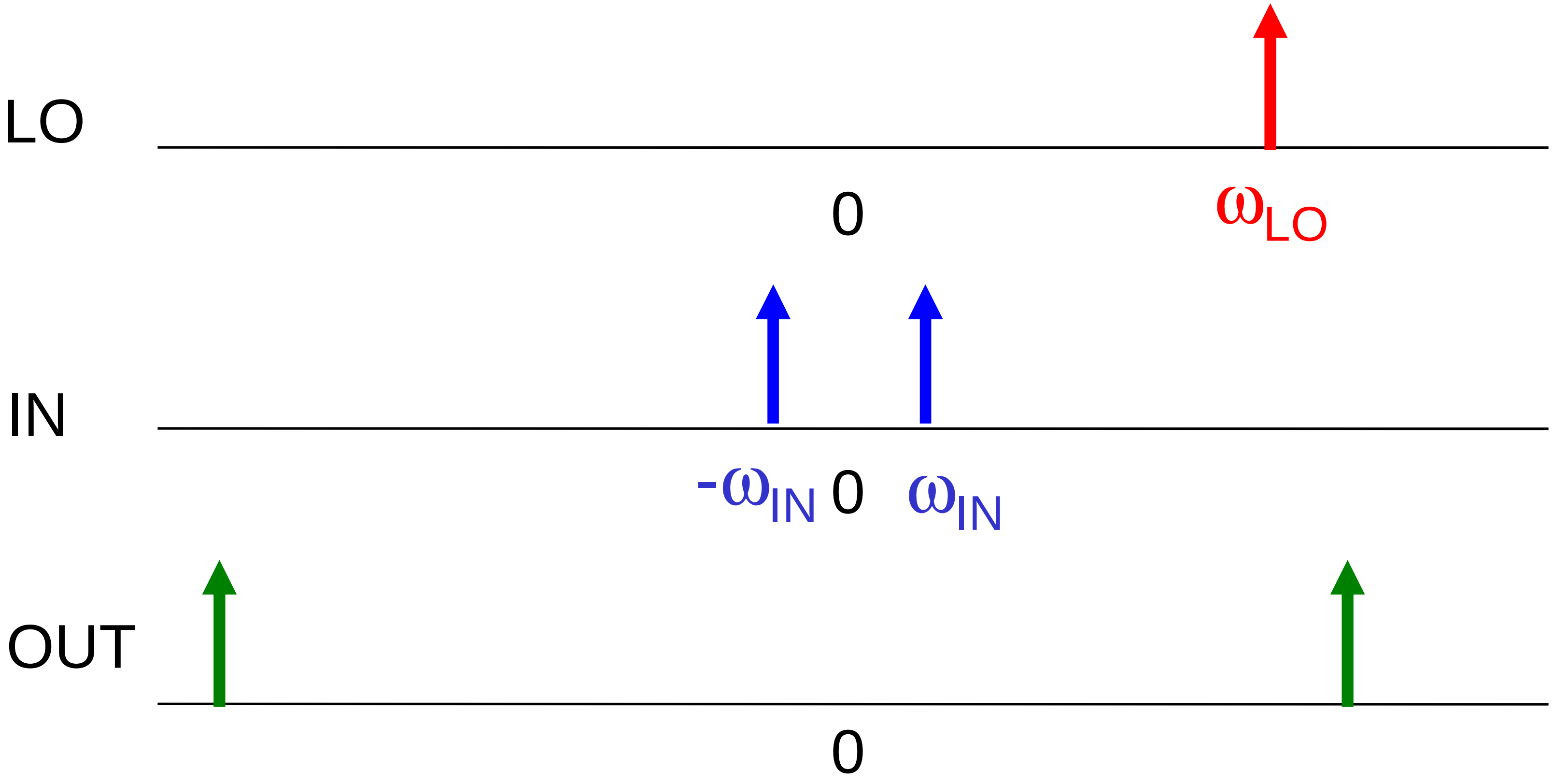
$$\cos(\omega t) = \frac{\exp(j\omega t) + \exp(-j\omega t)}{2}$$

$$\sin(\omega t) = -j\,\frac{\exp(j\omega t) - \exp(-j\omega t)}{2}$$

Single sideband mixer: multiply with ONLY exp(jωt) or exp(-jωt) (not a “mix of them”)

Desired: "One-Sided LO"

Multiply in t-domain ⇔ Convolution f-domain



Complex Spectral View of Mixing

Multiply in t-domain ⇔ Convolution f-domain