ECE 4880

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Chapter 8

Frequency Strategy

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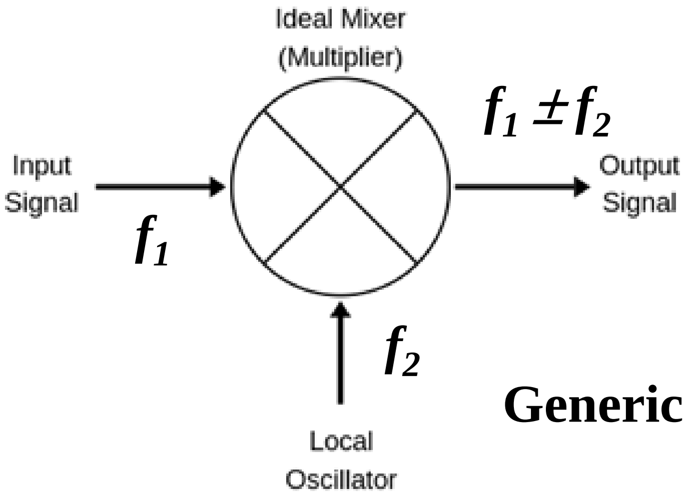
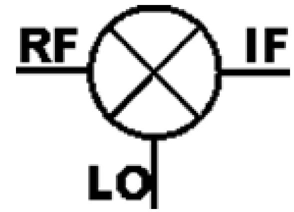
Goals

- Better understanding of mixers
- Review on image signals and noises
- Signals with high nonlinearity: M:N spurs
- Frequency strategy:
  - Superheterodyne
  - Homodyne
  - Up conversion
  - Direct sampling?

Mixers



Generic mixer



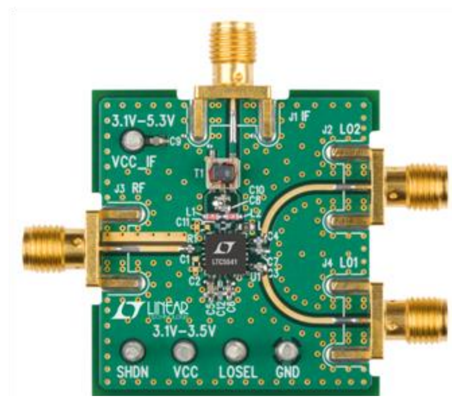
RF mixer where
$f_{RF} - f_{LO} = f_{IF}$

- The mixer plays a central role for frequency strategy in radios
- However, not a linear, time-invariant module (LTI): LTI can be represented by matrices of S, T, Y, Z, etc. This is NOT only because the mixer has three terminals.
- Frequency conversion is necessary:
  - Antenna size (quarter wavelength to be efficient)
  - Percentage bandwidth (20MHz channel in 2.4GHz carriers)
  - FCC regulation

Mixer: Nonlinear or Time Varying

- Mixer can be "nonlinear" (use the intermodulation term): can be passive such as diode mixers.
  - Can have better noise performance
- Mixer can be "time varying": Inject another frequency through multiplication function
  - Can have larger RF gain by larger LO
  - Active Gilber multiplier is a popular mixer choice

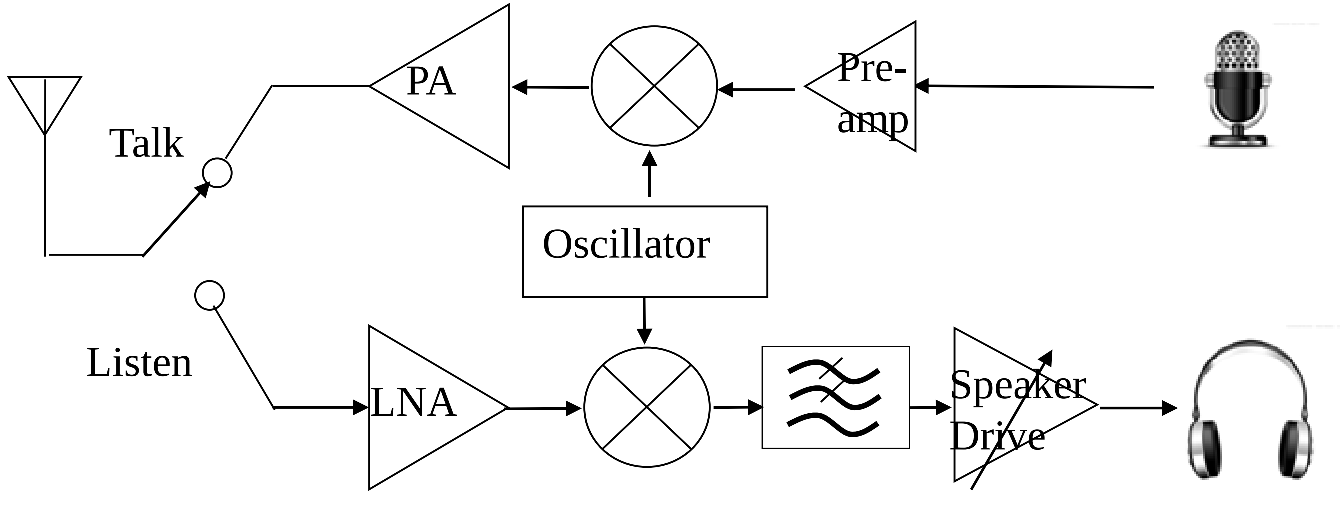
Passive RF mixer



Active RF quadrature mixer

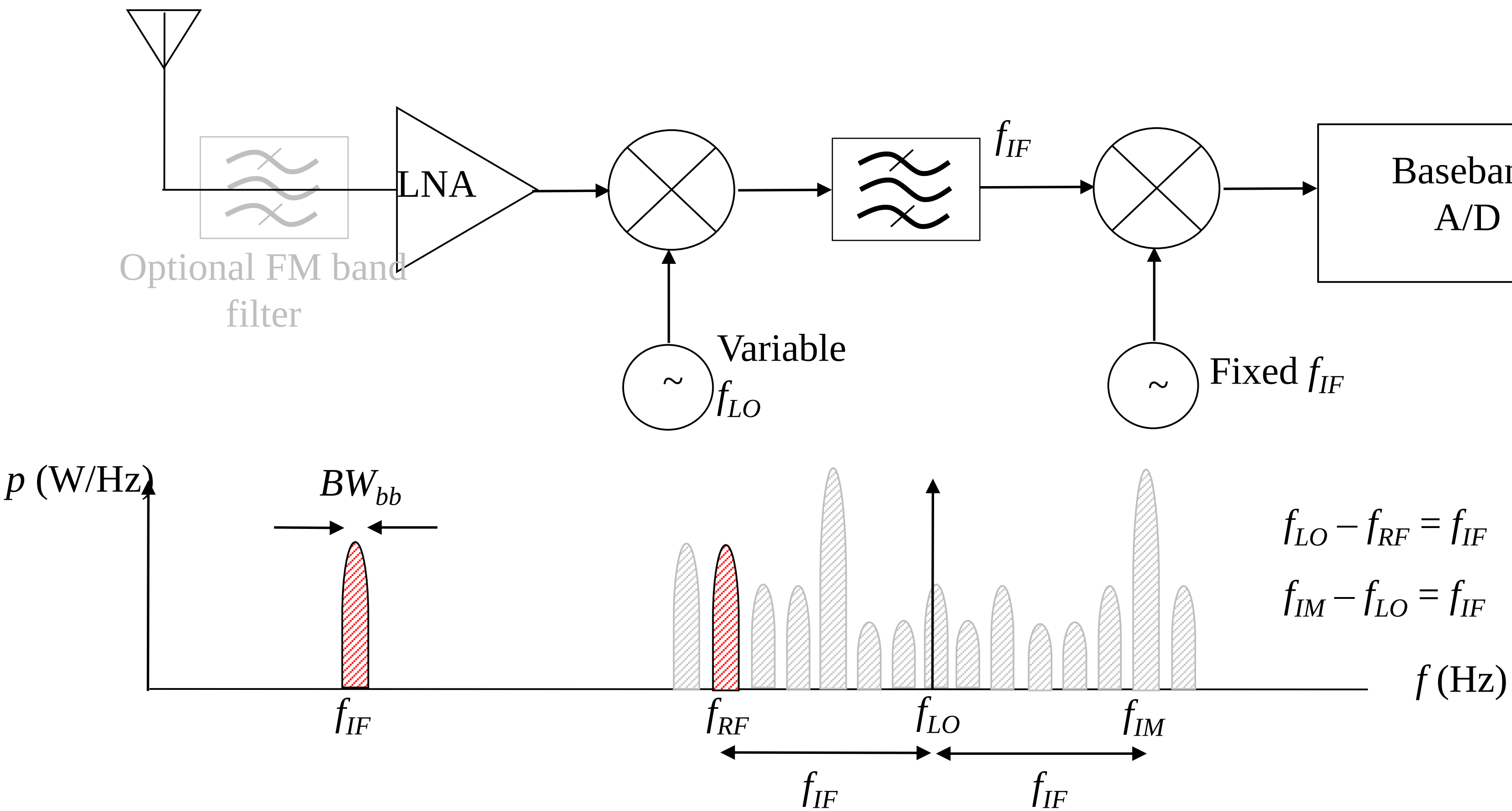
Heterodyne and Homodyne

- Heterodyne: different frequency or different power
- Reginald and Fessenden (1901): Direct conversion heterodyne receiver (audio band to RF band with reasonable antenna)
- Direct conversion heterodyne is later also called:
    - homodyne
    - synchrodyne
    - zero-IF



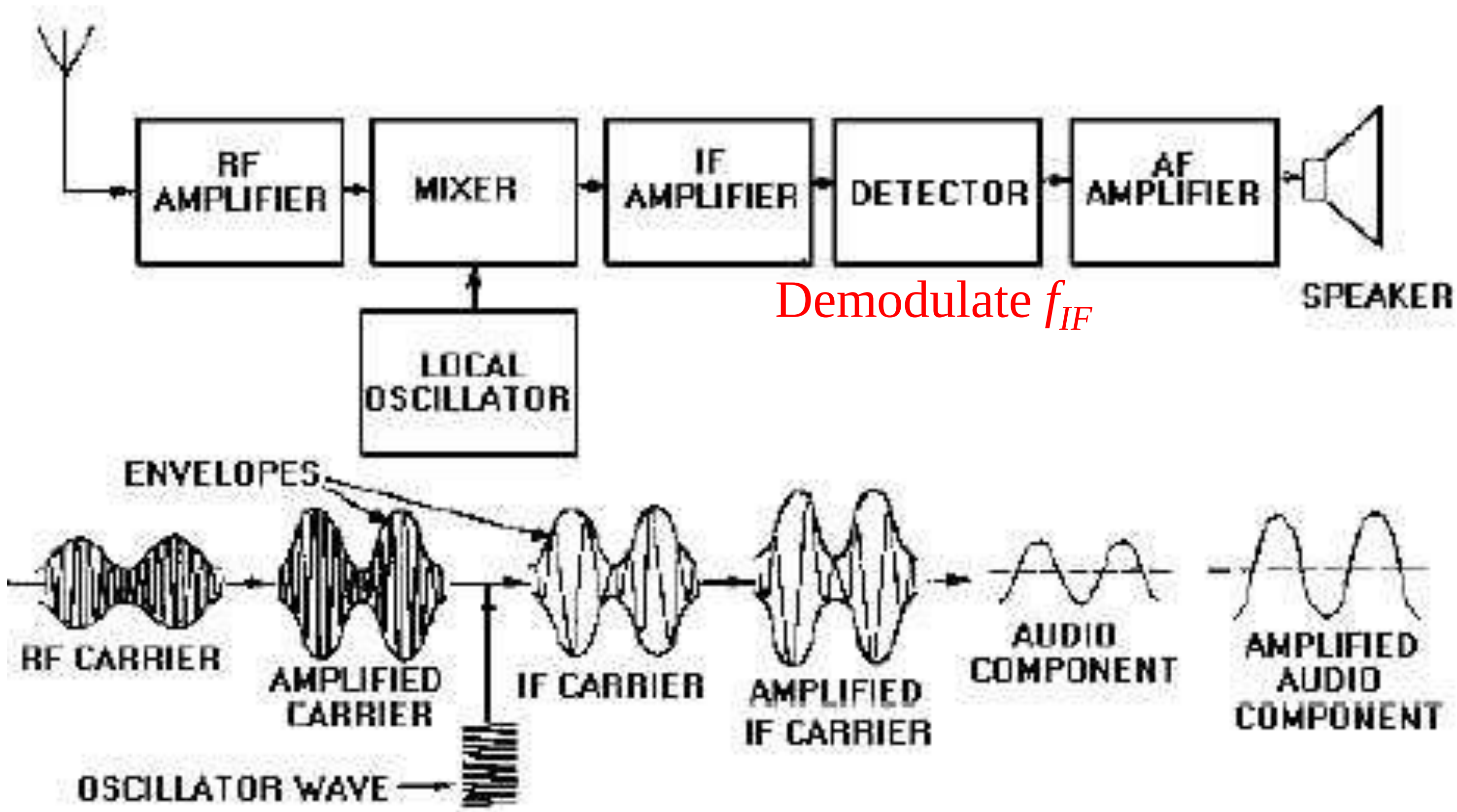
Superheterodyne

- Edwin Armstrong (1918): Superheterodyne: frequency conversion **two times**.

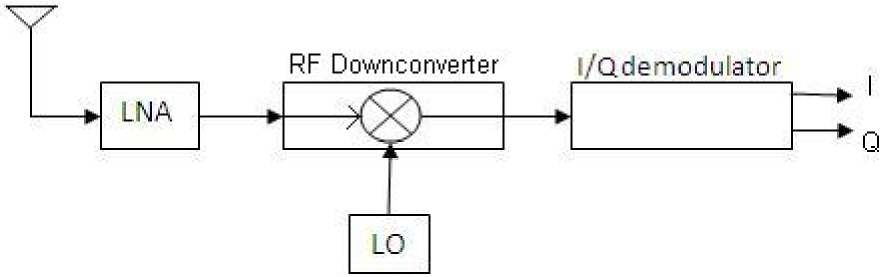


Base Band; IF; RF

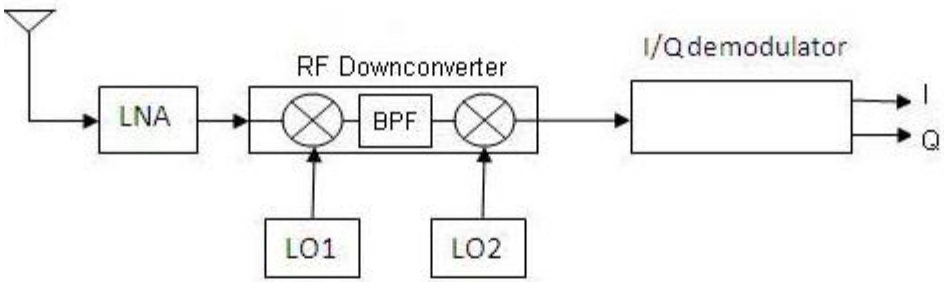
- Audio: 4Hz – 40kHz
- Baseband bandwidth: 200kHz
- f_{IF} (FM radio): 10.7MHz
- f_{RF}: 88MHz – 108MHz



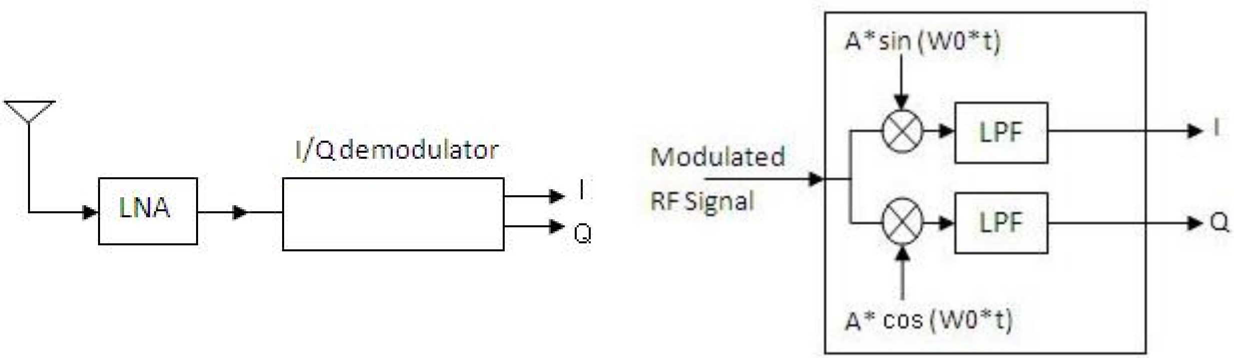
Naming Confusion



Heterodyne receiver



Superheterodyne receiver

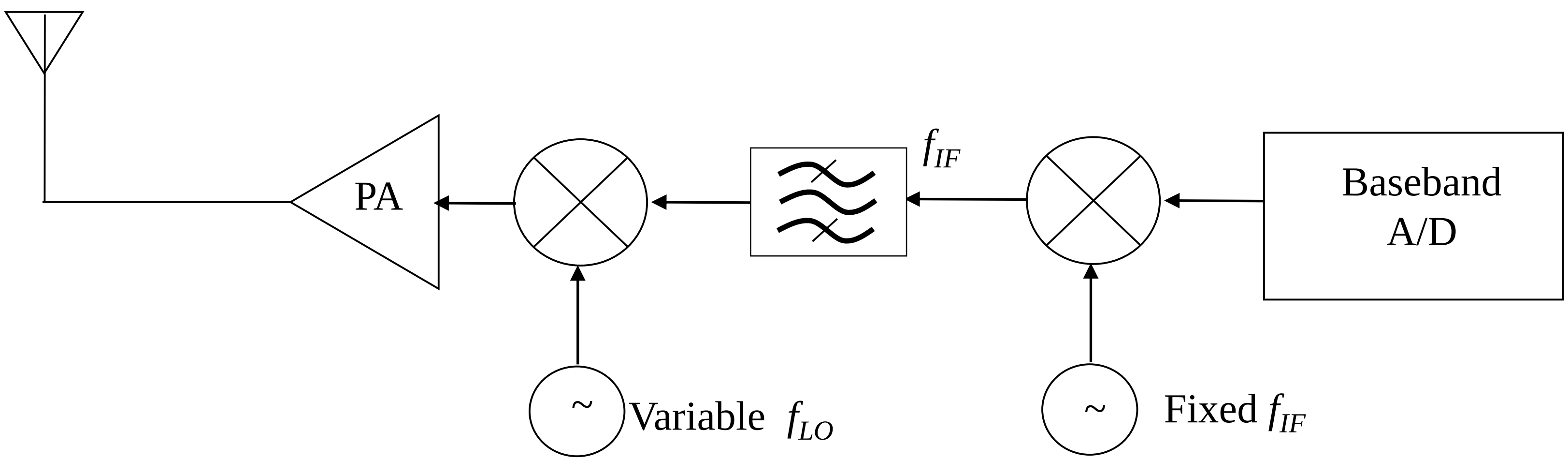


Homodyne receiver

Source: http://www.rfwireless-world.com/Terminology/heterodyne-receiver-versus-homodyne-receiver.html

The Case for Superheterodyne

- All basebands (channels) are converted to a smaller percentage bandwidth around f_{IF}: Simpler design afterwards (filters, etc.)
- Bandpass filter cost is proportional to $Q = f/\Delta f$. Small Δf means high Q: Picking out 200kHz from 100MHz is much more expensive than picking out 10MHz from 100MHz.
- Precision mixers are cheaper than precision filters. RF channel selection is done at changing f_{LO}.
- The cost function is different for software radio though.



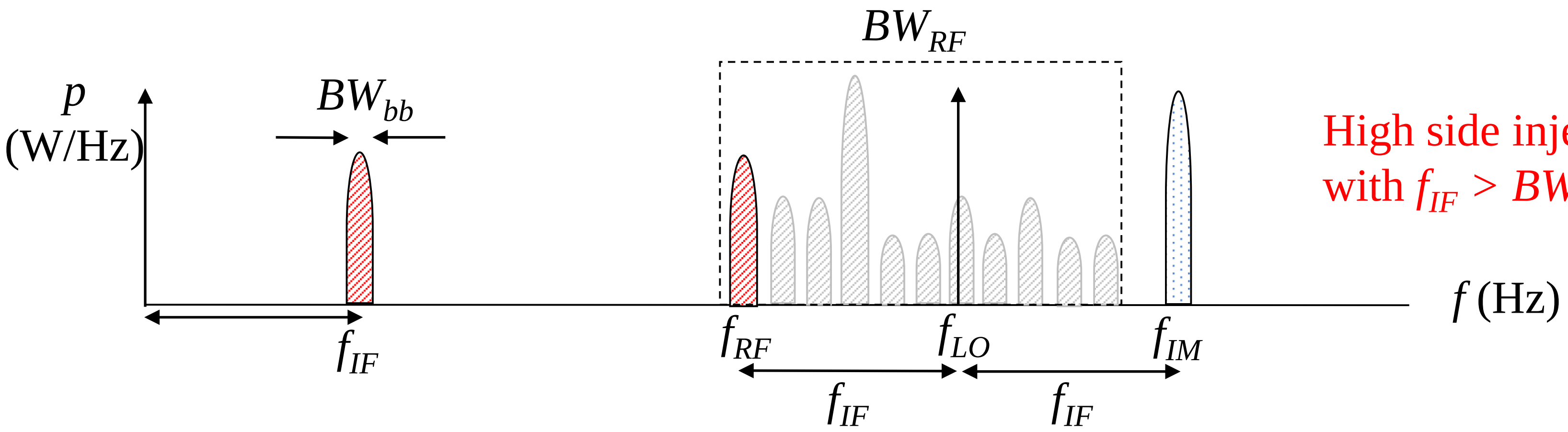
The Case for Superheterodyne (Cont.)

- Generation of f_{LO} will have $1/f^{\alpha}$ Flicker noise. When $f_{RF} = f_{LO} \pm f_{IF}$, we have more room to deal with f_{LO} phase noise.
- In the receiver, f_{IF} is internally defined, whereas f_{RF} has travelled long distance (possibly with moving source) and is less predictable. Filters around f_{IF} performs better and is cheaper.

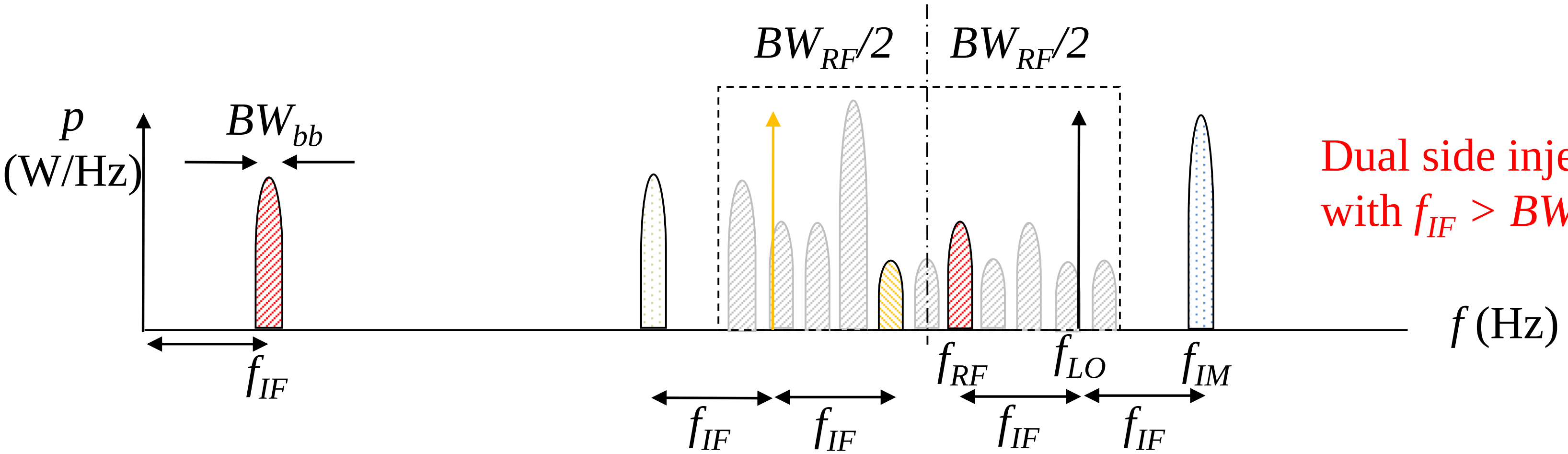
f_{LO} Injection into f_{RF}

- Double-side band (DSB): $f_{LO} = f_{RF} \pm f_{IF}$
- Single-side band (SSB)
  - High-side injection: $f_{LO} = f_{RF} + f_{IF}$
  - Low-side injection: $f_{LO} = f_{RF} - f_{IF}$
  - Dual-side injection: Lower half of f_{RF}: high-side injection; higher half of f_{RF}: low-side injection.
- Down conversion: $f_{IF} < f_{RF}$ (All cases above)
- Up conversion: $f_{IF} = f_{RF} + f_{LO}$
  - Station selection at a higher frequency
  - IF filters of higher Q needed
  - But the image frequency is far away!

High-Side and Dual-Side Injection



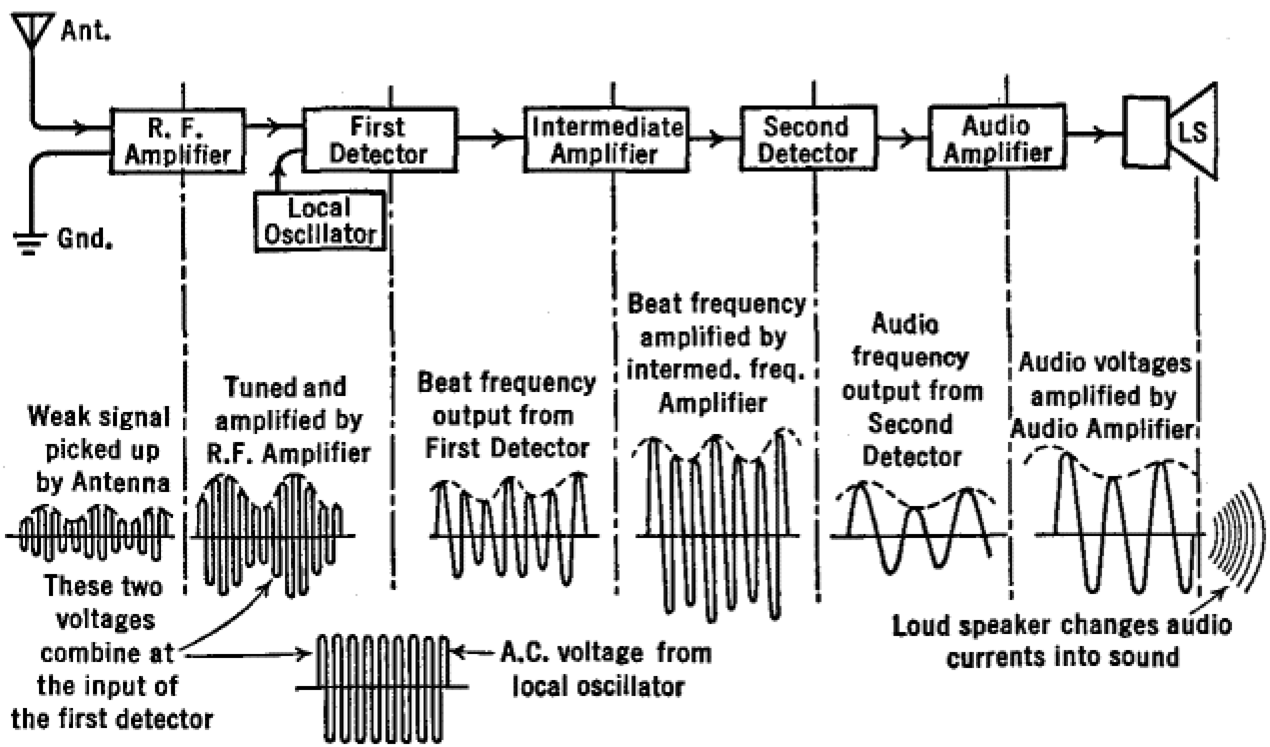
High side injection with $f_{IF} > BW_{RF}/2$.



Dual side injection with $f_{IF} > BW_{RF}/4$.

FM Radio Receiver

- FCC chose FM radio bands: 88 – 108MHz with BW_{bb} = 200kHz high-side injection (i.e., $f_{LO} > f_{RF}$). f_{IF} = 10.7MHz is selected.
- $f_{RF}/BW_{bb} \cong$ 100MHz/0.2MHz = 500;
- $f_{RF}/f_{IF} \cong$ 100MHz/10.7MHz = 9.3;
- $f_{IF}/BW_{bb} \cong$ 10.7MHz/0.2MHz = 53.5



FM Frequency Strategy: Image

- Q factor for FM band filter: 98/(108 – 88) = 4.9
- f_{IF} = (108MHz – 88MHz)/2 + 0.7MHz

Image rejected by FM band filter

Tolerance for component errors

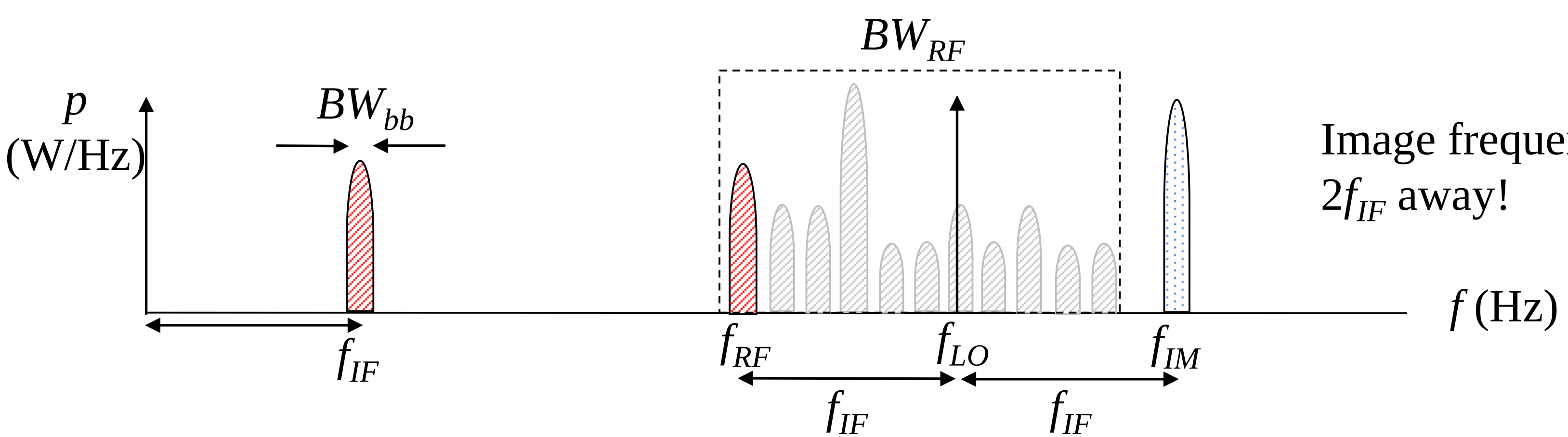
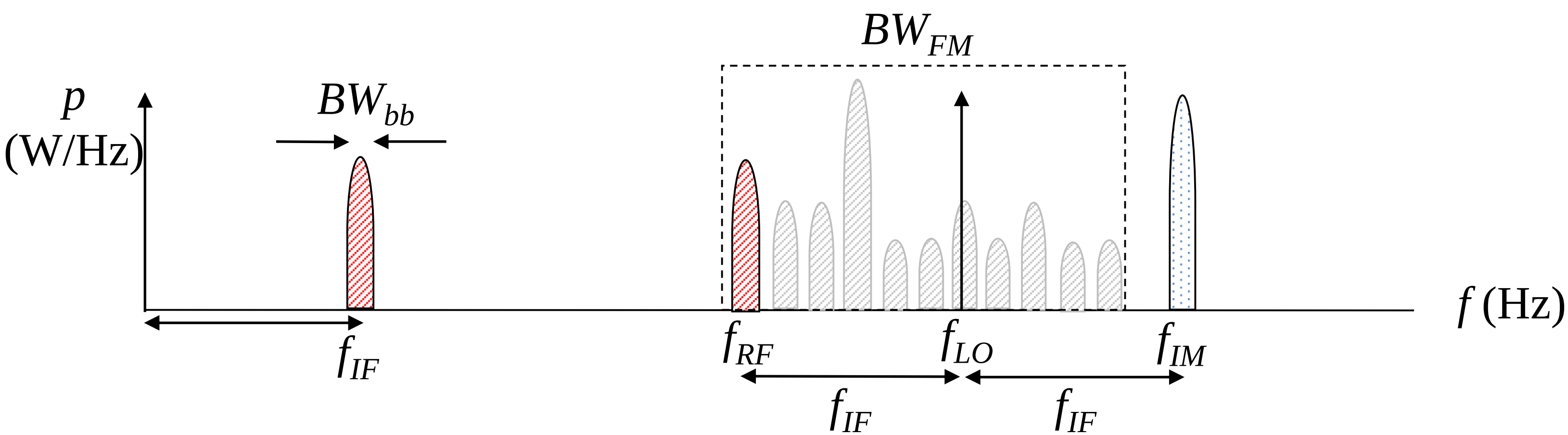


Image frequency is $2f_{IF}$ away!

- f_{LO} = 88.1MHz + 10.7MHz = 98.8MHz for the first station
- f_{LO} = 107.9MHz + 10.7MHz = 118.6MHz for the first station

FM Frequency Strategy: f_{LO} Range

- When the oscillator frequency selection is done by tuning L or C, the tuning range of f_{LO} is an important design factor.
- High-side injection: f_{LO} = 98.8MHz – 118.6MHz
  - $f_{LOmax}/f_{LOmin} = 1.2$
- Low-side injection: f_{LO} = 77.3MHz – 97.3MHz
  - $f_{LOmax}/f_{LOmin} = 1.3$



The Case for AM Radio

- FCC regulation: AM bands: 530kHz – 1610kHz
- The initial choice of f_{IF} = 455 kHz < 540kHz
- BW_{bb} = 20kHz.
- High-side injection: f_{LO} = 985kHz – 2065kHz
  - $f_{LOmax}/f_{LOmin} = 2.1$
- Low-side injection: f_{LO} = 75kHz and 1155kHz
  - $f_{LOmax}/f_{LOmin} = 15.4$

Low-Frequency Bands Still Important

- AM for emergency broadcast
- Ground radar
- Long-range amateur radio:
  - Ionspheres for 6 – 10km above the earth surface (gas ionized by sun UV radiation) will reflect most of the radio waves in the HF band (1.6 – 30MHz).
  - Radios that use this bouncing back and forth between ionspheres and earth surface are nicknamed as the “short-wave” radio.
- Near-field communication

Finally Sound in Radios

- The original purpose for radio is to transmit sound wirelessly (vs. telephone and telegraph)
- RCA (Radio Corporation of America): 1919 – 1986.
- As in telephone, the sound quality is decided by the worst element along the chain (microphone, wire, amp, speaker)
- AM sound: 20kHz bandwidth (phone-quality)
- FM sound: 200kHz of 40kHz combinations (stereo, Dolby, etc.)
- Digital sound track (.wav): 96kHz sampling of 24 bit depth

Choice of f_{IF}

- Low f_{IF}:
  - Better filter is needed around BW_{RF} for image rejection and channel selection
  - Larger tuning range for f_{LO} (f_{LO} tracks f_{RF} closely) for high-side injection.
  - Easier processing after conversion to around f_{IF}.

- High f_{IF}:
  - Easier image rejection
  - Less f_{LO} phase noise: higher RF gain possible
  - Difficult processing after conversion to around f_{IF}.

Image Rejection

- Two previous techniques for image rejection
  - Superheterodyne with $f_{IF} > BW_{RF}/2$ and a BW_{RF} filter.
  - Up conversion: $f_{IF} = f_{LO} + f_{RF}$ and $f_{image} = 2f_{LO} + f_{RF}$
- One more way: Use quadrature
  - For just the cosine function, we know:

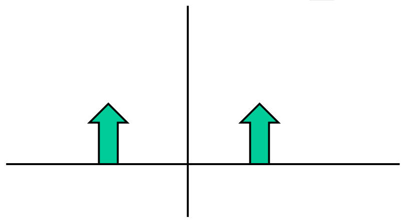
$$\cos(\omega_{LO} - \omega_{RF})t = \cos(\omega_{LO} - \omega_{IM})t = \cos(\pm\omega_{IF})t$$

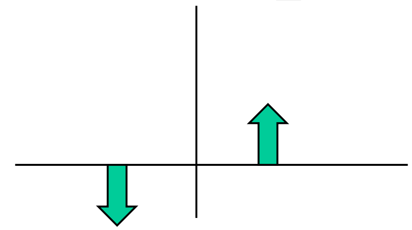
Not possible to distinguish f_{RF} and f_{IM}!

However, can we make f_{RF} to be in phase and f_{IM} to be out of phase like the scheme in quadrature or 180º hybrid?

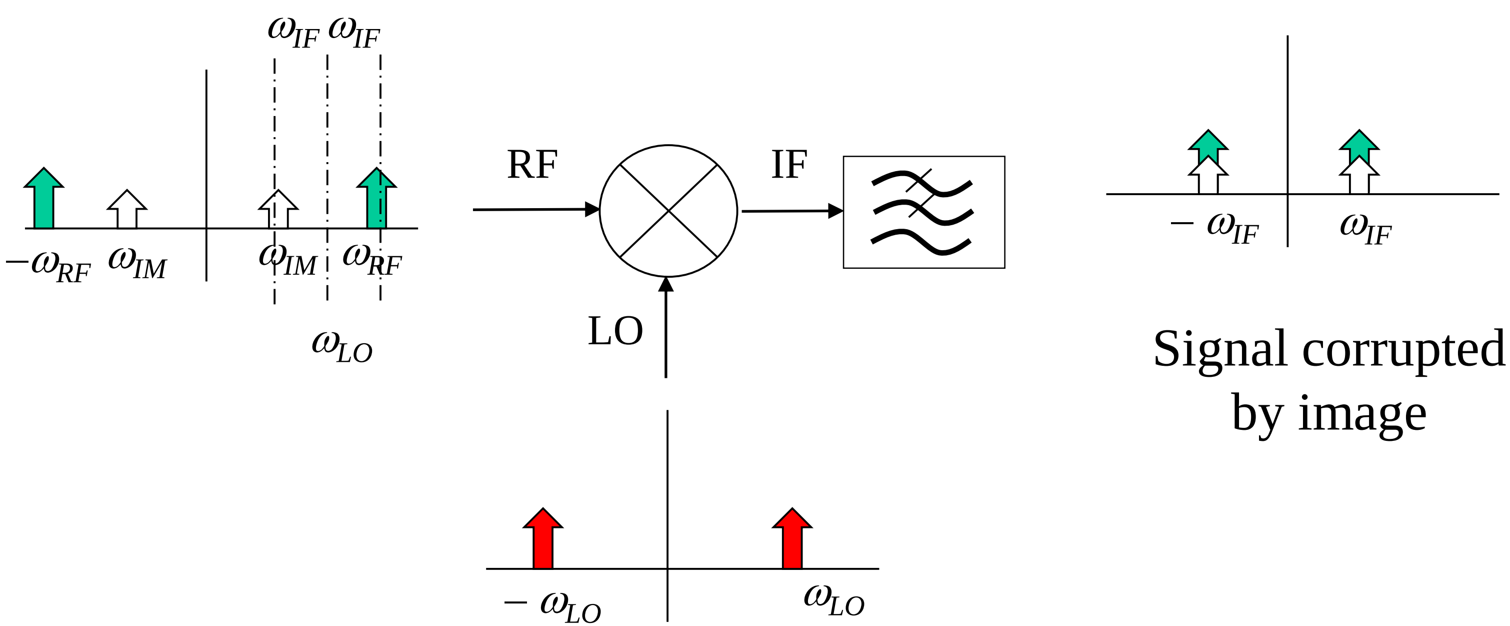
Spectral Representation of Images

$$\cos(\omega t) = \frac{e^{j\omega t} + e^{-j\omega t}}{2}; \qquad \sin(\omega t) = \frac{e^{j\omega t} - e^{-j\omega t}}{2}$$





Low side injection example



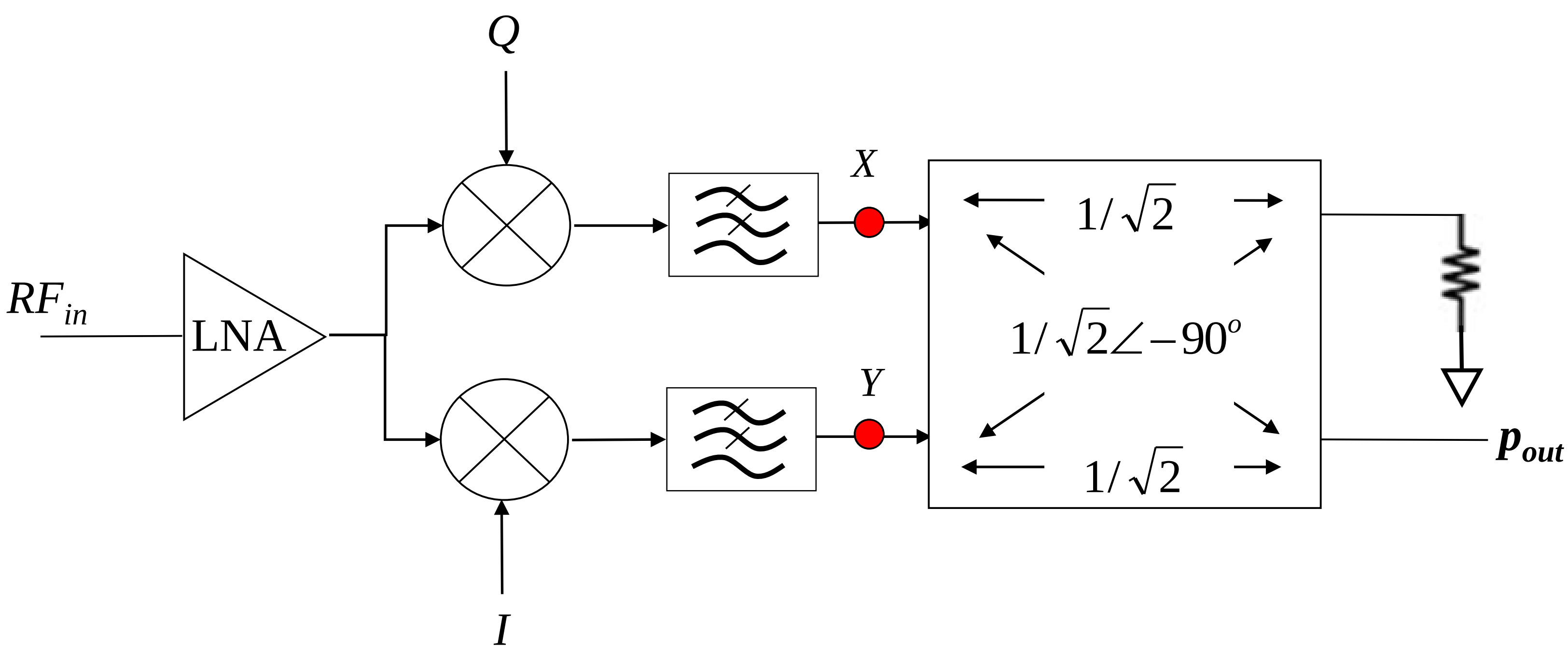
Hartley Image Rejection

- High side injection where $f_{IM} - f_{LO} = f_{LO} - f_{RF} = f_{IF}$

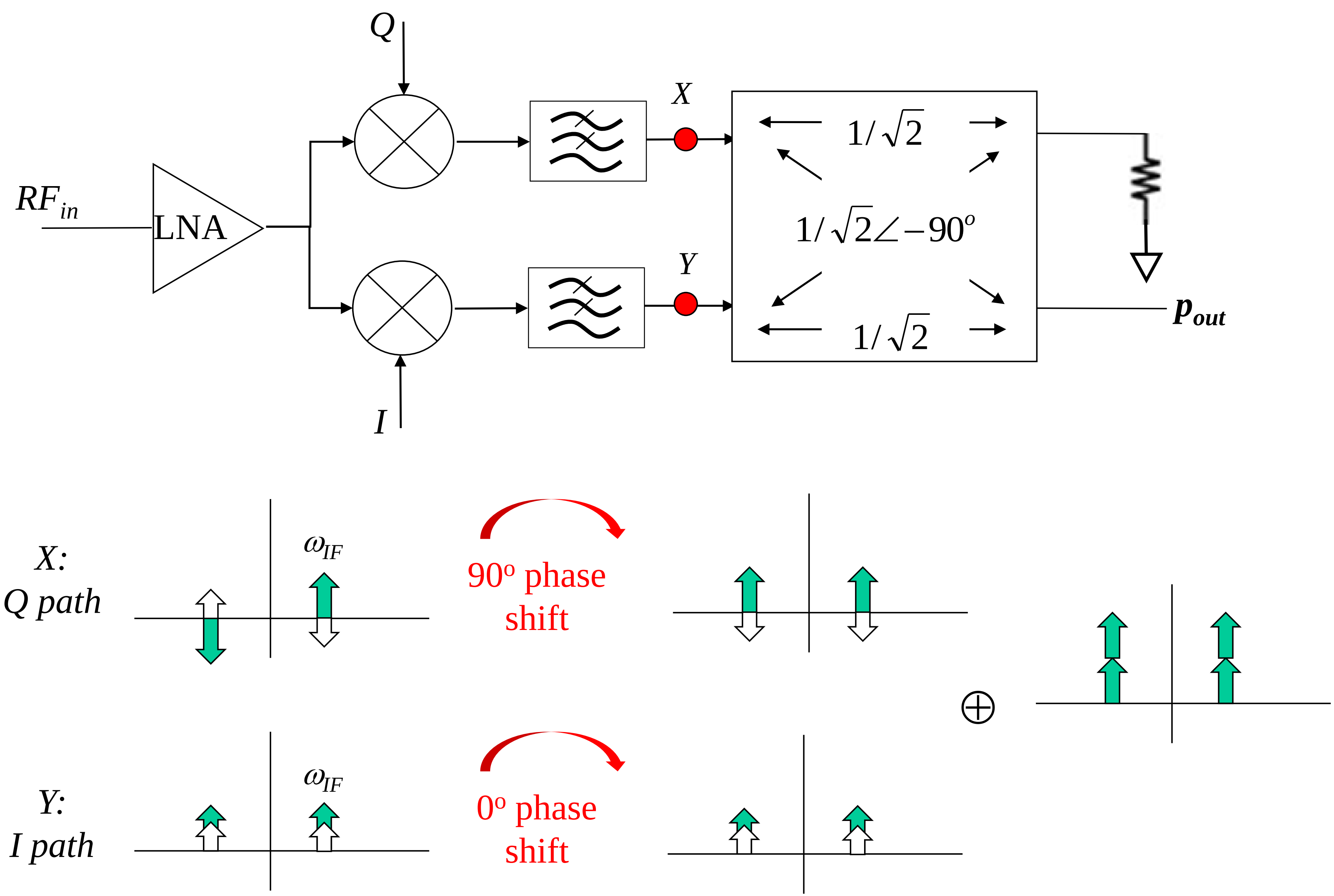
$$p_{out,Q} = g_{multi} \cdot A_{RF}\left[\cos(\omega_{RF} t) + \cos(\omega_{IM} t)\right] \cdot A_{LO} \sin(\omega_{LO} t)$$

$$= g_{multi} \cdot \frac{A_{RF} A_{LO}}{2}\left[\sin(\omega_{LO} - \omega_{RF})t - \sin(\omega_{IM} - \omega_{LO})t + \sin(\omega_{RF} + \omega_{LO})t + \sin(\omega_{IM} + \omega_{LO})t\right]$$

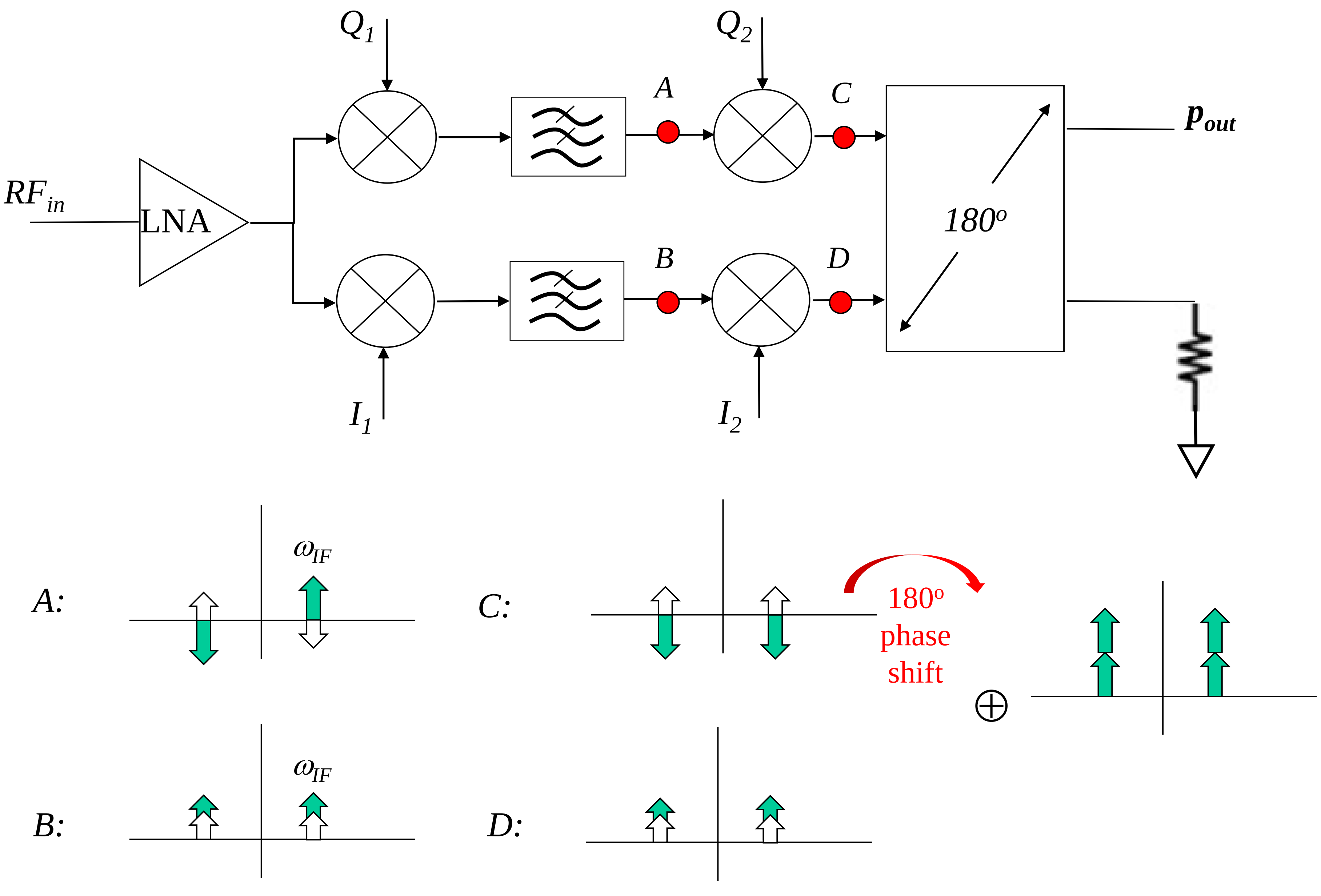
180° difference



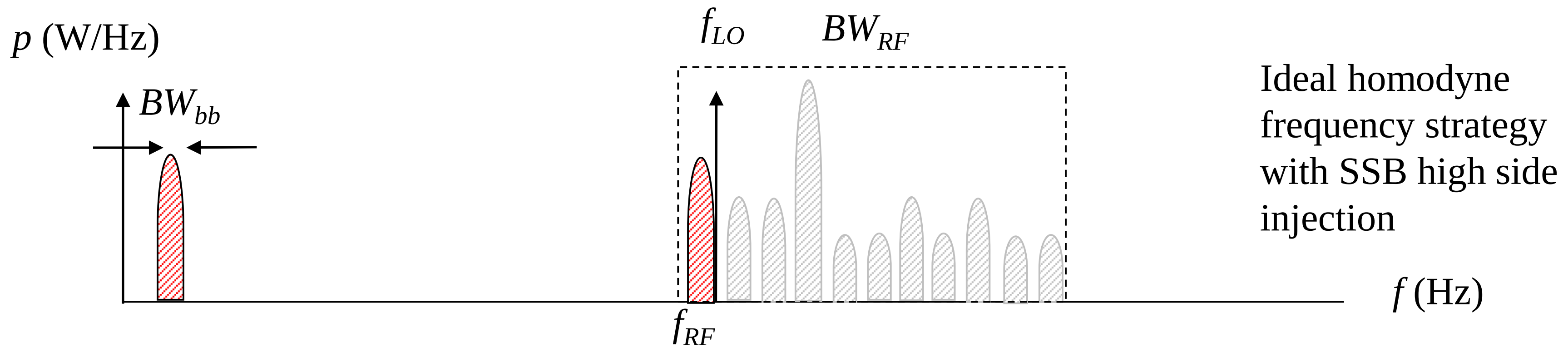
Hartley Spectral Representation

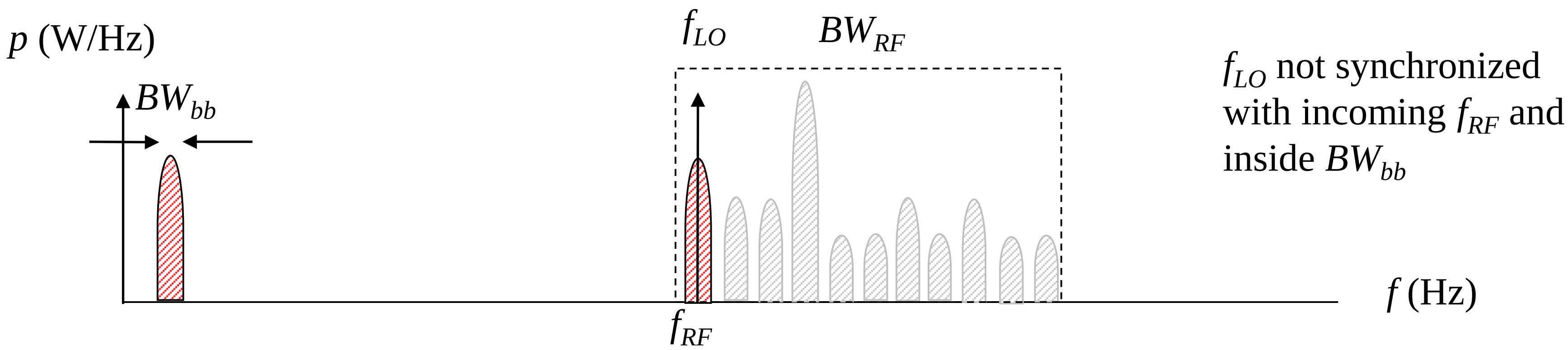


Weaver Image Rejection



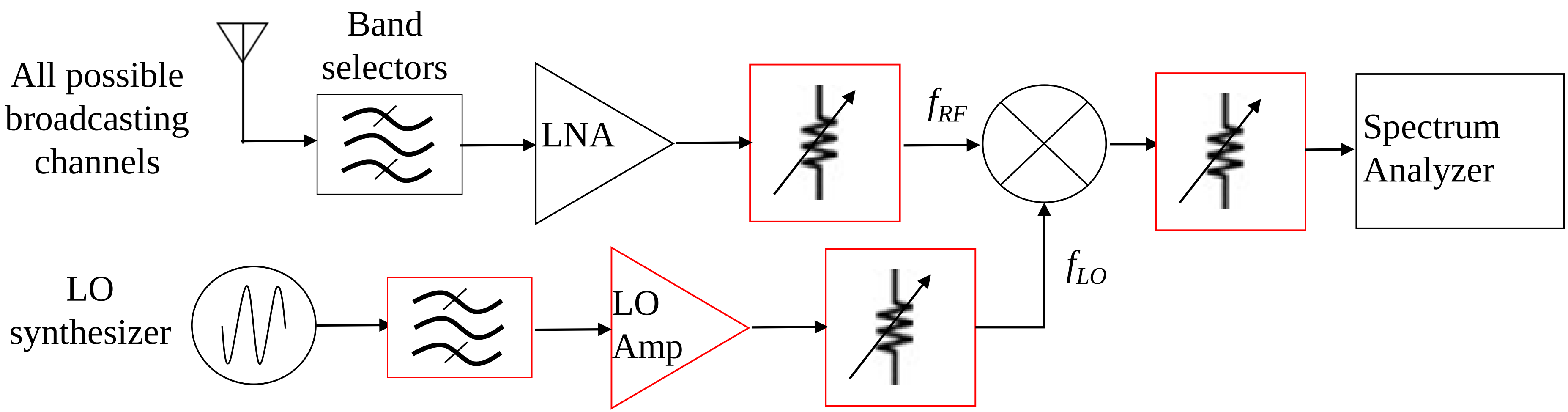
The Case for Homodyne





- f_{LO} needs to be accurately synchronize for TX/RX
- Image rejection can be dealt with by either quadrature scheme or precision digital filtering
- Base band close to DC, and H2/IM2 of LNA is important.

Mixer Spurs



- Mixer is nonlinear by definition, and intermodulation is its main function.
- The magnitude of LO is directly translate to gain in the signal chain. This is the second stage in the receiver, and has still advantages to provide better SNR for later stages.
- The LO harmonics and phase noise will be “multiplied” to the signals, instead of being added on.
- Tracing the origins of spurs is needed for the worst case in f_{RF}.

Table of *m:n* Spurs

- Small LO: larger phase noise influence
- Large LO: spurs from LO harmonics

m	n	$f_{RF,low}$ (MHz)	$f_{RF,high}$ (MHz)	Spur power level below signal (dB)
–3	3	73.8	93.9	50
–2	2	72.0	92.1	74
1	**–1**	**88.0**	**108.2**	**0**
2	–2	82.7	102.8	73
3	–3	80.9	101.0	49

- Tracing *m:n* spurs from the mixer to identify the origin from frequency synthesizer, LNA nonlinearity, mixer nonlinearity, or any other components.
- Less serious with early digital filtering.

What Have You Learned?

- The role and number of mixing in a radio architecture
- Intermediate frequency: choices and problems
- Image frequency and noises
- FM and AM radio examples
- Image cancellation techniques
- Tracing spurs