EE230-02 RFIC II
Fall 2018

Lecture 5: Receiver Architecture

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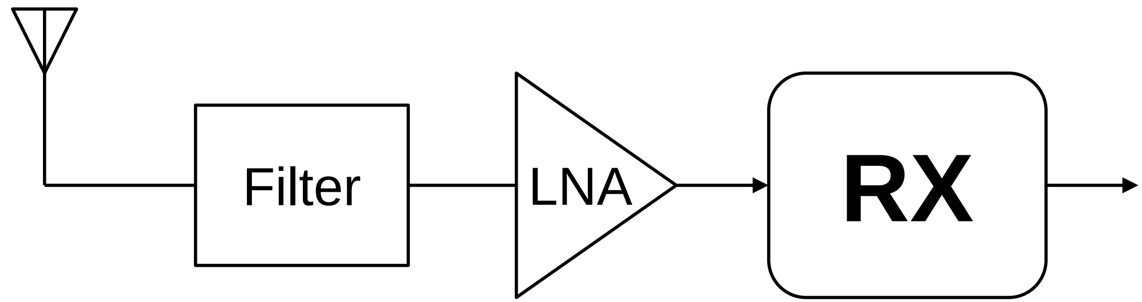
ENG-259

Receiver Architecture Types



- Heterodyne
- Super-Heterodyne
- Homodyne (Direct conversion or Zero IF)

NB-IoT

Palma Ceia SemiDesign Announces Silicon-Proven LTE NB-IOT Transceiver for IoT Applications

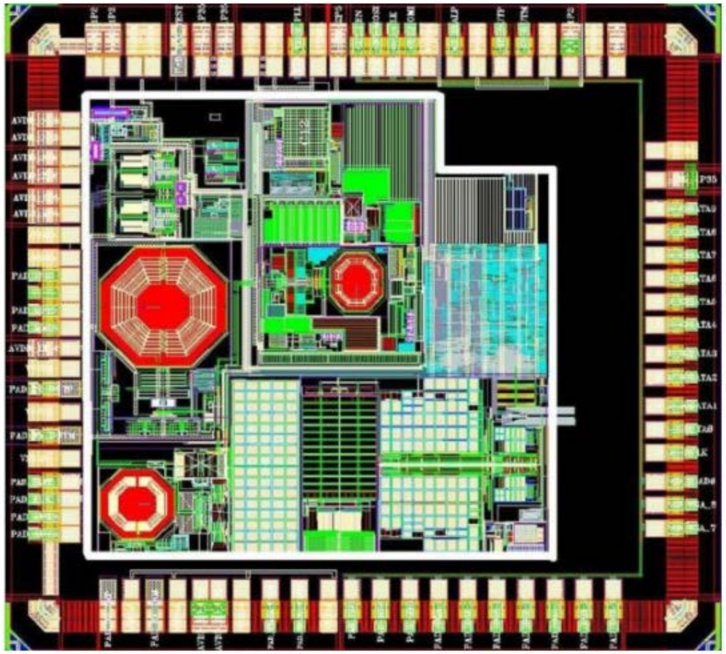
SANTA CLARA, Calif., Sept. 4, 2018 — Palma Ceia SemiDesignTM (PCS), a provider of next-generation wireless connectivity solutions, today announced a silicon-proven LTE NB-IOT transceiver for the Internet of Things (IoT) and Machine-to-Machine (M2M) applications. The transceiver performance conforms to the LTE NB-IOT specification, part of Release 13 from 3GPP. Release 13 defines two cellular standards, LTE NB1 (Narrowband) and LTE M (eMTC-enhanced Machine Type Communications), for Low Power Wide Area (LPWA) applications that connect large numbers of sensor-type devices. (An enhancement for Release 14 providing a dual-band capability will be available shortly.) Verizon, ATT, and China Telecom, among others, have announced support for some of these new capabilities for IoT.

“Completing this low-power, highly linear integrated transceiver establishes Palma Ceia as the only wireless IP and chip provider offering both an LTE NB-IOT (LTE NB1) and WiFi (HaLow-802.11ah) transceiver solution for IoT applications,” said James E. Flowers, co-founder & chief operating officer of Palma Ceia. “This transceiver, verified for TSMC’s 40LP process node, is a standard CMOS implementation designed for SoC integration and chip production. It includes data converters on board for a complete digital interface.”

Features of the PCS integrated transceiver include:

- Direct conversion receiver with a noise figure of less than 2.5 dB
- Highly linear architecture offering operating margin exceeding 3GPP linearity requirements
- Self-contained calibration and correction schemes for better performance and high yield
- Fully automated DC offset correction and I/Q calibration scheme
- Total RX current of 15mA and TX current of 22mA at max power
- Targeted 200kHz implementation offers lower power versus LTE-M1 at 1.4MHz

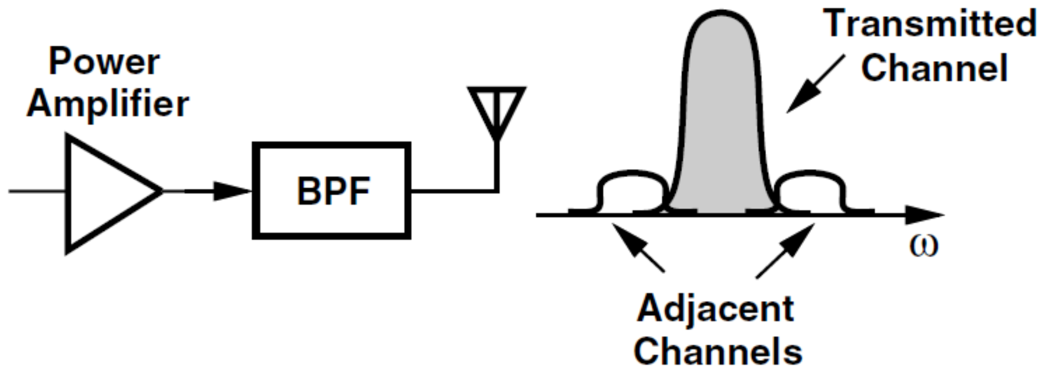
NB-IoT

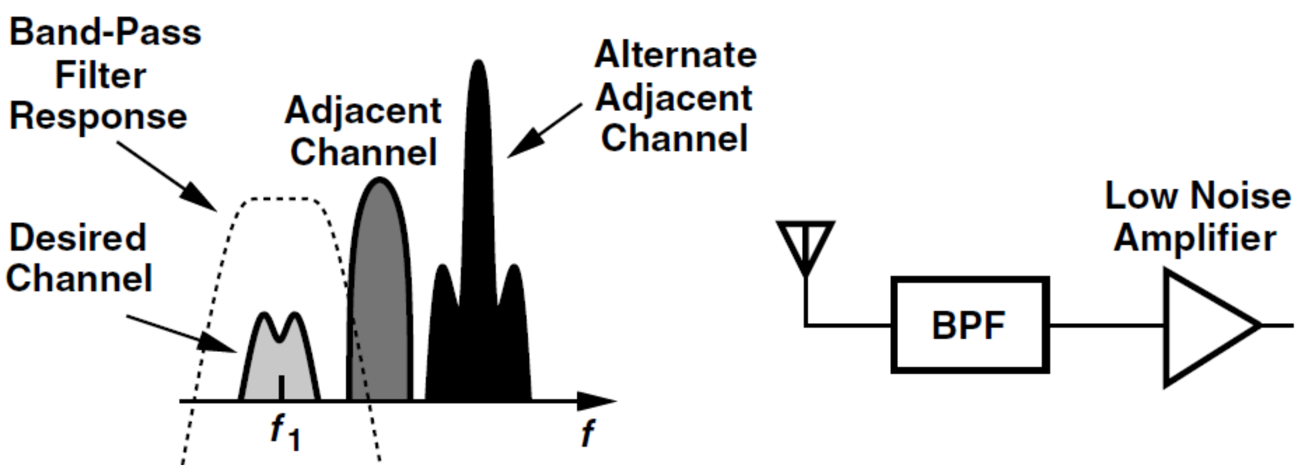


Operating Frequency	703-960 MHz
Supported Bandwidth	200 kHz
NF	<3 dB
IIP3	> -17 dBm
Max Signal	-10 dBm

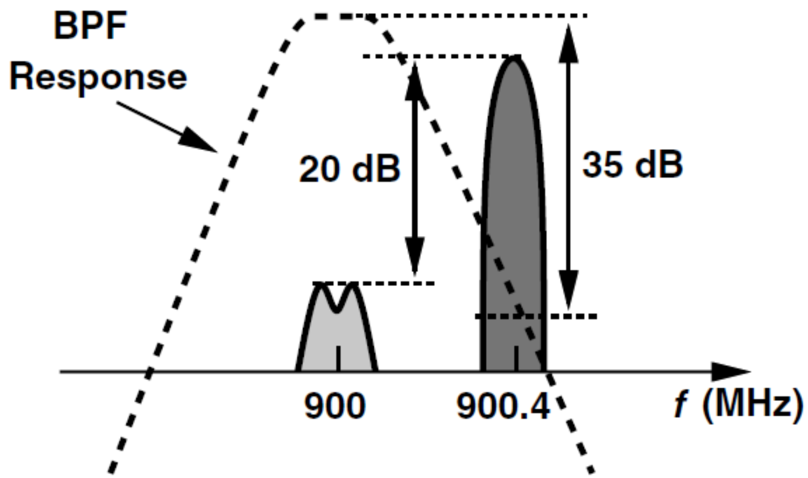
Palma Ceia SemiDesign offers low power, 3GPP Release 13 NB-IOT (LTE Cat NB1) transceiver. The transceiver is built to comply with the Release 13 standard from 3GPP. The NB-IOT transceiver chip is single mode specifically for the bandwidth per channel and modulation requirements for NB1 and as such provides optimal power for the performance required.

Transceiver Front-End



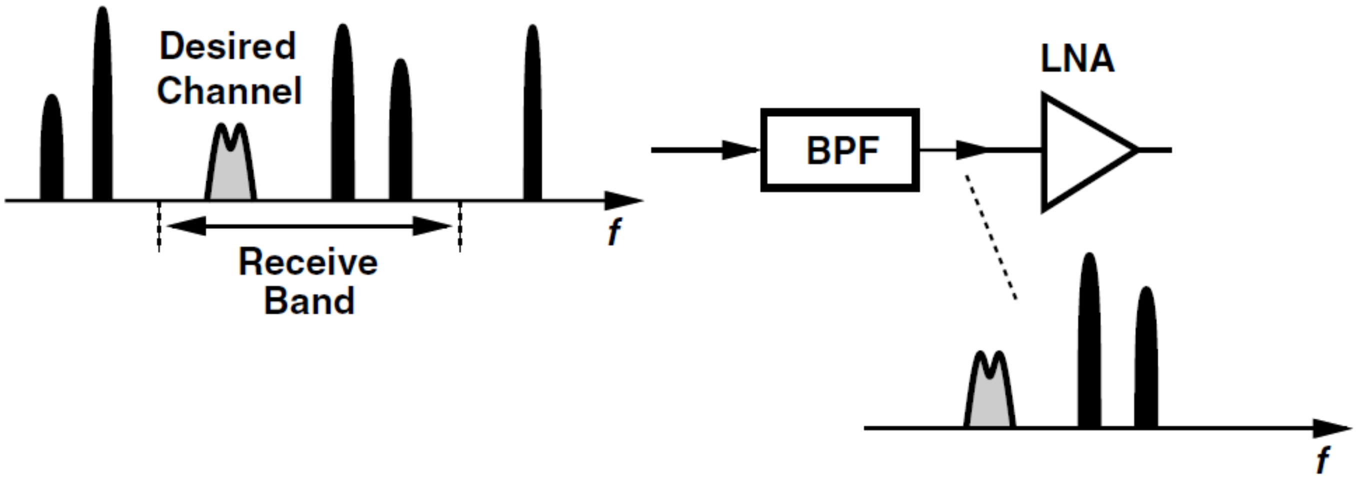


Band Pass Filter



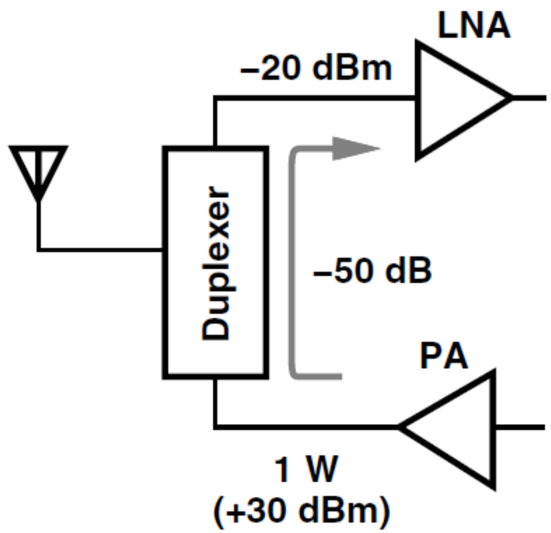
- First, the filter must provide a very high *Q*
- Second, the filter would need a variable, yet precise center frequency

Band Selection Filtering



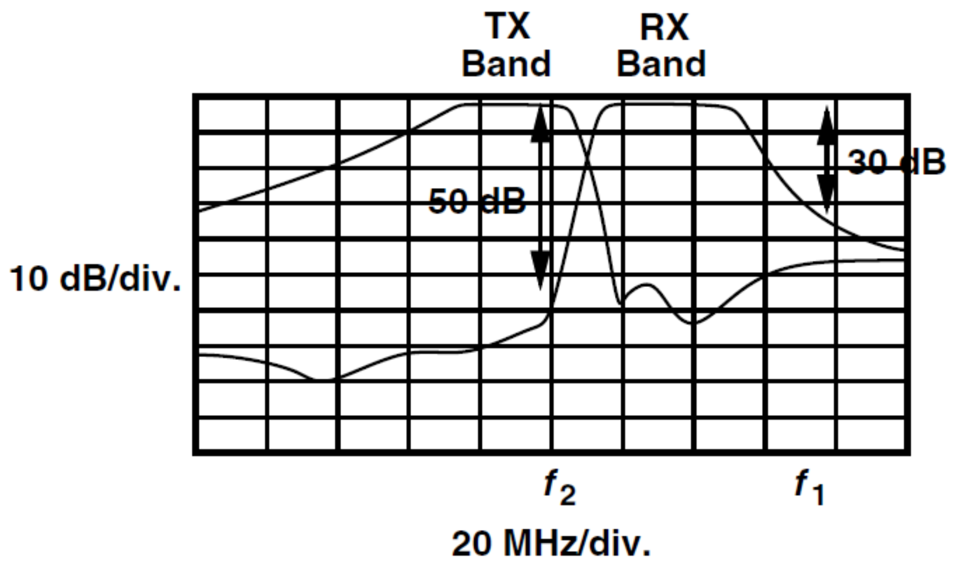
- All of the stages in the receiver chain that precede channel-selection filtering must be sufficiently linear
- Channel selection must be deferred to some other point where center frequency is lower and hence required Q is more reasonable
- Most receiver front ends do incorporate a “band-select” filter

TX–RX Feedthrough



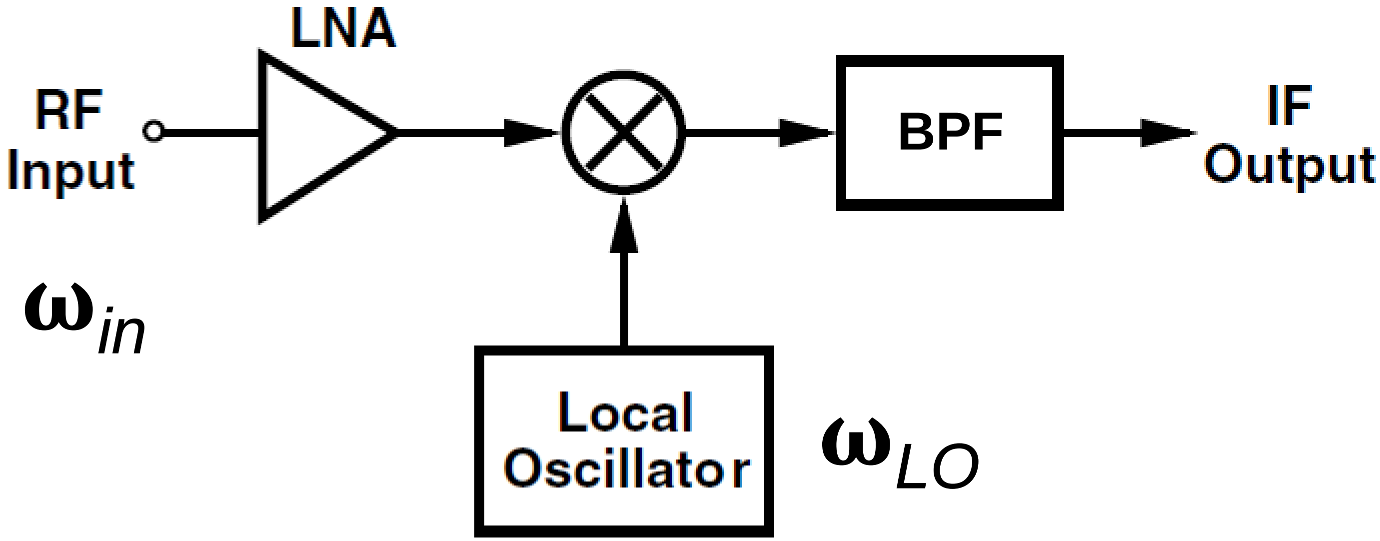
- In full-duplex standards, the TX and the RX operate concurrently.
- With a 1-W TX power, the leakage sensed by LNA can reach -20dBm, dictating a substantially higher RX compression point.

Duplexer Characteristics



- The front-end band-select filter suffers from a trade-off between its selectivity and its in-band loss because the edges of the band-pass frequency response can be sharpened only by increasing the order of the filter.
- Front-end loss directly raises the *NF* of the entire receiver

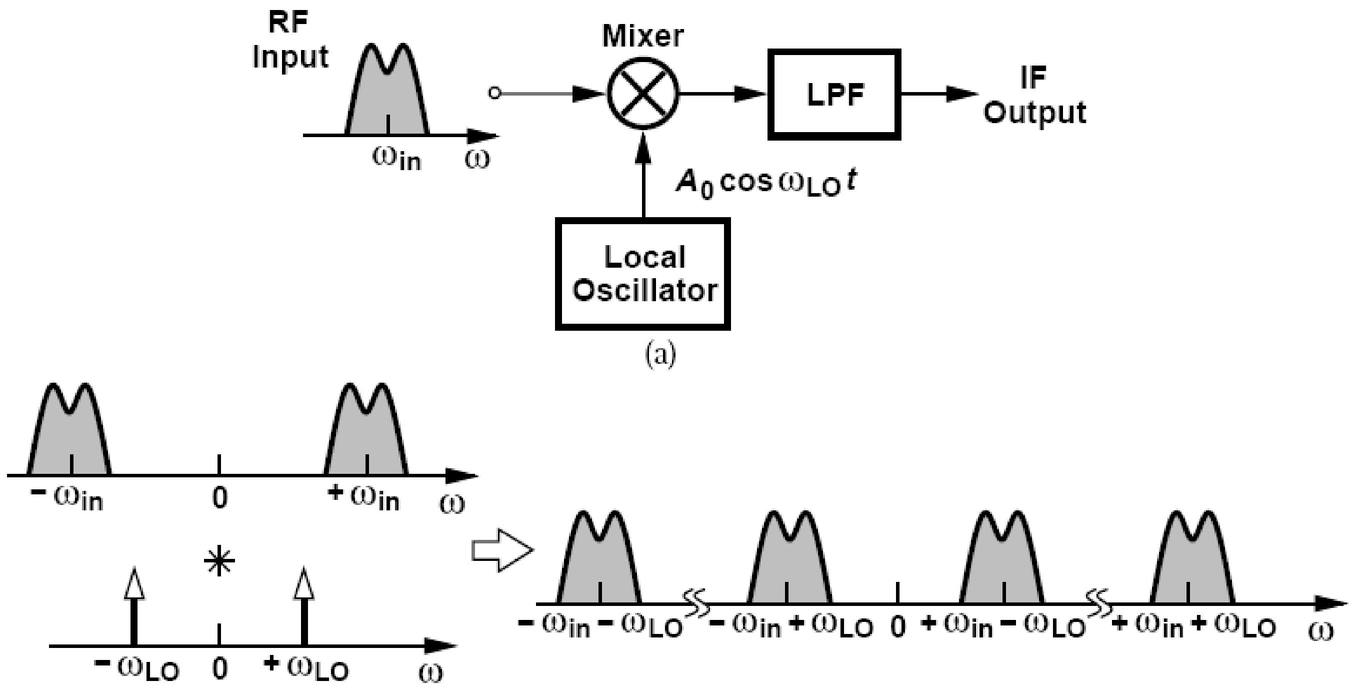
Heterodyne Receiver Architecture



$$\omega_{in} \neq \omega_{LO}$$

$$\omega_{in} - \omega_{LO} = \omega_{IF}$$

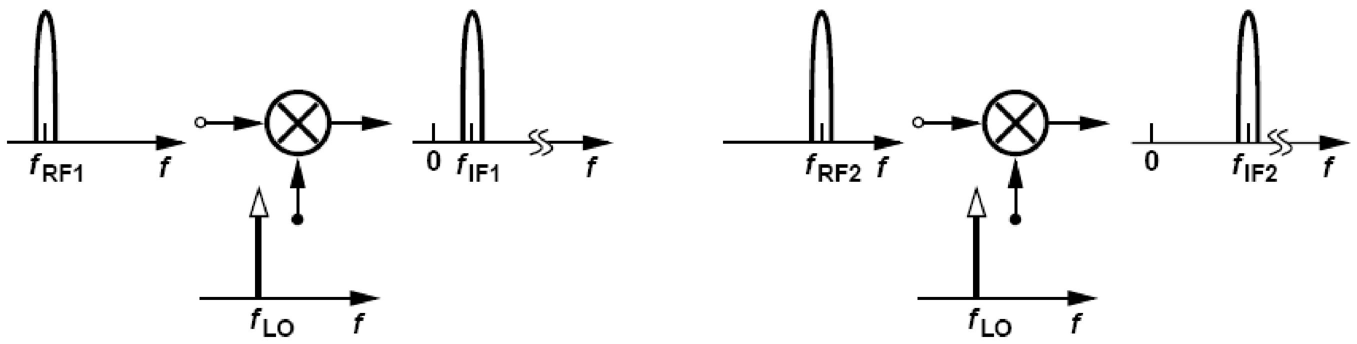
Basic Heterodyne Receiver



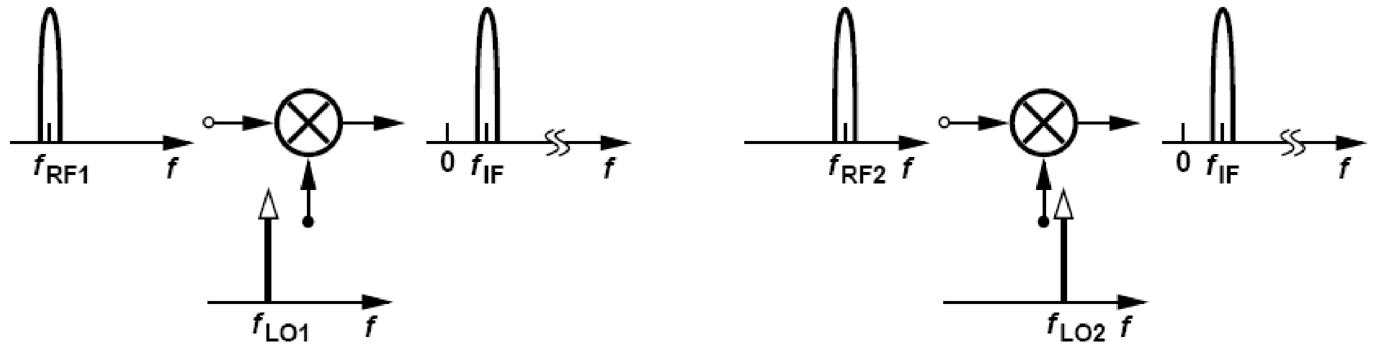
- **"Heterodyne" receivers employ an LO frequency unequal to ω_{in} and hence a nonzero IF**
- **A Mixer performs downconversion.**
- **Due to its high noise, the downconversion mixer is preceded by a low-noise amplifier**

Channel Selection in Heterodyne Receiver

- Constant LO: each RF channel is downconverted to a different IF channel

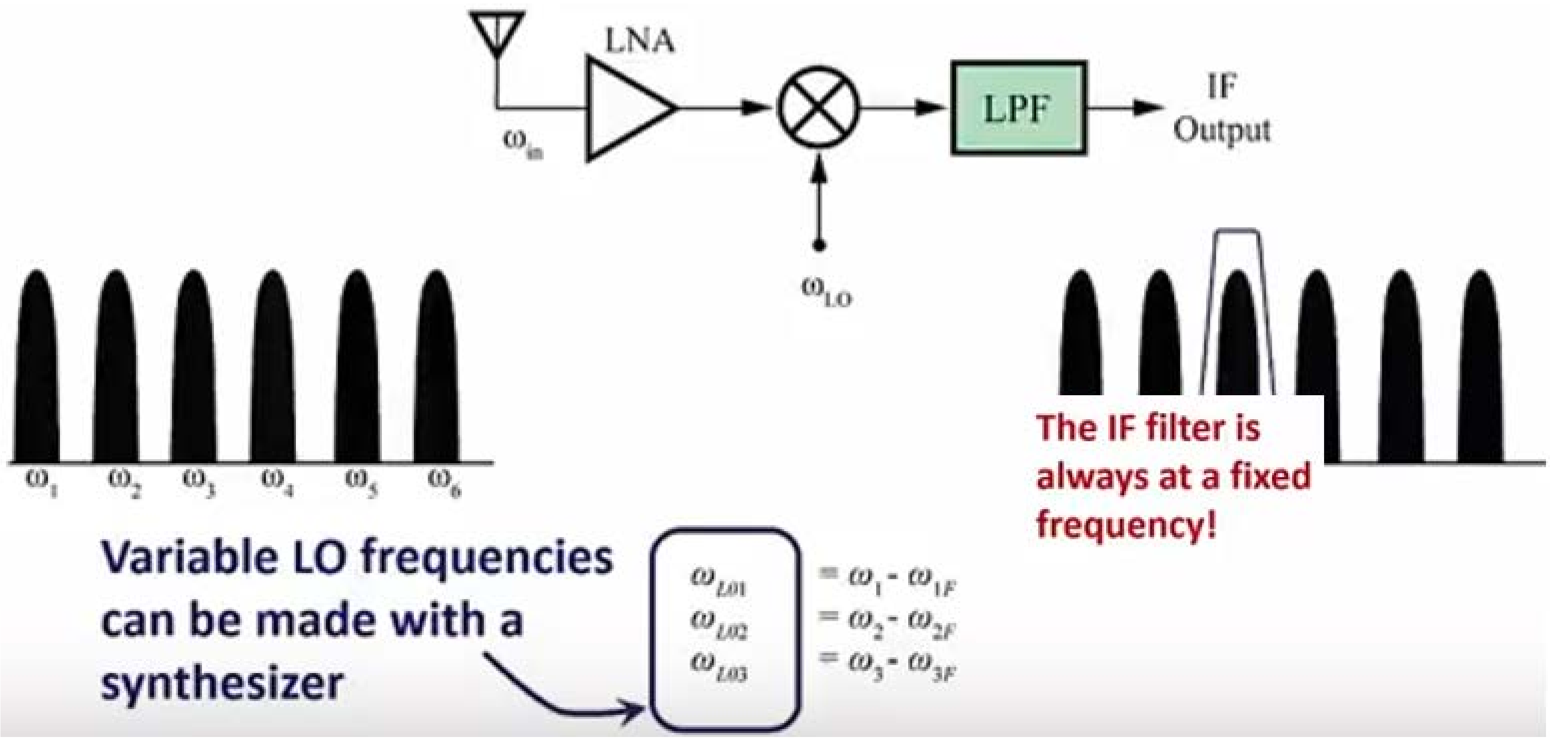


- Constant IF: LO frequency is variable, all RF channels within the band of interest translated to a single value of IF.

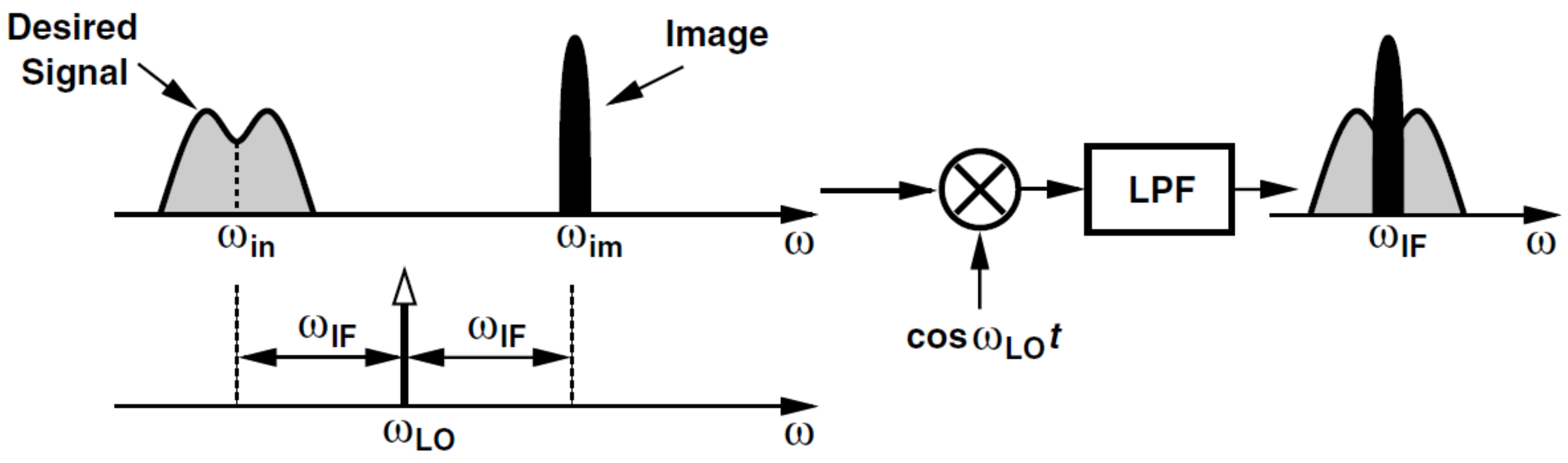


Channel Selection in Heterodyne Receiver

- By changing ω_{LO}, different ω_{in} will be down-converted to the same IF



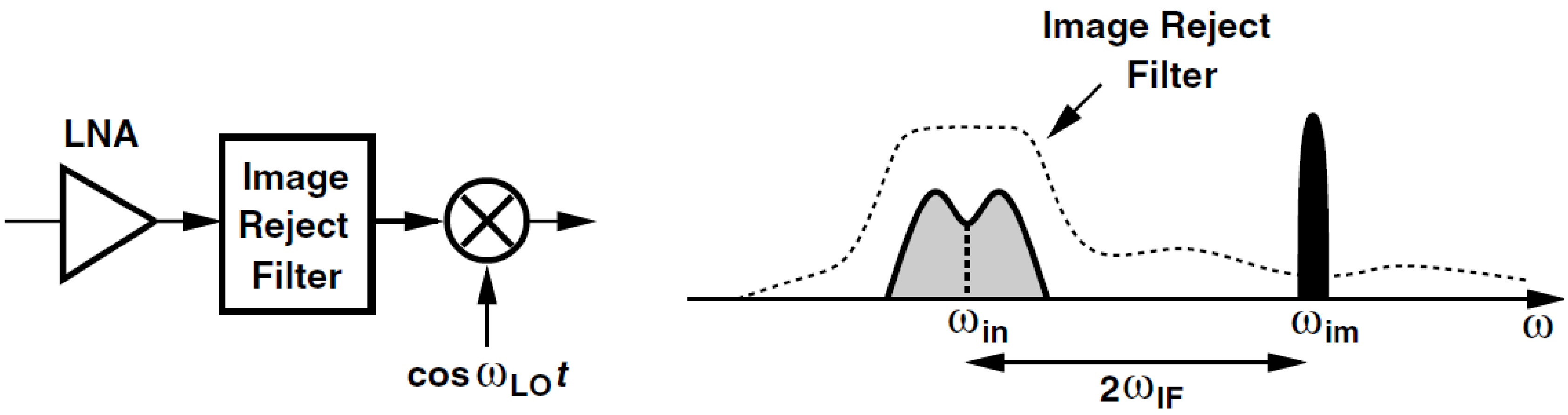
Problem of Image



$$A\cos\omega_{IF}t = A\cos(\omega_{im} - \omega_{LO})t$$
$$= A\cos(\omega_{LO} - \omega_{in})t$$

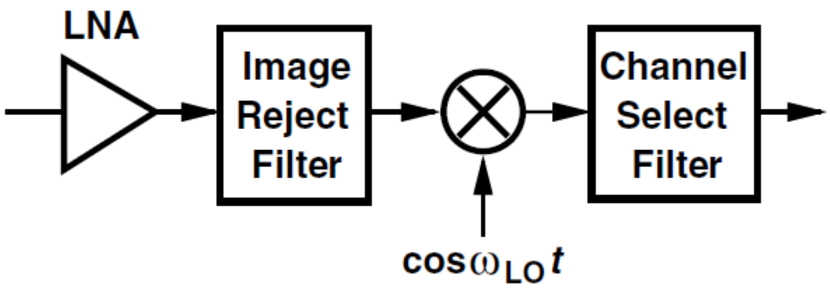
- **Two spectra located symmetrically around ω_{LO} are downconverted to the IF**

Image Reject Filter

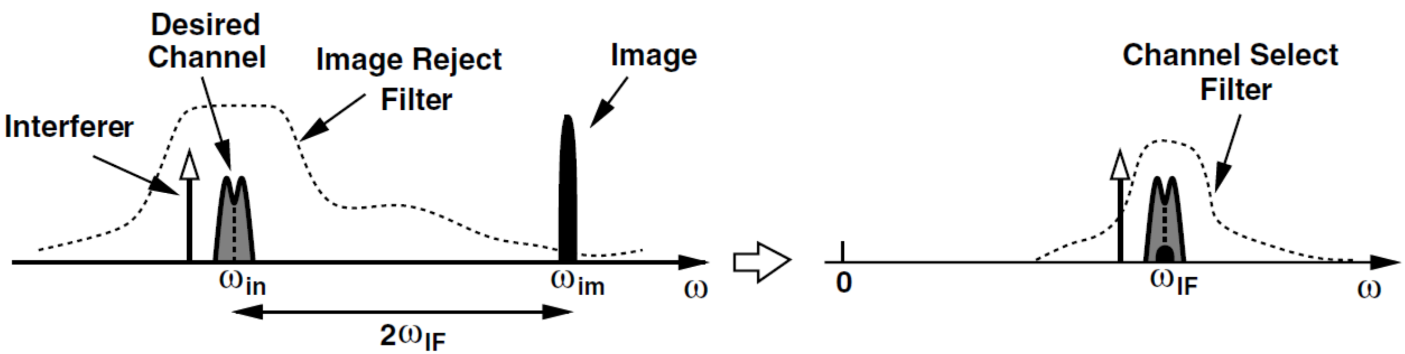


- The most common approach is to precede the mixer with an “image-reject filter”
- A filter with high image rejection typically appears between the LNA and the mixer so that the gain of the LNA lowers the filter’s contribution to the receiver noise figure
- The linearity and selectivity required of the image-reject filter have dictated passive, off-chip implementations.

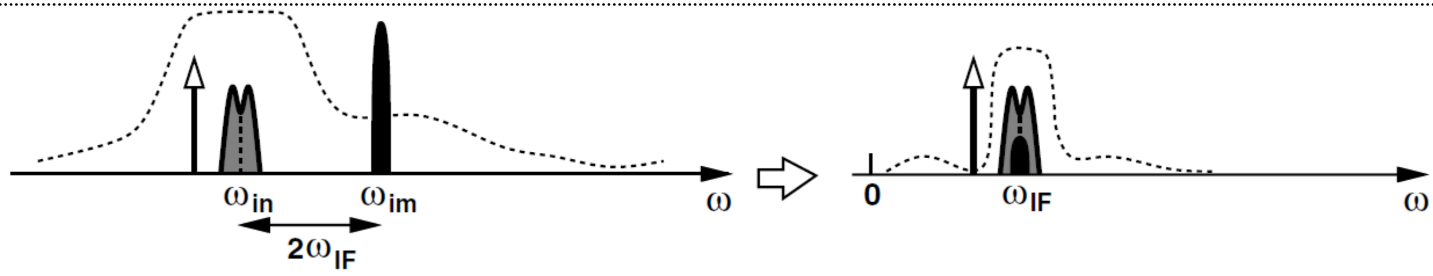
Trade-off between High IF and Low IF



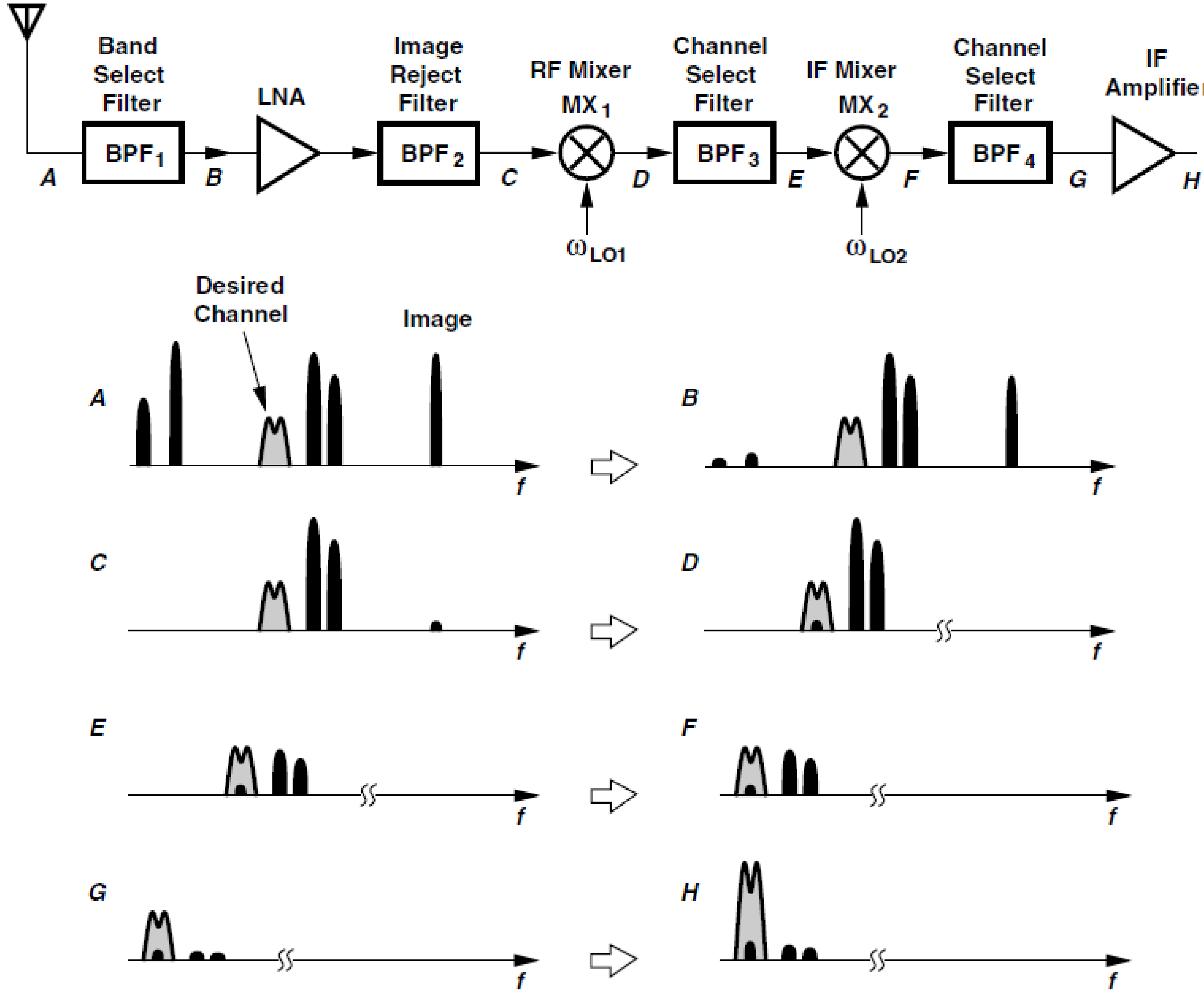
➢ **A high IF allows substantial rejection of the image.**



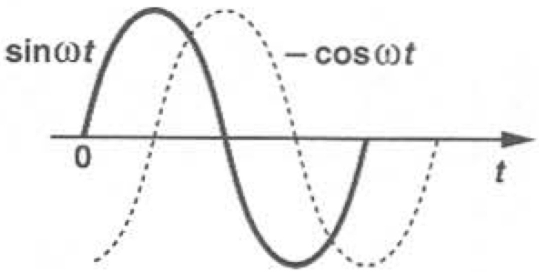
➢ **A low IF helps with the suppression of in-band interferers.**



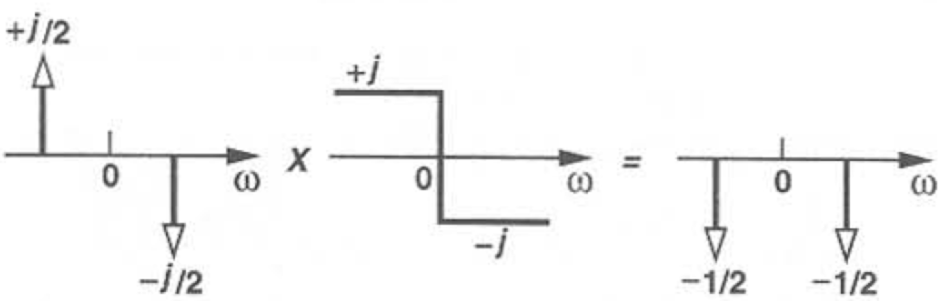
Dual Downconversion (Super Heterodyne)



Shift by 90º

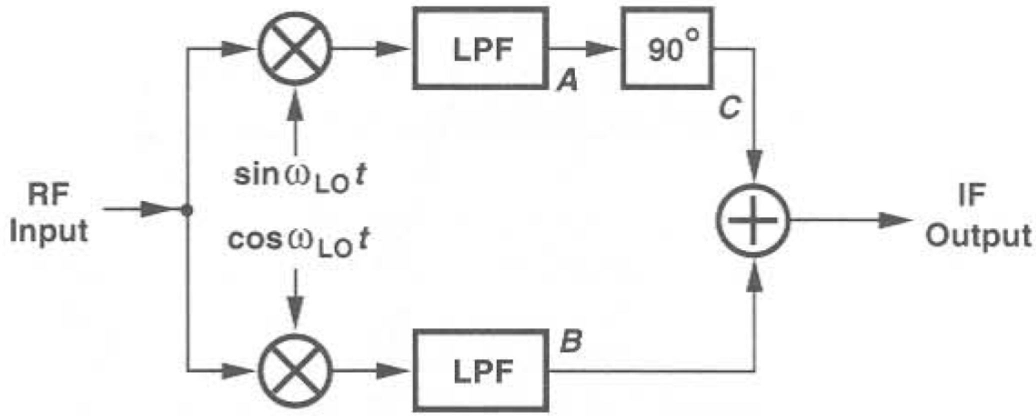


(a)



(b)

Hartley Image-Reject Receiver



$$x(t) = A_{RF}\cos\omega_{RF}t + A_{im}\cos\omega_{im}t$$

$$\begin{aligned} x_A(t) &= \frac{A_{RF}}{2}\sin(\omega_{LO} - \omega_{RF})t + \frac{A_{im}}{2}\sin(\omega_{LO} - \omega_{im})t \\ &= -\frac{A_{RF}}{2}\sin(\omega_{RF} - \omega_{LO})t + \frac{A_{im}}{2}\sin(\omega_{LO} - \omega_{im})t \end{aligned}$$

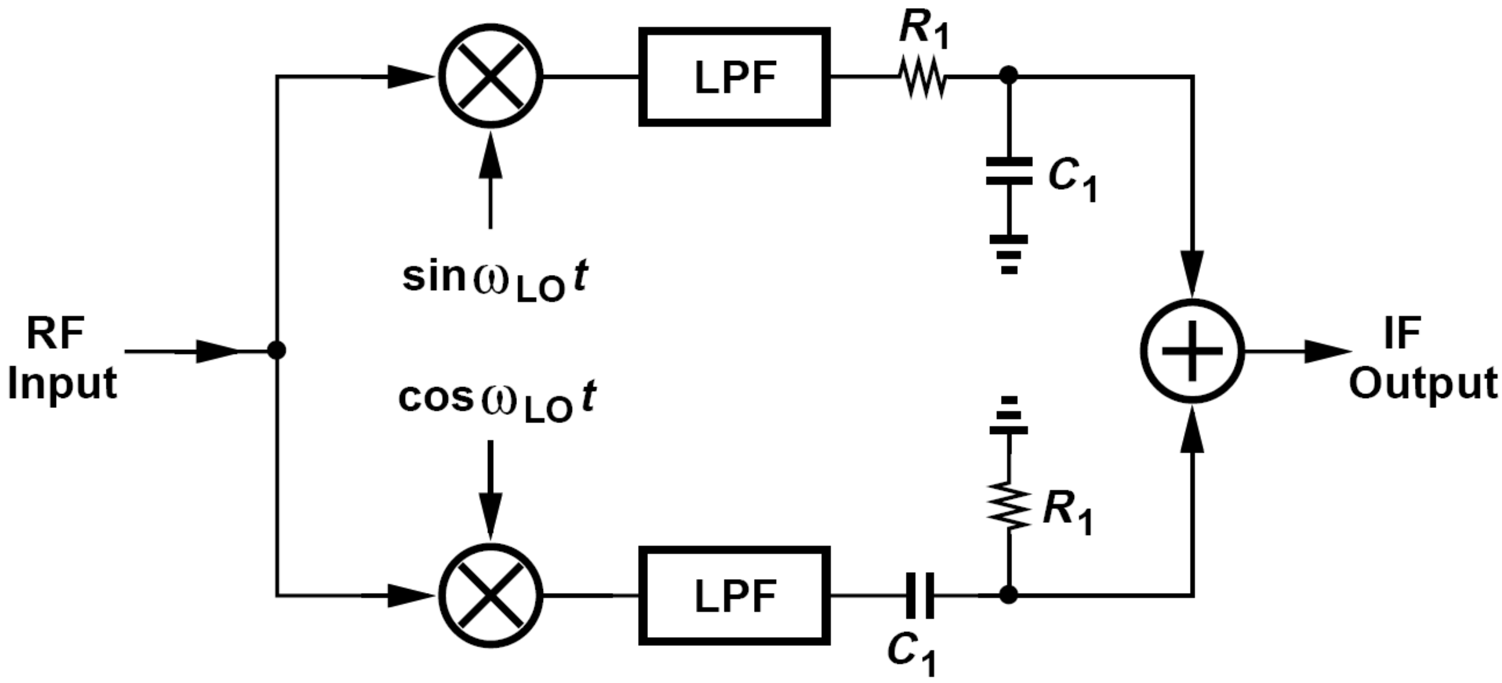
$$x_C(t) = +\frac{A_{RF}}{2}\cos(\omega_{RF} - \omega_{LO})t - \frac{A_{im}}{2}\cos(\omega_{LO} - \omega_{im})t$$

$$x_B(t) = \frac{A_{RF}}{2}\cos(\omega_{LO} - \omega_{RF})t + \frac{A_{im}}{2}\cos(\omega_{LO} - \omega_{im})t$$

$$\oplus \longrightarrow A_{RF}\cos(\omega_{LO} - \omega_{RF})t$$

Implementation of 90º in Hartley Receiver

The 90° phase shift depicted before is typically realized as a +45° shift in one path and -45° shift in the other.



- **This is because it is difficult to shift a single signal by 90° while circuit components vary with process and temperature.**

Drawback of Hartley Architecture

- **The principal drawback of the Hartley architecture stems from its sensitivity to mismatches**

We lump the mismatches of the receiver as a single amplitude error, ε, and phase error, $\Delta\theta$. We divide the image-to-signal ratio at the input by the same ratio at the output, the result is called the "image rejection ratio" (IRR).

$$\mathrm{IRR} \approx \frac{4}{\epsilon^2 + \Delta\theta^2}$$

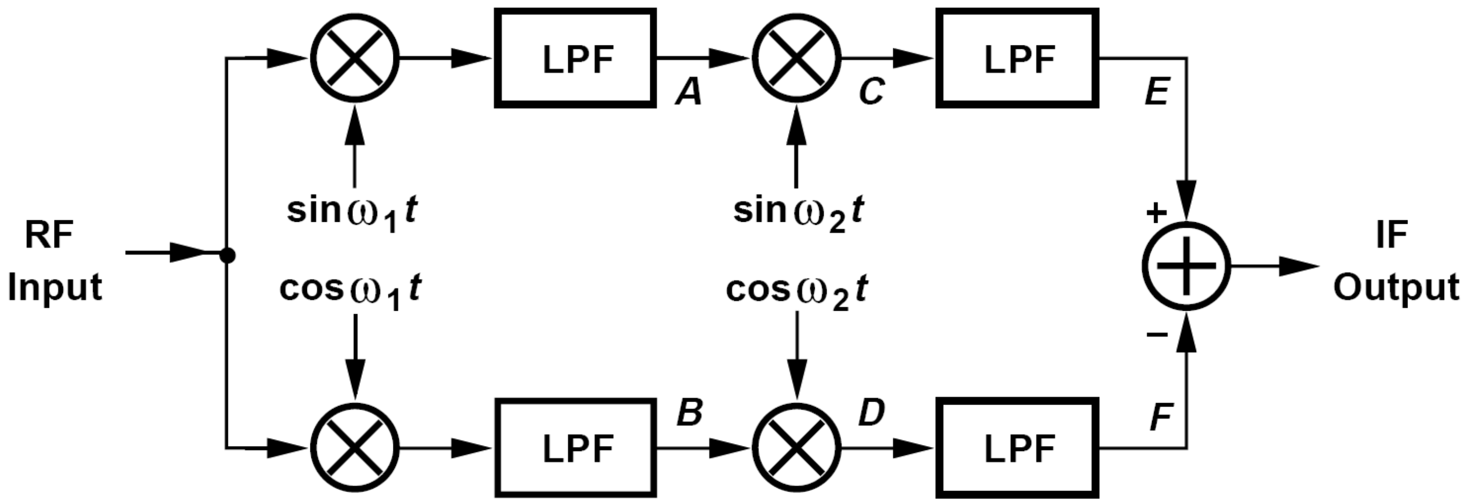
For example, ε = 10% (≈ 0.83 dB) limits the IRR to 26 dB. Similarly, $\Delta\theta = 10^\circ$ yields an IRR of 21 dB.

- **Another critical drawback originates from the variation of the absolute values of R_1 and C_1.**

- **The *RC-CR* sections used above also introduce attenuation and noise.**

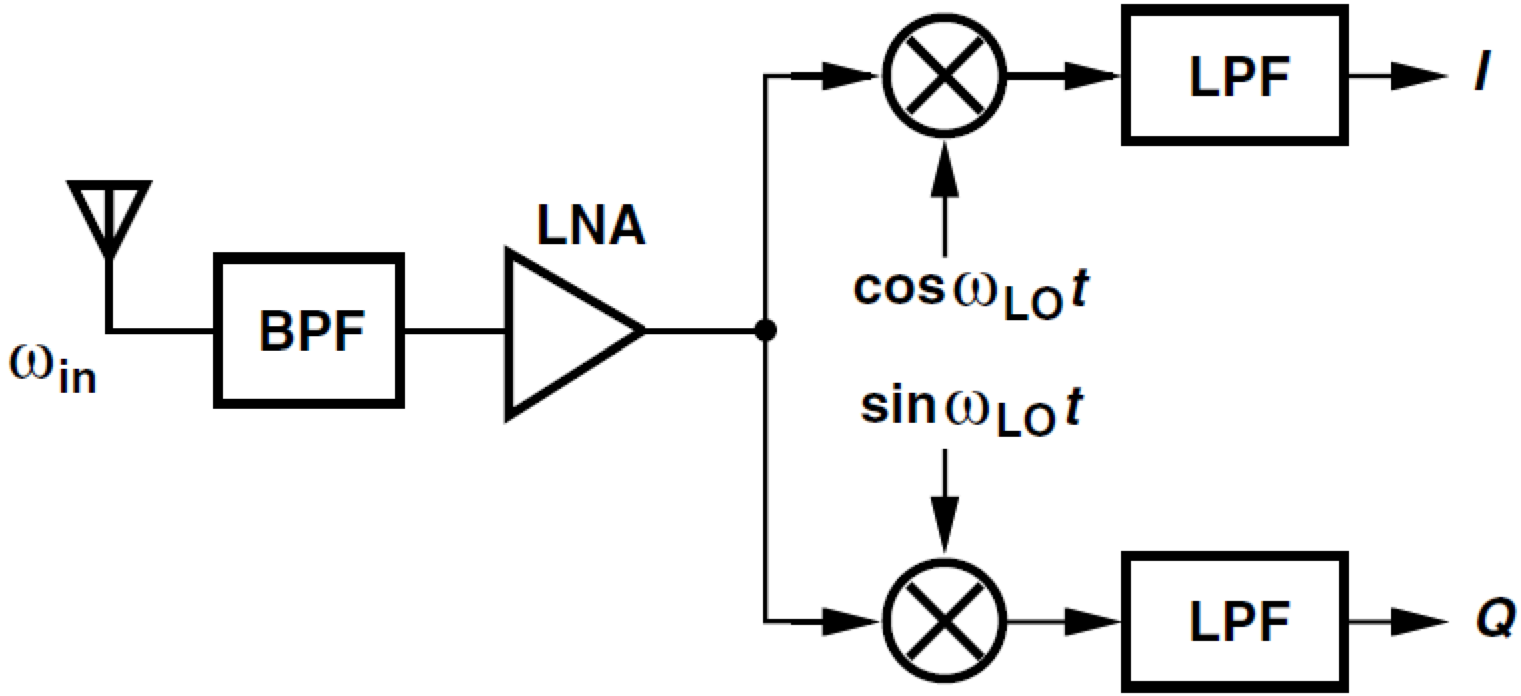
Weaver Architecture

The Weaver receiver, derived from its transmitter counterpart, avoids those issues in Hartley architecture.



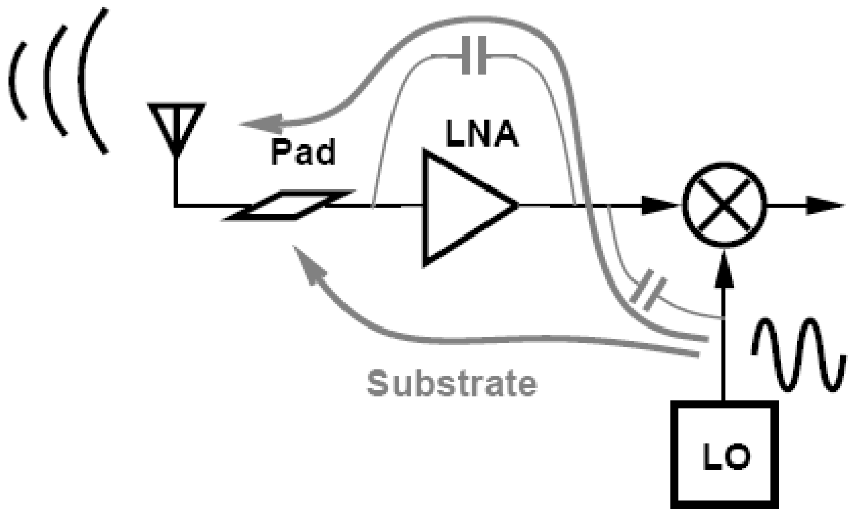
- **Mixing a signal with quadrature phases of an LO takes the Hilbert transform. Depicted above, the Weaver architecture replaces the 90° phase shift network with quadrature mixing.**

Direct Conversion Receiver



- **Absence of an image greatly simplifies the design process**
- **Channel selection is performed by on-chip low-pass filter**
- **Mixing spurs are considerably reduced in number**

LO Leakage

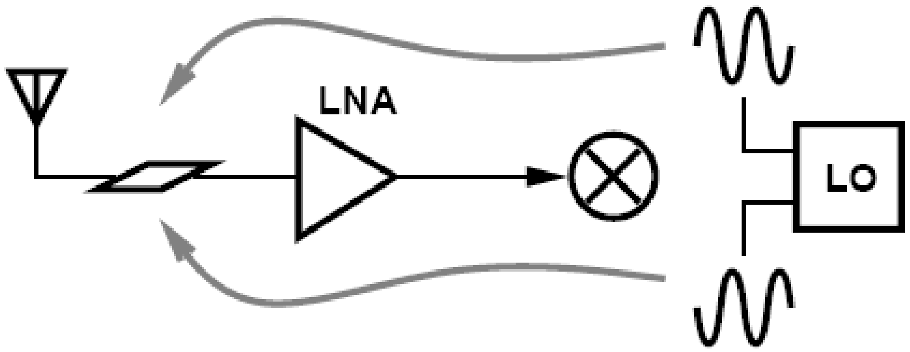


- LO couples to the antenna through:

  (a)device capacitances between LO and RF ports of mixer and device capacitances or resistances between the output and input of the LNA

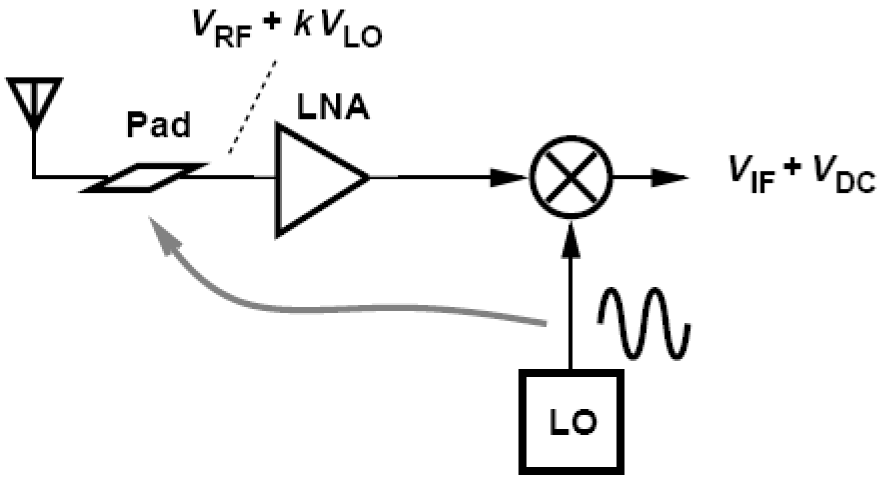
  (b)the substrate to the input pad, especially because the LO employs large on-chip spiral inductors

Cancellation of LO Leakage



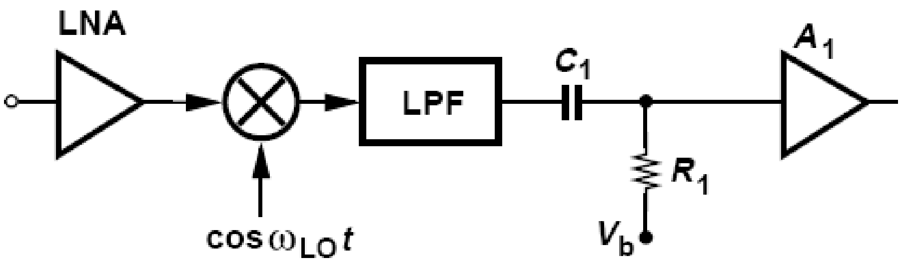
- LO leakage arises primarily from random or deterministic asymmetries in the circuits and the LO waveform
- LO leakage can be minimized through symmetric layout of the oscillator and the RF signal path

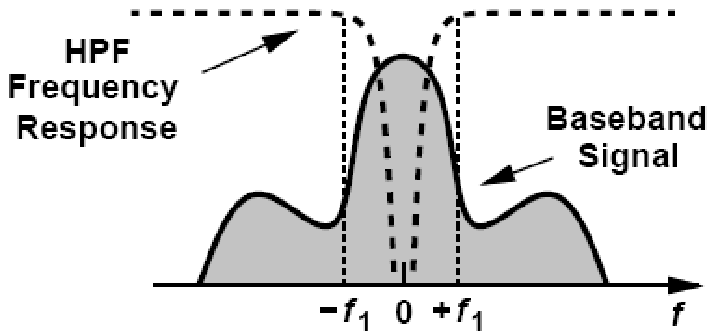
DC Offsets



- A finite amount of in-band LO leakage appears at the LNA input. Along with the desired signal, this component is amplified and mixed with LO.
- May saturates baseband circuits, simply prohibiting signal detection.

Cancellation of DC Offsets

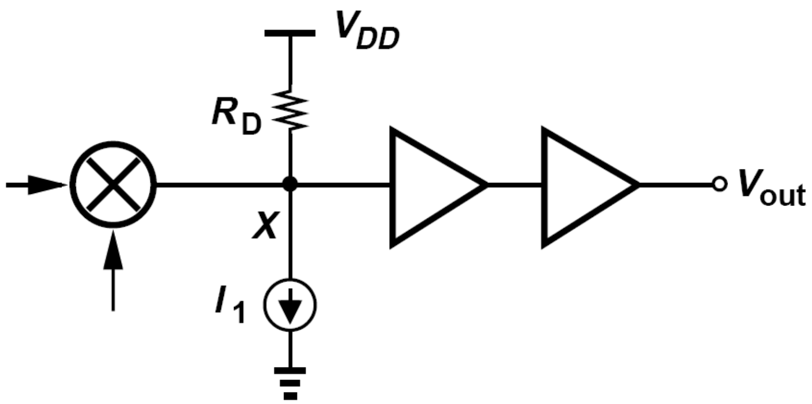


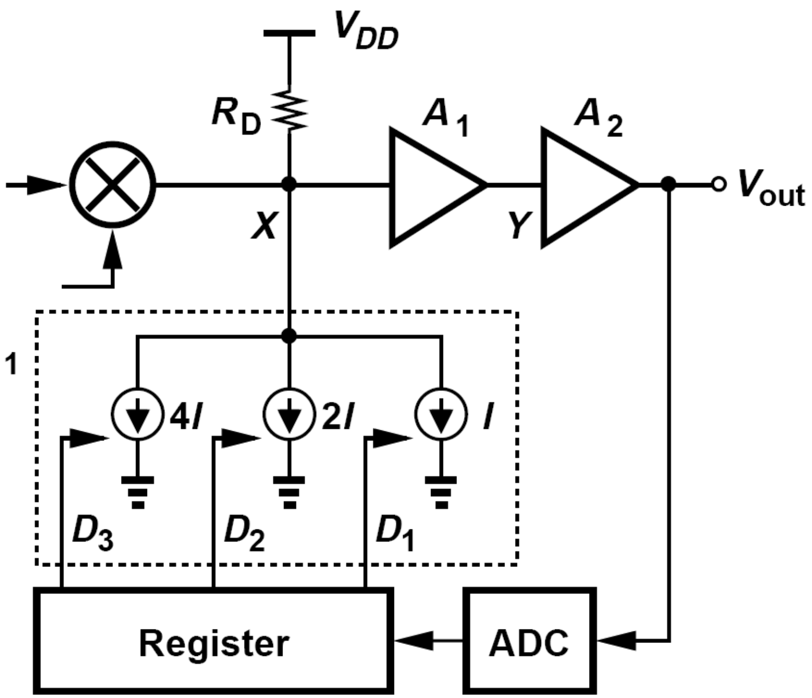


- Offset cancellation: high-pass filter
- Such network also removes a fraction of the signal's spectrum near zero frequency, introducing intersymbol interference

- A drawback of ac coupling stems from its slow response to transient input.
- DC free coding: Modulation schemes that contain little energy around the carrier better lend themselves to ac coupling in the baseband.

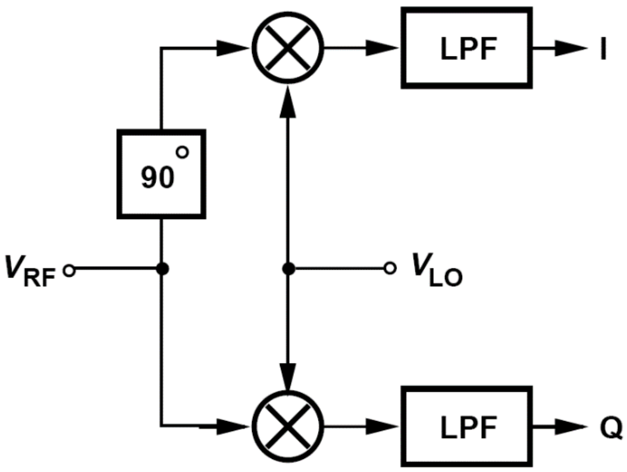
Cancellation of DC Offsets

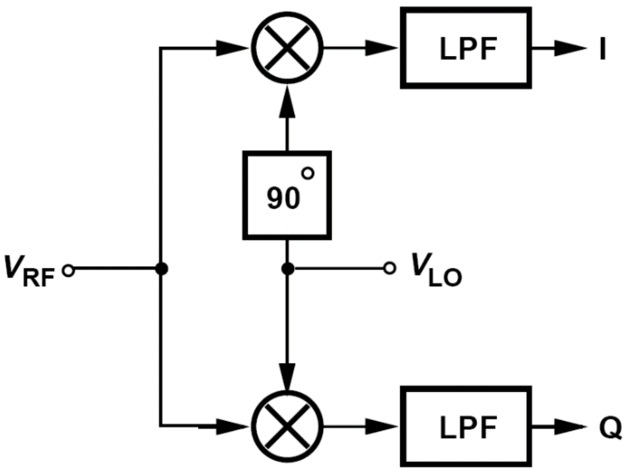




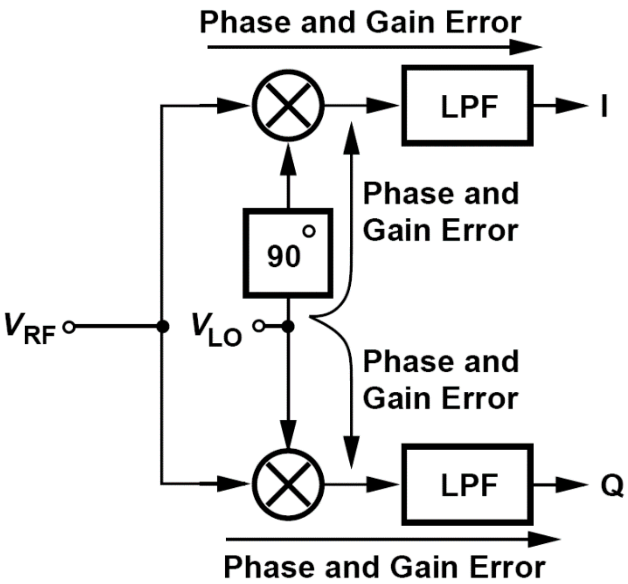
- The entire negative-feedback loop converges such that V_{out} is minimized. The resulting values are then stored in the register and remain frozen during the actual operation of the receiver.
- The principal drawback of digital storage originates from the finite resolution with which the offset is cancelled. A higher resolution or multiple DACs can be tied to different nodes to alleviate this issue.

I/Q Mismatch

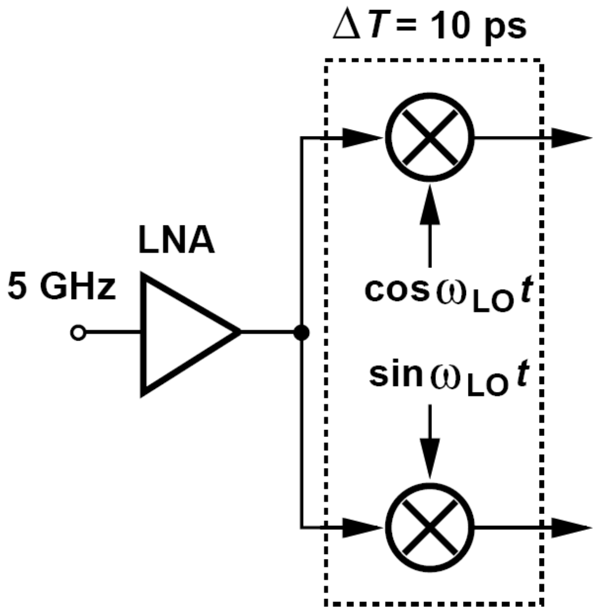


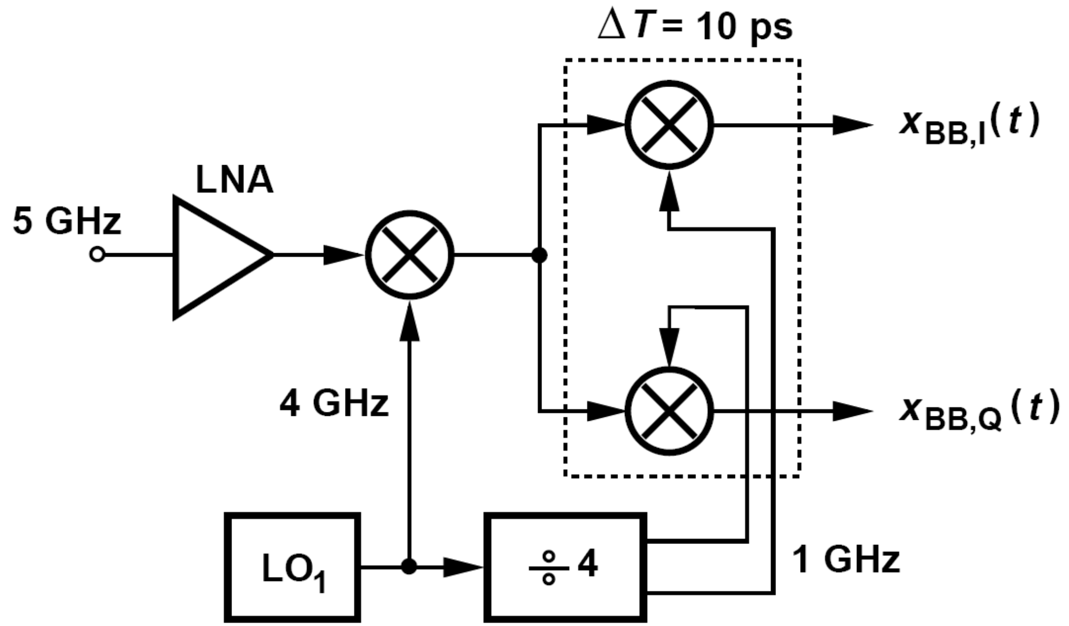


- Separation into quadrature phases can be accomplished by shifting either the RF signal or the LO waveform by 90°
- Errors in the 90° phase shift circuit and mismatches between the quadrature mixers result in imbalances in the amplitudes and phases of the baseband I and Q outputs.



I/Q Mismatch





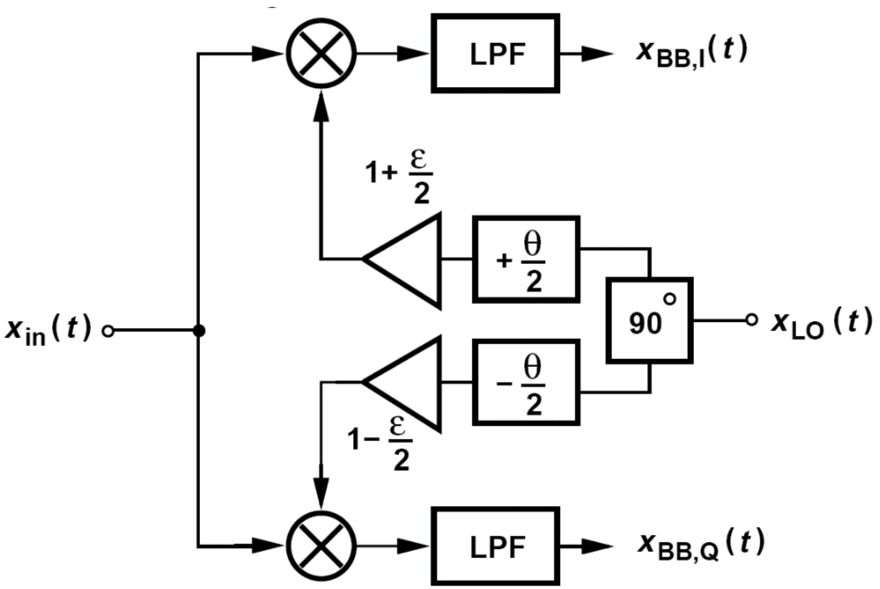
- **Quadrature mismatches tend to be larger in direct-conversion receivers than in heterodyne topologies.**
- **This occurs because**

(1) the propagation of a higher frequency (f_{in}) through quadrature mixers experiences greater mismatches;

(2) the quadrature phases of the LO itself suffer from greater mismatches at higher frequencies;

Effect of I/Q Mismatch

Let us lump all of the gain and phase mismatches shown below:



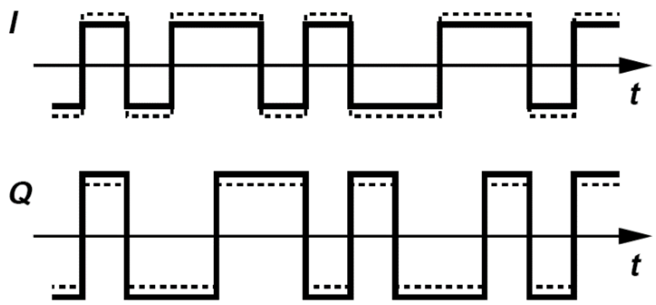
$$x_{LO,I}(t) = 2\left(1+\frac{\epsilon}{2}\right)\cos\left(\omega_c t+\frac{\theta}{2}\right)$$
$$x_{LO,Q}(t) = 2\left(1-\frac{\epsilon}{2}\right)\sin\left(\omega_c t-\frac{\theta}{2}\right),$$

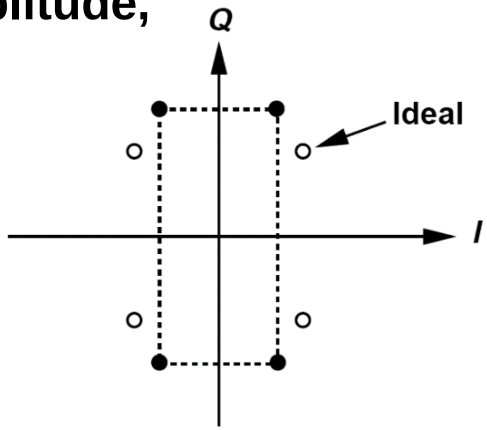
$$x_{BB,I}(t) = a\left(1+\frac{\epsilon}{2}\right)\cos\frac{\theta}{2} - b\left(1+\frac{\epsilon}{2}\right)\sin\frac{\theta}{2}$$

$$x_{BB,Q}(t) = -a\left(1-\frac{\epsilon}{2}\right)\sin\frac{\theta}{2} + b\left(1-\frac{\epsilon}{2}\right)\cos\frac{\theta}{2}$$

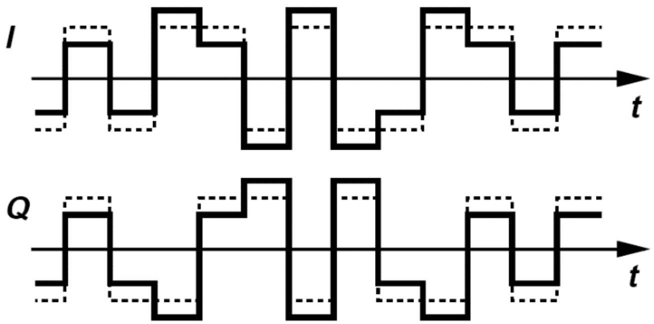
Effect of I/Q Mismatch for Two Cases

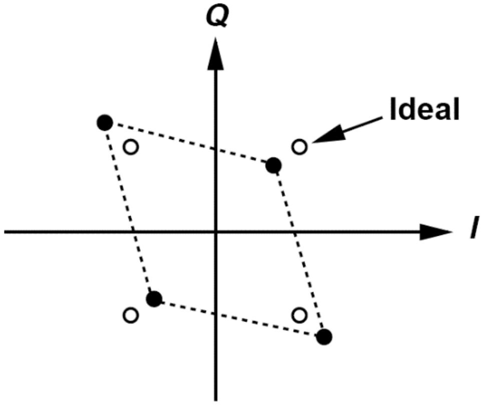
(1) ε ≠ 0, θ = 0 : the quadrature baseband symbols are scaled differently in amplitude,





(2) ε = 0, θ ≠ 0 : each baseband output is corrupted by a fraction of the data symbols in the other output

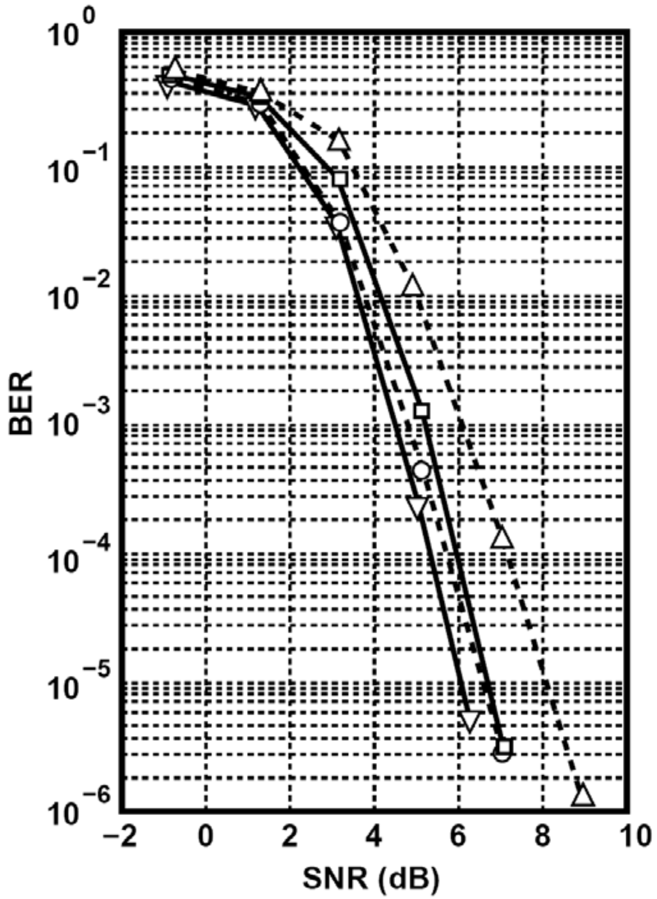




Requirement of I/Q Mismatch

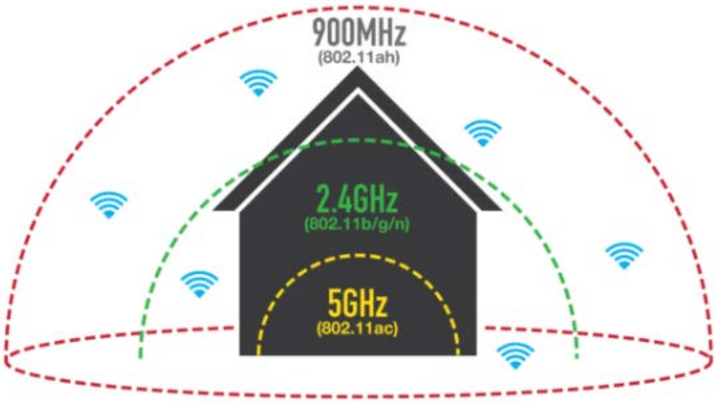
For complex signal waveforms such as OFDM with QAM, the maximum tolerable I/Q mismatch can be obtained by simulations

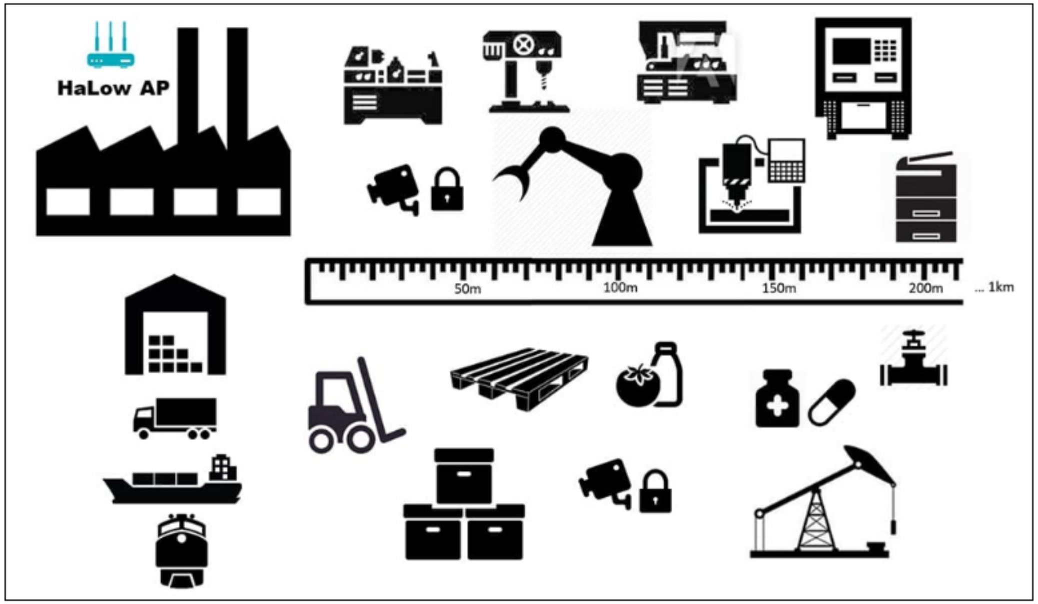
- **The bit error rate is plotted for different combinations of gain and phase mismatches, providing the maximum mismatch values that affect the performance negligibly.**
- **For example, in a system employing OFDM with 128 subchannels and QPSK modulation in each subchannel shown on right, we observe that gain/phase mismatches below -0.6 dB/6° have negligible effect.**



Effect of I/Q mismatch on an OFDM signal with QPSK modulation. (▽: no imbalance; °: $\theta = 6^\circ, \epsilon = 0.6\,dB$; □: $\theta = 10^\circ, \epsilon = 0.8\,dB$; △: $\theta = 16^\circ, \epsilon = 1.4\,dB$.)

HaLow - 802.11ah



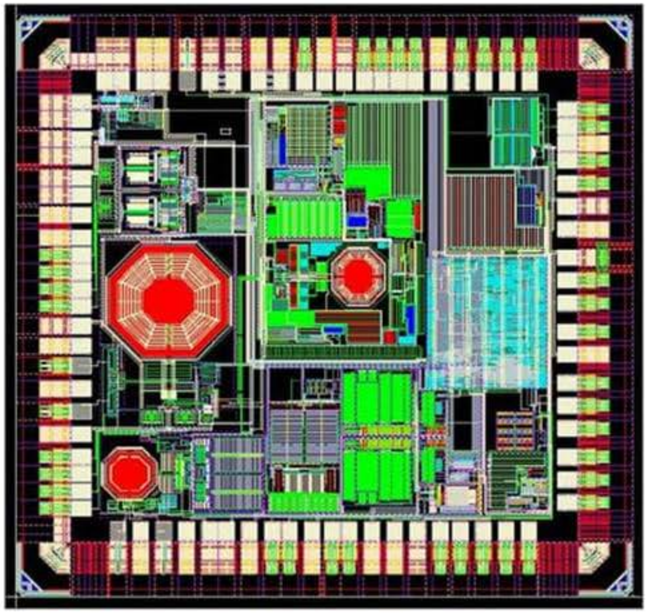


HaLow extends IoT/M2M Hotspot up to 1km

802.11ah from Wikipedia

- **IEEE 802.11ah** is a wireless networking protocol published in 2017[1] to be called **Wi-Fi HaLow**[2][3] (pronounced "HEY-Low") as an amendment of the IEEE 802.11-2007 wireless networking standard.
- It uses 900 MHz license exempt bands to provide extended range Wi-Fi networks, compared to conventional Wi-Fi networks operating in the 2.4 GHz and 5 GHz bands.
- It also benefits from lower energy consumption, allowing the creation of large groups of stations or sensors that cooperate to share signals, supporting the concept of the Internet of Things (IoT).[4]
- The protocol's low power consumption competes with Bluetooth and has the added benefit of higher data rates and wider coverage range.[2]

HaLow Transceiver from PC Semi



IEEE 802.11ah HaLow transceiver provides the bandwidth and power consumption requirements of a new generation of IoT and mobile devices, where battery life and extended range are prerequisites for successful deployment.

Power optimized for battery-powered sensor networks.

— All global ISM bands from 755MHz to 928MHz covered by HaLow

— 1, 2, & 4 MHz HaLow bandwidth modes

Device: PCS 802.11ah Transceiver for IOT Applications

Operating Frequency	**700-950 MHz**
Analog Supply Voltage	**3/1.35 V**
NF Max LNA Gain	**3 dB**
IIP3 Max LNA Gain Frequency spacing 5th and 10th channel	**-17 dBm**
Maximum Input Level	**-10 dBm**