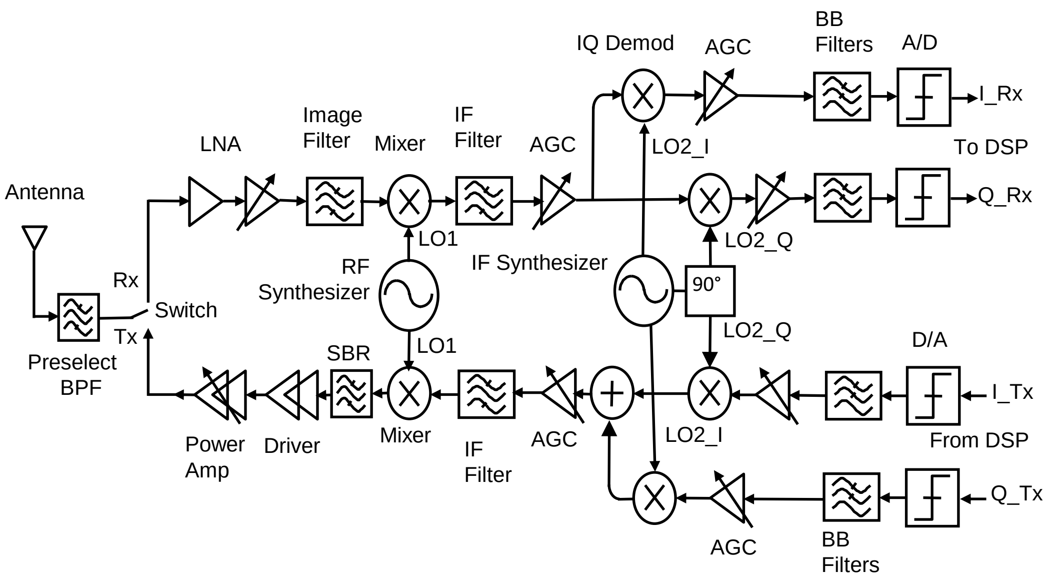
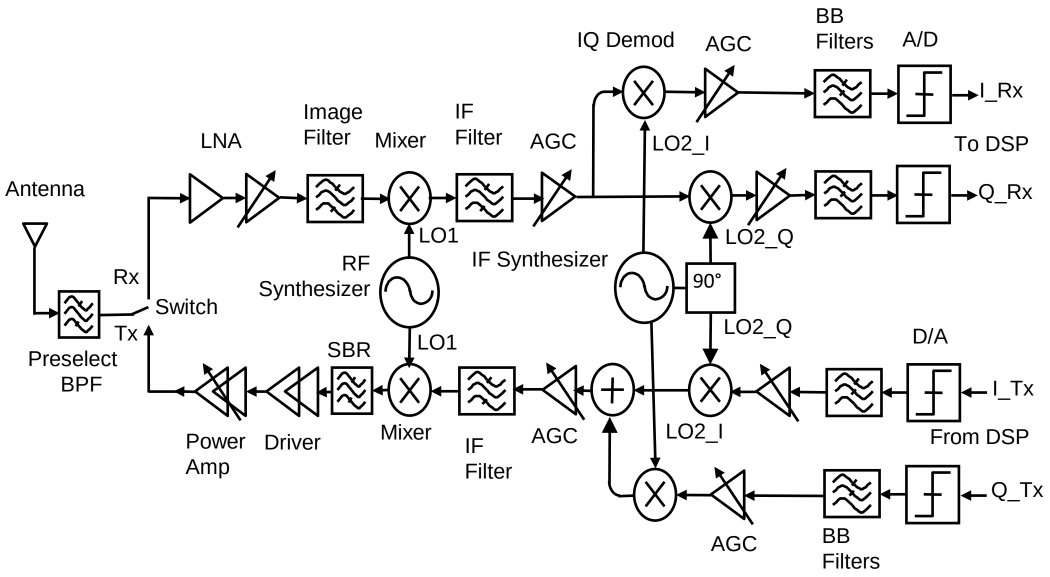
RF Systems Course: RF Archetectures I

Superheterodyne Transceivers

- Modulated signals Tx/Rx at some freq by antenna.
- If the radio is receiving information -> signals passed from antenna to Rx
- If the radio is transmitting -> signals passed to antenna from Tx
- Radios that transmit/receive at same time -> *full-duplex transceiver*
- Radios that alternate between transmit/receive -> *half-duplex transceiver*
- half-duplex transceiver possible to put switch between antenna and Rx/Tx paths -> improved isolation
- full duplex transceiver no switch -> 2 input filters (usually called a *duplexor*)

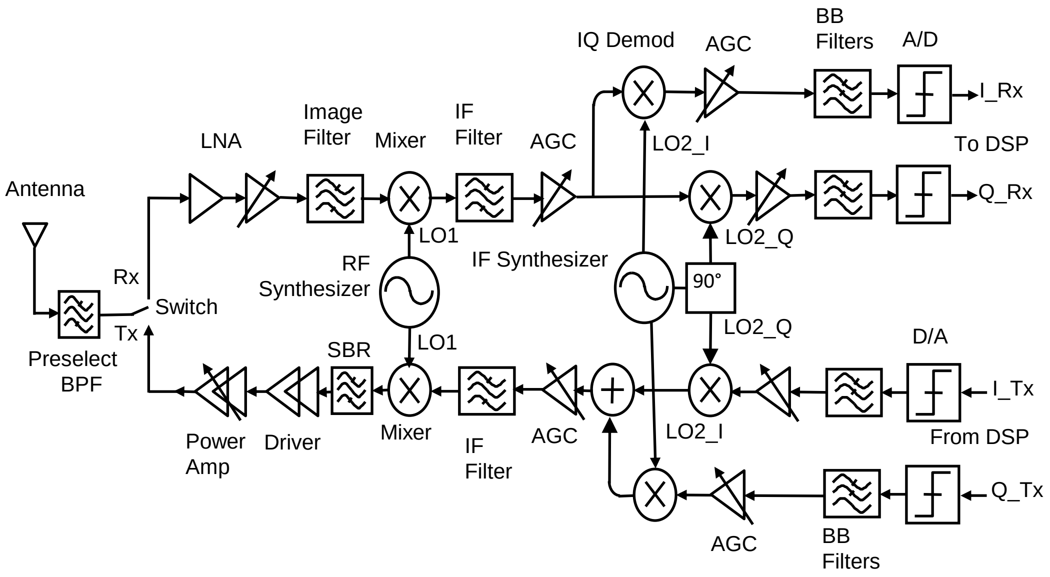


Superheterodyne Transceivers



- Rx path -> signals first passed through preselect BPF to remove interference from other freq bands
- PBPF bad for NF of radio, but placing filter here makes design of Rx input easier ->will reduce power levels that front end must deal with.
- Next LNA
- gain step complicates design of LNA, but allows gain to be reduced for larger input levels, thus reducing lin requirements of rest of the radio.
- image filter next
- required since PBPF will typically not provide enough image rejection, or may have been omitted for noise reasons.
- signal then down converted by a mixer to an *intermediate frequency* (IF).

Superheterodyne Transceivers

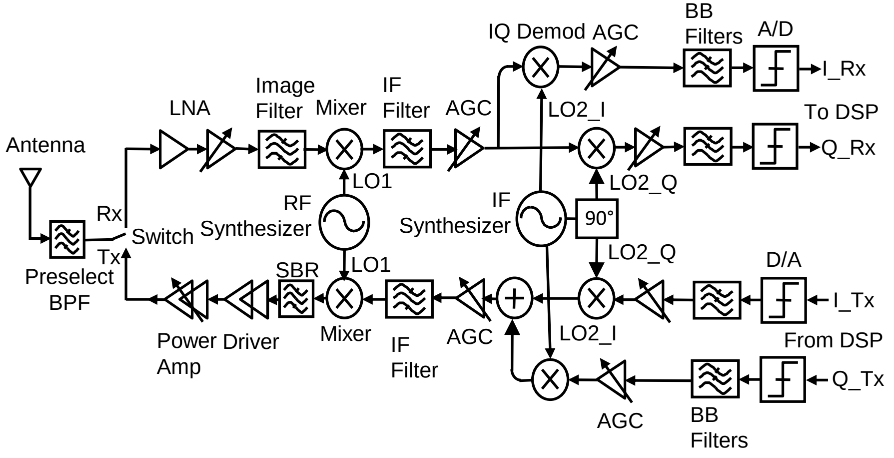


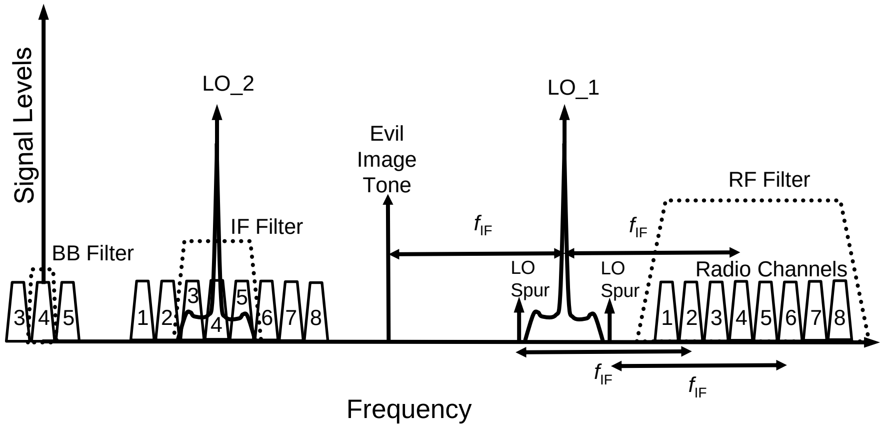
- IF freq must be chosen with great care -> many factors including interaction of spurs, mixing of LO harmonics.
- higher IF freq will make job of image filter easier, BUT IF stage especially the IF filter harder as it will need to work at higher freq.
- mixer mixes incoming RF signal with output from RF frequency synthesizer (LO).
- LO is tuned so that freq of desired IF signal is always at the same freq.
- LO can be either low-side injected or high-side injected

$$f_{\mathrm{IF}} = f_{\mathrm{RF}} - f_{\mathrm{LO}} \qquad\qquad f_{\mathrm{IF}} = f_{\mathrm{LO}} - f_{\mathrm{RF}}$$

Superheterodyne Transceivers

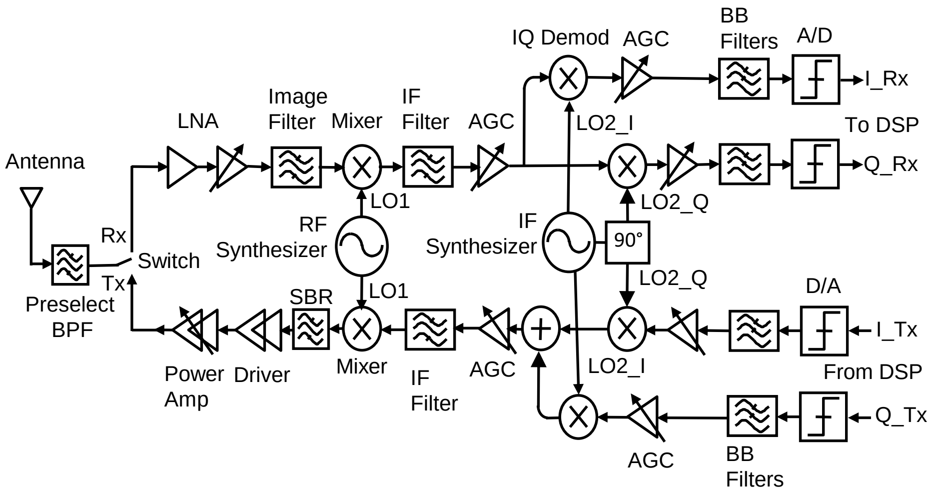
- After mixing to an IF, additional filtering is usually performed.
- At IF, unwanted channels can be filtered out
- *automatic gain control* (AGC) amplifiers also included at IF.
- They adjust gain of radio so that output amp always constant.
- AGC is performed at IF to avoid mismatches in gain between I and Q paths
- signals then down converted a 2nd time to baseband.
- 2nd down conversion requires a second freq synth -> produces both 0° and 90° output signals at IF freq.
- 2 mixers produce I and Q paths.
- By using 2 paths, both amp/phase can be recovered -> incoming phase of RF signal does not need to be synchronized to phase of LO.
- I and Q signals then passed through baseband filters -> remove rest of unwanted channels.
- signal passed through an ADC and into back end of radio.
- may be additional, possibly programmable, gain stages in the base band.
- better the quality of base band filter easier job of ADC
- good quality BB filter will remove more unwanted out-of-band energy
- there is direct tradeoff between performance level of these 2 components.
- Further signal processing performed in BBSP.





Superheterodyne Transceivers

- Tx works much same way in reverse.
- BBSP circuitry followed by DAC produces I and Q signals
- signals then filtered
- spectrum of the signals has already been shaped in BBSP, but harmonics or other unwanted tones can be generated by DAC.
- Tx will usually have some AGC function which may be either in base band or IF
- AGC in base band creates matching issues, while implementing it at higher freqs will make circuit implementation harder.
- IF signal is up-converted to RF freq by mixer.
- If LO is low-side injected mixer is used to generate sum, rather than difference products.

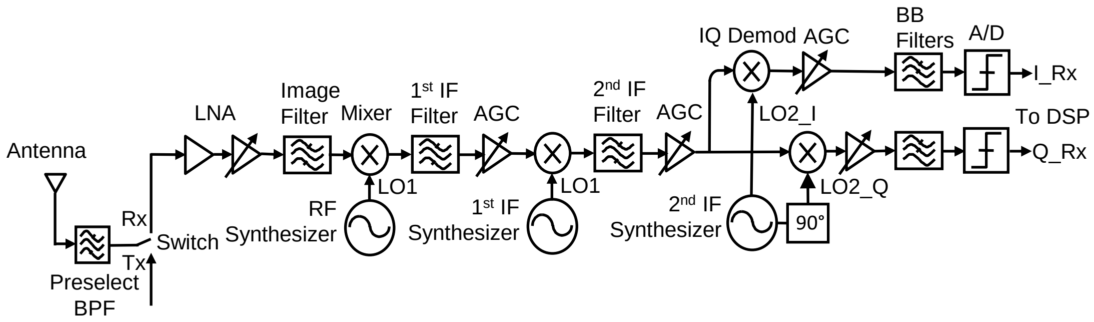


$$f_{\mathrm{RF}} = f_{\mathrm{LO}} + f_{\mathrm{IF}} \qquad f_{\mathrm{RF}} = f_{\mathrm{LO}} - f_{\mathrm{IF}}$$

- mixer in either case will create unwanted sideband as both sum and difference freqs will be generated
- Once up-converted to RF, signal is passed through a sideband select filter (SBS) to remove unwanted sideband and any LO feed through
- this is done before PA to avoid amplifying an unwanted signal.
- After PA additional filters may be present to remove PA harmonics and make sure that Tx power masks are not violated
- RF signal is then radiated by antenna into air
- In RF section PA itself may have a power control function or additional AGC.
- If power level is constant, it must be high enough so that signal can be detected at max distance dictated by system specs.

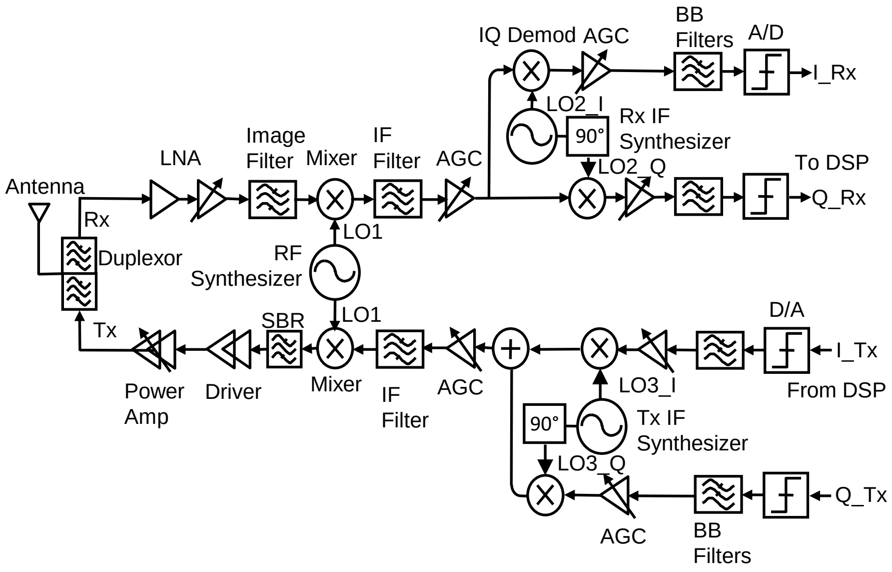
Superheterodyne Transceivers

- Another refinement that can be made to superheterodyne architecture is to design Rx to have 2 IFs rather than just 1
- main advantage to this refinement to architecture is seen in Rx.
- first IF can be chosen to be at a higher freq easing requirements of image reject filter
- 2nd IF can be chosen to be at a much lower freq allowing 2nd IF filter to achieve better channel selection with a lower Q
- final down conversion and IQ generation can be performed at a lower freq making this task easier.
- disadvantage is that it requires more circuitry and another synthesizer



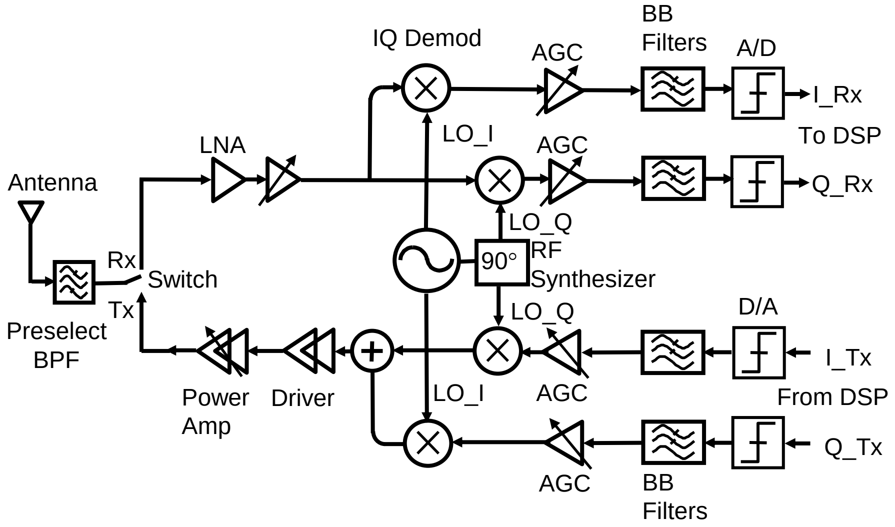
Superheterodyne Transceivers

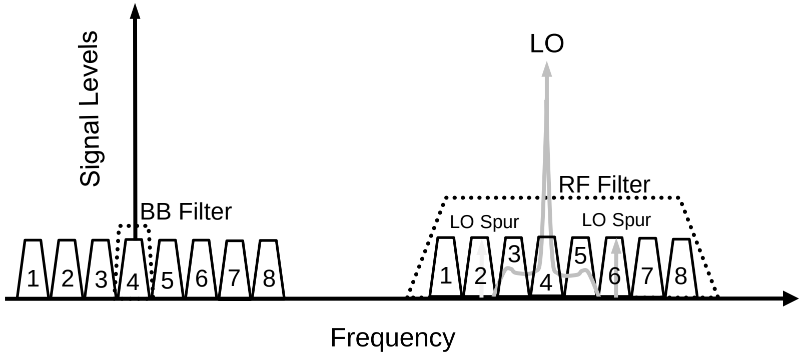
- In full duplex radio Tx and Rx operate at different freqs, therefore it is no longer possible to share all synthesizers.
- Usually it is RF synthesizer which is shared and 2 IF synthesizers which are separated.
- if further isolation were needed in a full duplex application, then one might employ 2 antennas, but since these antennas would likely have to be close to each other this would not remove the need for a duplexor as energy radiated by transmitting antenna would be absorbed by receiving antenna.



Direct Conversion Transceivers

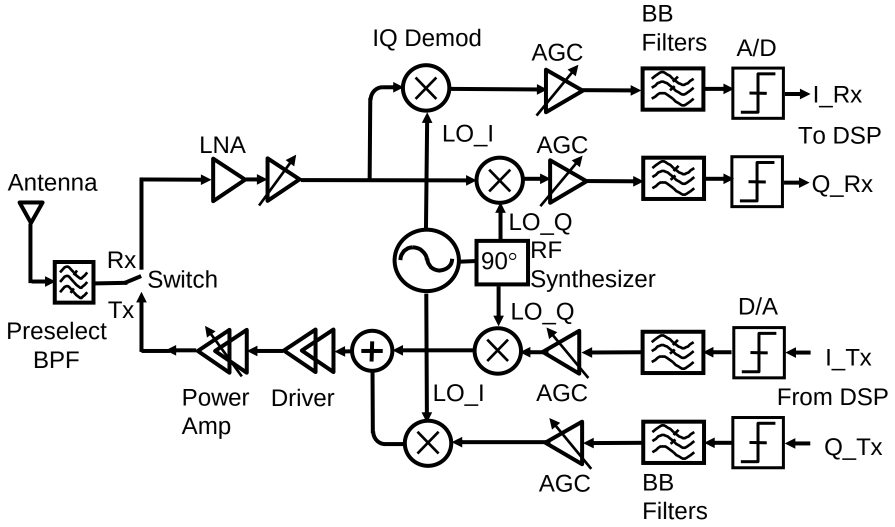
- In this architecture, IF stage is omitted and signals are converted directly to DC.
- sometimes called a *zero-IF* radio
- direct-conversion transceiver has become popular in recent years because it saves area and power associated with a 2nd synthesizer although if it was made into a full duplex radio 2 RF synthesizers would still be needed.
- requires fewer filters making it more compatible with modern IC technologies.
- no image filter needed and LO freq selection trivial.
- generating I and Q signals from a synthesizer at higher freqs much more difficult than at IF.
- Since LO now at same freq as RF signal, LO energy can couple into RF path and cause problems.
- Without IF stage more gain and gain control must be done at base band making amp and phase matching more difficult
- LO spurs can be troublesome in a direct down conversion radio.
- Here 2 sideband spurs will act to convert unwanted channels 2 and 6 to baseband possibly corrupting the desired signal.

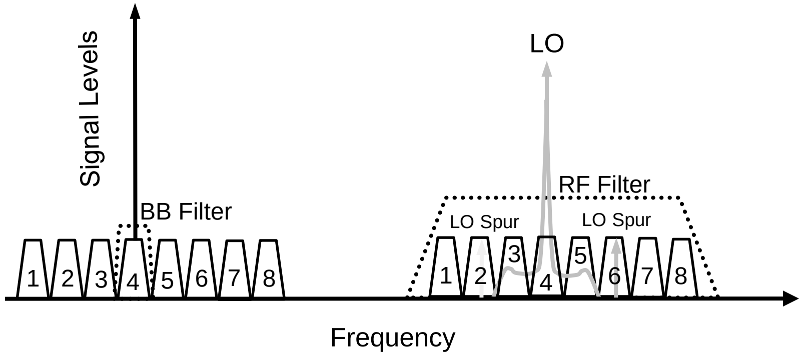




Direct Conversion Transceivers

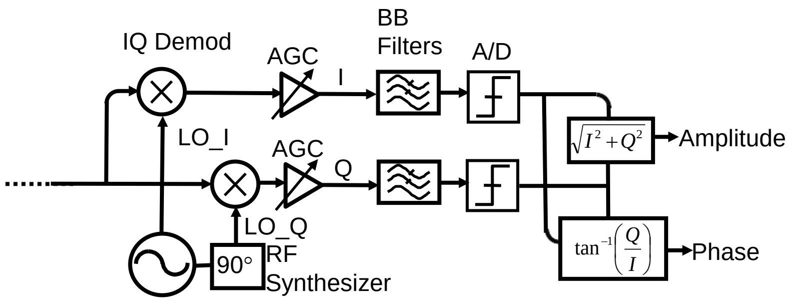
- Tx path is also simpler than superheterodyne case -> signal is converted directly to RF.
- part of AGC function will need to be done at RF to avoid matching problems.
- RF filter requirements on Tx are greatly reduced since direct conversion means there is no unwanted sideband to be filtered out or LO feedthrough to worry about.
- Sometimes combine superheterodyne Rx with direct conversion Tx.
- Another problem with direct conversion architecture when used in full duplex radio is two high freq VCOs operating at close to same freq.
- VCOs would likely try and pull each other off freq
- One VCO would likely have to operate at another freq band and a freq translation network would be needed to generate final LO freq.





Coherent Vs. Non Coherent Receivers

- receivers presented so far are examples of non-coherent receivers -> no attempt is made to determine the phase of the transmitted carrier.
- Since there is no knowledge of phase, transmitted carrier will have an arbitrary phase relative to LO used in Rx.
- if only one mixer were used then output amplitude would depend on this relative phase difference.
- If they happened to be in phase then output amp would be maximized, but if they happened to be phase shifted by 90° then output would be zero
- 2 mixers are employed such that base band signal can recover both phase and amp information.
- coherent radio will recover phase of transmitted waveform and remove need for 2nd mixer
- This architecture isn't very common as reconstructing phase of incoming RF carrier would likely be a very hard circuit to implement.
- In either case, there is still problem of having no reference set to compare against.
- If modulation is DPSK then no problem, but still has problem of aligning reference to determine what was sent if a modulation scheme like BPSK or 16QAM is used.
- If OFDM signal is being used, then likely some carriers will contain reference tones so that both amp and phase references can be established.
- For non-OFDM waveforms, then often at the start of communication, training information will be transmitted to align a local reference to the data.
- E.g. 16QAM, then at start of transmission there may be a DPSK sequence sent to train Rx
- Once relative phase and amp has been established then link can gear up into more complicated data mode.



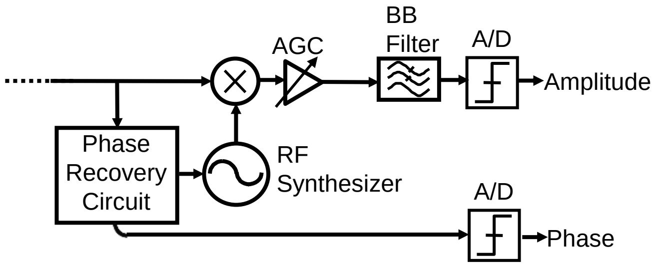


Image Rejecting/Sideband Suppression Architectures

- Mixing always produces 2 sidebands: $\omega_{LO}+\omega_{IF}$ and $\omega_{LO}-\omega_{IF}$
- It is possible to use a filter *after* mixer in Tx to get rid of unwanted sideband for up-conversion case.
- Similarly, possible to use filter *before* mixer in Rx to eliminate unwanted signals at image freq for down-conversion
- Alternatively, *single-sideband mixer* for Tx path, or image-reject mixer for Rx path can be used.

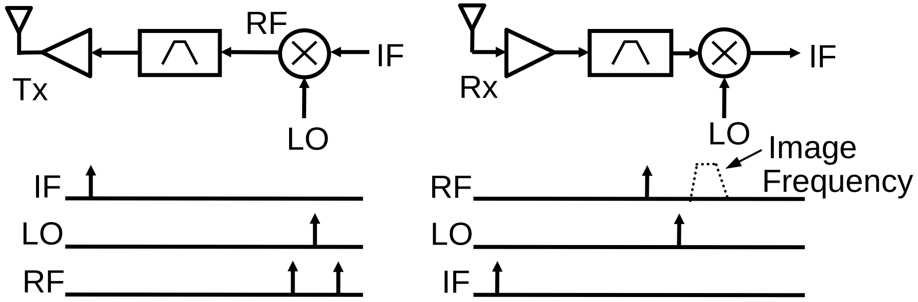
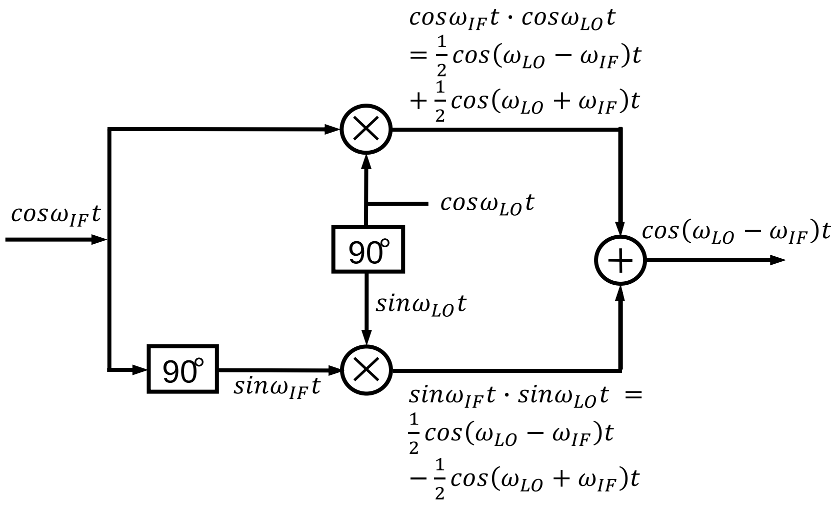
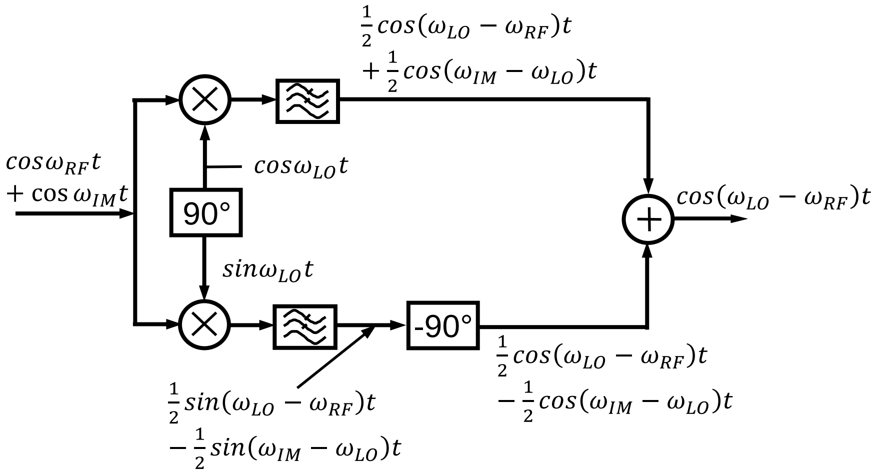


Image Rejecting/Sideband Suppression Architectures

- E.g. of single-sideband up-conversion mixer consists of two basic mixer circuits, two 90° phase shifters and summing stage.
- use of phase shifters and mixers will cause one sideband to add in phase and other to add in antiphase, leaving only desired sideband at output.
- Which sideband is rejected depends on placement of phase shifts or polarity of summing block.
- three signals in this circuit: input, output, LO: 90° phase shift must be present in two of these signals, but any two of three signals may be used.
- Changing placement of phase shifters and/or sign of phase shift it is easy to select either sideband at output.





An Alternative Single Sideband Mixer

- previous image-reject configuration is also known as *Hartley architecture*.
- Another possible implementation is *Weaver architecture*.
- phase shifter after mixer is replaced by another set of mixers to perform an equivalent operation.
- advantage is that all phase shifting takes place only in LO path and there are no phase shifters in signal path.
- less sensitive to amp mismatch in phase shifting networks and so image rejection is improved.
- disadvantage is additional mixers required, but if Rx has a two-stage down-conversion architecture, then these mixers are already present so there is no penalty.
- depending on whether high side or low side injected LOs are chosen two phase shifts may have to be changed from 90° to -90° or summing block might need to be replaced with a subtraction.

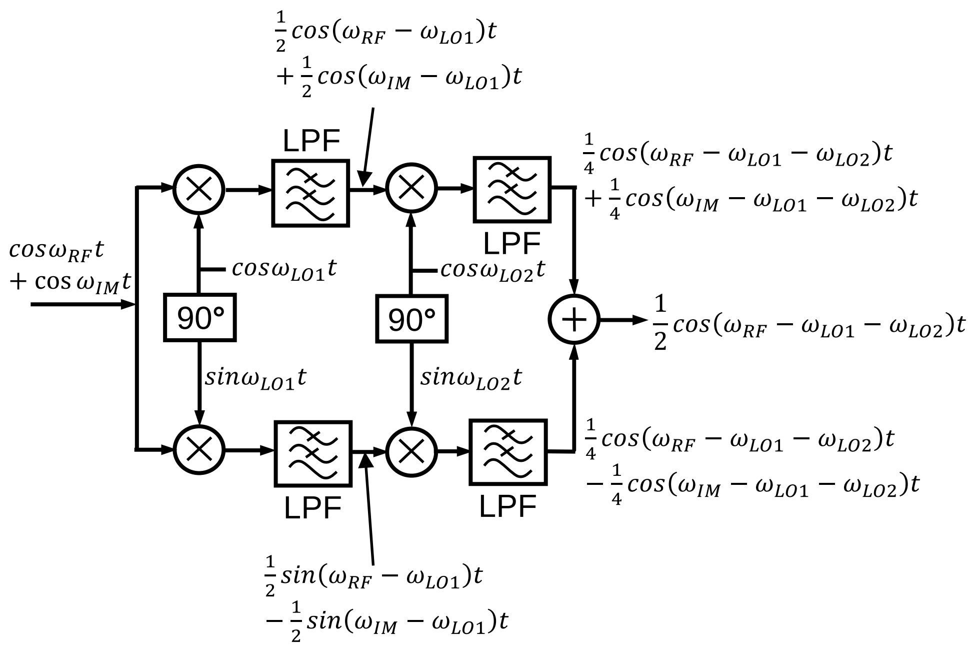
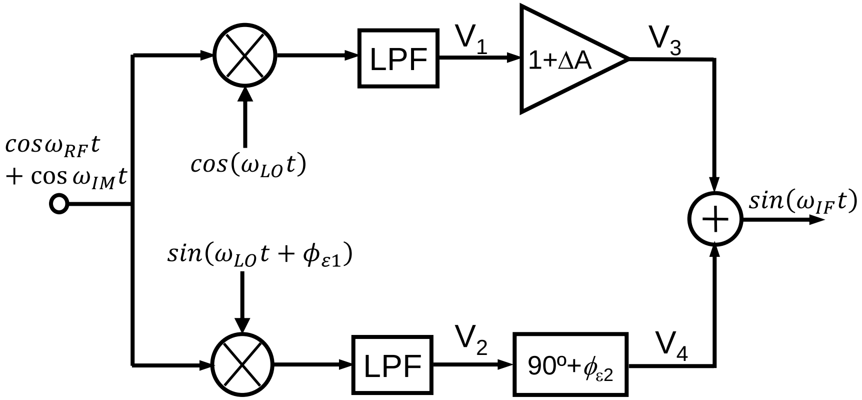
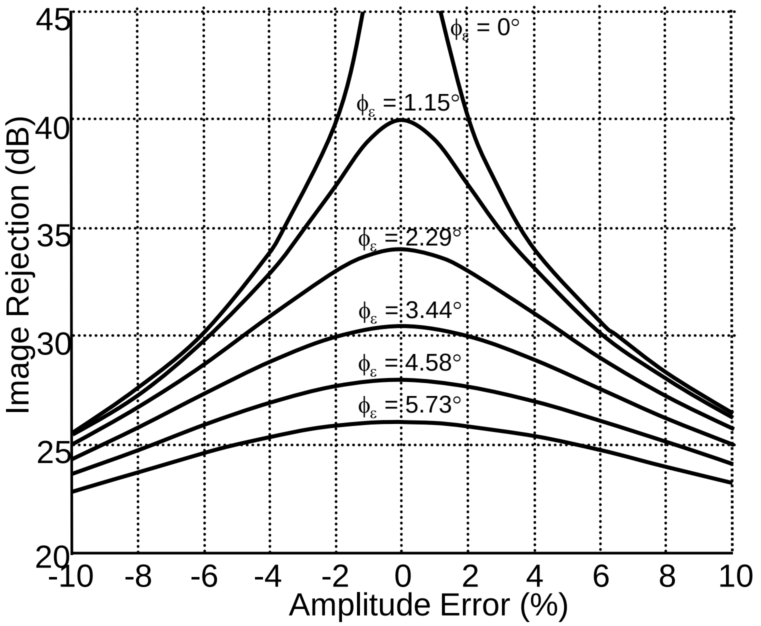
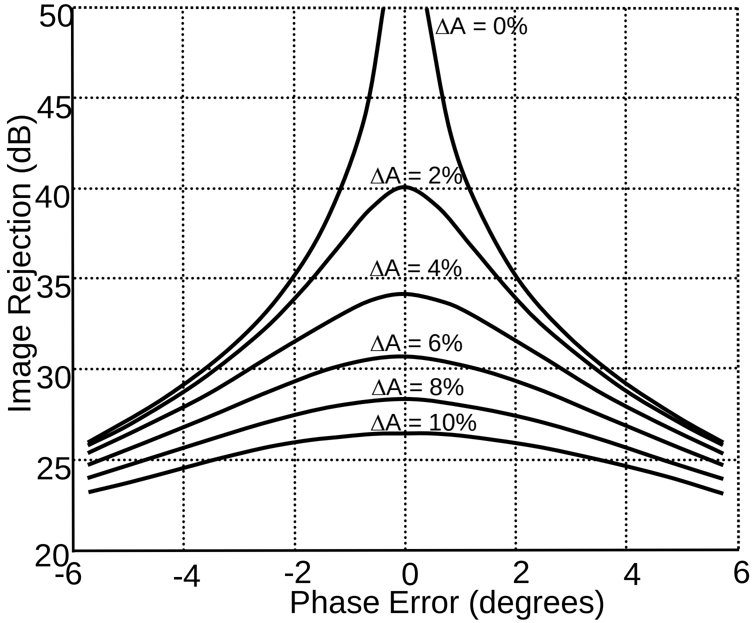


Image Rejection with Amplitude and Phase Mismatch



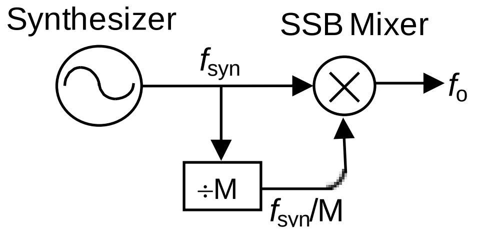
$$\mathrm{IRR} = 10\log\frac{|V_{\mathrm{RF}}|^2}{|V_{\mathrm{IM}}|^2} = 10\log\left\{\frac{1+(1+\Delta A)^2+2(1+\Delta A)\cos(\phi_{\varepsilon 1}+\phi_{\varepsilon 2})}{1+(1+\Delta A)^2-2(1+\Delta A)\cos(\phi_{\varepsilon 2}-\phi_{\varepsilon 1})}\right\}$$





LO Generation

- There are many reasons why it may not be desirable to have a synthesizer running at exactly the freq needed for mixer.
- E.g. in full duplex radios, two synthesizers running at close to same freq could pull each other off freq.
- direct down conversion radios can have LO feedback reach antenna and get radiated.
- If LO is off freq, necessary to design an LO freq translation network.
- One simple way to do this is with integer dividers, which are fairly easy to implement at RF freqs.
- Divide-by-two very popular because a common implementation of this function naturally produces quadrature outputs.
- If a more complicated freq translation shown below
- uses a single sideband mixer and divider.



$$f_o = f_{syn}\left(\frac{M \pm 1}{M}\right)$$

Example Generating a Reference Tone
A GPS receiver which operates at 1.575 GHz is to be integrated with a 2.4GHz WLAN chip.
How can synthesizer be reused for GPS receiver?

Solution:
If the WLAN synthesizer can be tuned above the band to 2.625GHz then using a division ratio of 3/5 will yield the GPS frequency.
If we use the divider structure shown with M = 5, using the higher frequency output yields a 6/5 output.
Following the output with a divide by two will give an overall output at 3/5 of the input frequency.

LO Generation

Example Generating LOs for an UWB radio.

- An ultra-wideband radio employs a freq hopping spread spectrum technique.
- This technique requires radio to be able to change channels in less than 9ns.
- A synthesizer cannot be designed to switch is this length of time.
- Thus instead all channels must be derived from a single source tone of 16896MHz.
- Design a LO network that takes signal at 16896MHz and with SSB mixers, MUXs, and dividers generates all these freqs which correspond to the center of each UWB channel: 3432MHz, 3960MHz, 4488MHz, 5016MHz, 5544MHz, 6072MHz, 6600MHz, 7128MHz, 7656MHz, 8184MHz, 8712MHz, 9240MHz, 9768MHz, and 10296MHz.

Solution:

- Note first that the channels are spaced by 528MHz.
- Passing the 16896MHz source signal through a series of ÷2 stages will generate 8448MHz, 4224MHz, 2112MHz, 1056MHz, 528MHz, and 264MHz.
- Combinations of these signals can be used to generate all the required channels
- Either 8448 or 4224 is mixed with either 1056 or 2112 in a single sideband mixer to produce sum/difference.
- result of this operation will be 264MHz from the center of at least one channel.
- final mixer can combine result of the first operation with 264MHz and produce desired output freq.
- Channel switching can now be accomplished in the length of time it takes to change the control on three MUX circuits.

Table 4.1 Summary of a solution to generate all the UWB tones for a radio.

Channel	Band Group	Desired LO frequency (MHz)	Signals Used to Sinthesize
1	1	3432	4224-1056+264
2	1	3960	4224-264
3	1	4488	4224+264
4	2	5016	4224+1056-264
5	2	5544	4224+1056+264
6	2	6072	8448-2112-264
7	3	6600	8448-2112+264
8	3	7128	8448-1056-264
9	3	7656	8448-1056+264
10	4	8184	8448-264
11	4	8712	8448+264
12	4	9240	8448+1056-264
13	5	9768	8448+1056+264
14	5	10296	8448+2112-264