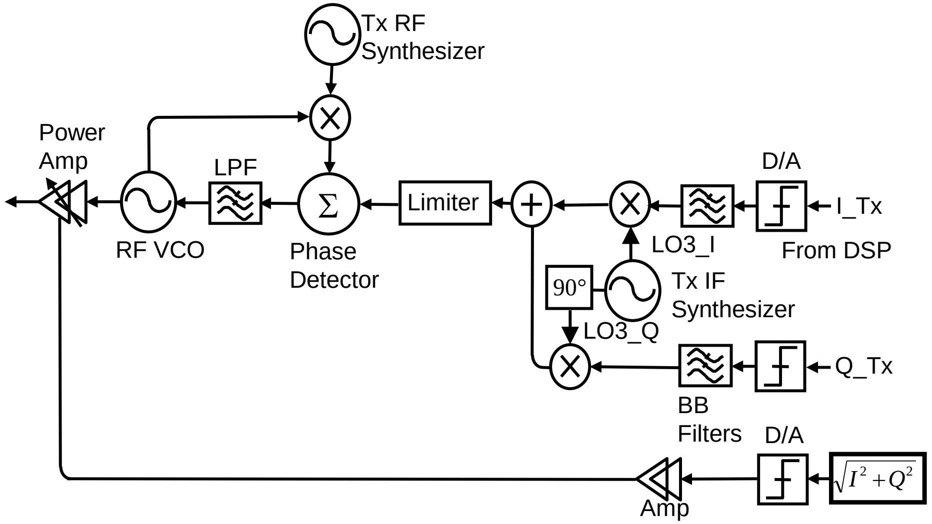
RF Systems Course: RF Archetectures II

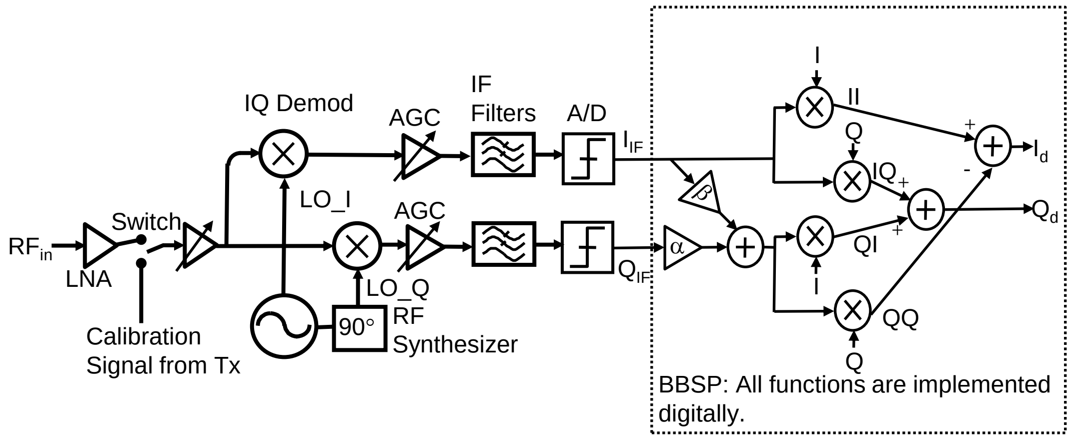
Offset Phase Locked Loop Transmitters

- Good for constant envelope modulations -> has numerous advantages.
- Tx path starts in traditional way, but amp information is removed with limiter.
- PD, mixer, LPF, VCO form feedback loop -> forces phase of VCO to track phase of data.
- mixer in feedback path so IF freq = difference in freq of Tx RF synthesizer and VCO.
- mixer is used instead of a divider to convert VCO freq back down because mixer will not divide phase of VCO -> phase of data can be upconverted without being multiplied by difference in freq between data and VCO.
- LPF is included to adjust feedback system parameters.
- VCO directly drives PA.
- phase-only modulation -> PA can be highly efficient nonlinear device.
- VCO drives PA directly -> out-of-channel noise floor can be much lower
- big deal in full duplex radio where energy leakage into Rx band can be problematic.
- removing mixer from Tx path means no other sideband to be filtered.
- AM modulation can be added back into waveform by dynamically adjusting PA power supply



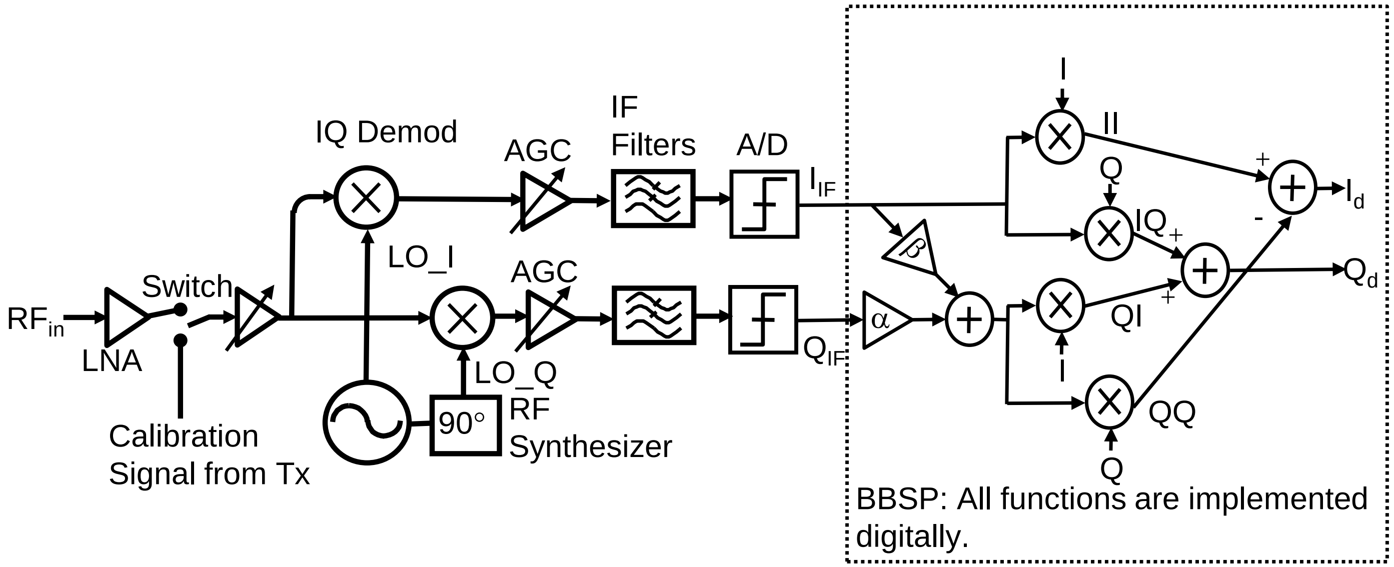
Low IF Transceiver

- superheterodyne radio, but IF freq chosen to be so low that both IF and base band processing can be performed in the digital domain.
- To make ADC easier, IF should be chosen as low as possible and can be as low as signal BW
- Unlike offset PLL, low IF architecture sees most of its advantages on receive side.
- RF circuitry as simple as direct down conversion, but won't suffer from DC offset problem and flicker noise.
- main problem is image freq very close to desired freq -> impossible to filter out.
- image-reject architecture needed



Low IF Transceiver

- solves image problem with Weaver image reject architecture.
- advantage here is that 2nd set of mixers and LO signal is implemented in BBSP.
- phase shift of 2nd set of LOs will be perfect.
- Since analog parts will suffer from imperfections, this can also be calibrated out in BBSP.
- 2 amps with gain α and β fix both amp and phase mismatch in analog hardware.
- If no mismatch $\alpha = 1$ and $\beta = 0$.
- to calibrate Rx, first it is placed in a test mode where a signal from Tx is fed back to receiver.
- 1st test performed with $\alpha = 1$, $\beta = 0$.
- In this test adjusting sign of last digital addition both desired and image sidebands can be recovered.
- assume RF paths have some amp mismatch ΔA and some phase error in RF synthesizer ϕ_{e}.



Low IF Transceiver

- because correction applied to Q path only, assume errors occur in Q path and I path is ideal
- assuming that RF is high side injected:

$$I_{IF} = \cos(\omega_{IF}t + \varphi(t))$$
$$Q_{IF} = -(1+\Delta A)\sin(\omega_{IF}t + \phi_e + \varphi(t))$$

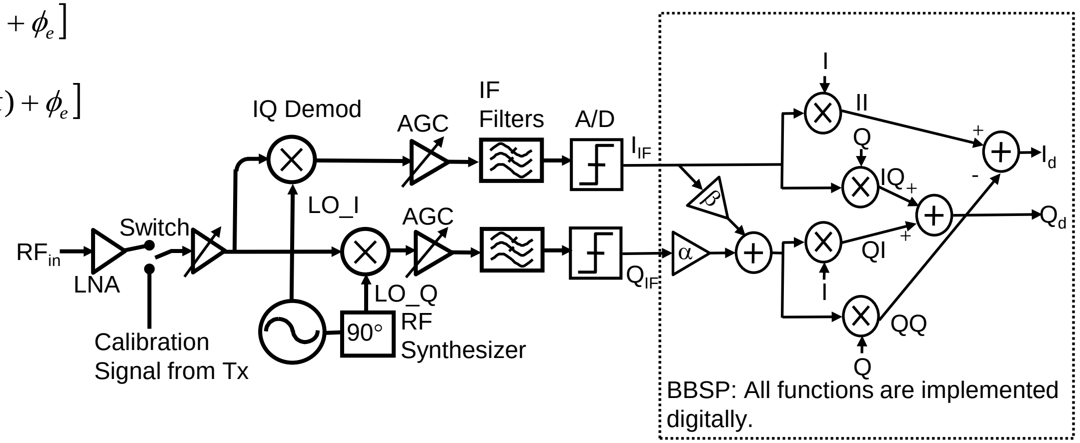
- since these are now digital signals, they can be normalized to an amp of 1.
- result after 2nd down conversion is:

$$II = \frac{1}{2}\cos\varphi(t)$$
$$IQ = -\frac{1}{2}\sin\varphi(t)$$
$$QI = -\frac{1+\Delta A}{2}\sin[\varphi(t)+\phi_e]$$
$$QQ = -\frac{1+\Delta A}{2}\cos[\varphi(t)+\phi_e]$$

$$I_d = II - QQ \approx \cos\varphi(t)\cos(\frac{\phi_e}{2})$$
$$Q_d = IQ + QI \approx \sin\varphi(t)\cos(\frac{\phi_e}{2})$$

- reverse signs of final addition -> can set mixer to recover other sideband.
- If we are still feeding in same signal at RF it will now be at image freq for this new BBSP configuration.
- we can evaluate how much image gets through mixers.
- image signal can also be determined (remembering to reverse the additions and subtractions so now mixer is trying to reject RF signal as it is unwanted sideband) as:

$$I_{im} = II + QQ \approx -\frac{1}{2}\left[-\Delta A\cos(\phi_e)\cos\varphi(t) - 2\sin(\frac{\phi_e}{2})\sin\varphi(t)\right]$$
$$Q_{im} = IQ - QI \approx \frac{1}{2}\left[\Delta A\cos(\phi_e)\sin\varphi(t) - 2\sin(\frac{\phi_e}{2})\cos\varphi(t)\right]$$



Low IF Transceiver

From the previous slide

$$\frac{I_{im}}{I_d} = -\frac{1}{2}\left[-\Delta A\frac{\cos(\phi_e)}{\cos(\frac{\phi_e}{2})} - 2\tan(\frac{\phi_e}{2})\tan\varphi(t)\right] \approx -\frac{1}{2}\left[-\Delta A - 2\tan(\frac{\phi_e}{2})\tan\varphi(t)\right] = \frac{1}{2}\left[\Delta A + 2\tan(\frac{\phi_e}{2})\frac{Q_d}{I_d}\right]$$

$$\frac{Q_{im}}{Q_d} = \frac{1}{2}\left[\Delta A\frac{\cos(\phi_e)}{\cos(\frac{\phi_e}{2})} - 2\tan(\frac{\phi_e}{2})\cot\varphi(t)\right] \approx \frac{1}{2}\left[\Delta A - 2\tan(\frac{\phi_e}{2})\cot\varphi(t)\right] = \frac{1}{2}\left[\Delta A - 2\tan(\frac{\phi_e}{2})\frac{I_d}{Q_d}\right]$$

Solving for the errors:

$$\Delta A = \frac{-2(Q_d Q_{im} + I_d I_{im})}{I_d^{\ 2} + Q_d^{\ 2}} \qquad \phi_e = 2\tan^{-1}\left[\frac{Q_d I_{im} - I_d Q_{im}}{Q_d^{\ 2} + I_d^{\ 2}}\right]$$

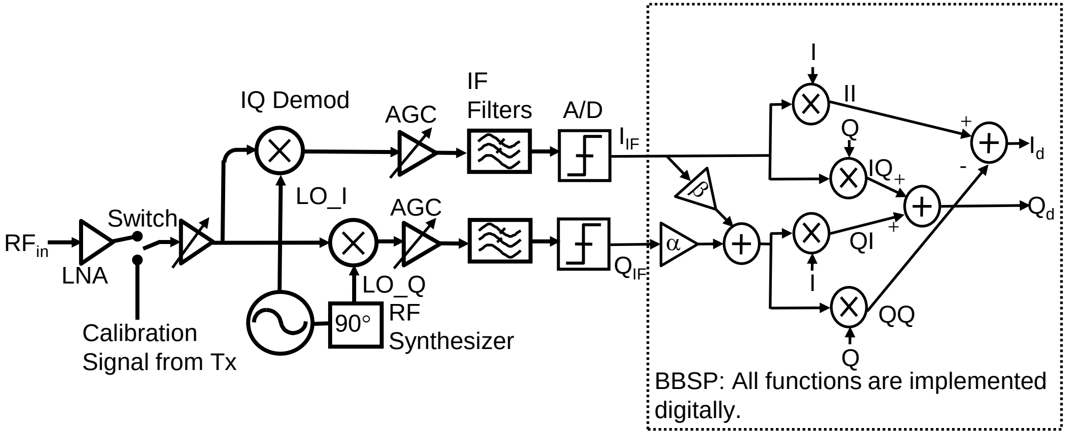
Now we know the errors

$$Q_{IF} = -\alpha\cos(\phi_e)\cdot(1+\Delta A)\sin(\omega_{IF}t + \varphi(t)) - [\beta + \alpha(1+\Delta A)\sin(\phi_e)]\cos(\omega_{IF}t + \varphi(t))$$

Set α and β so this is perfect:

$$\alpha = \frac{1}{(1+\Delta A)\cos(\phi_e)}$$

$$\beta = -\tan(\phi_e)$$



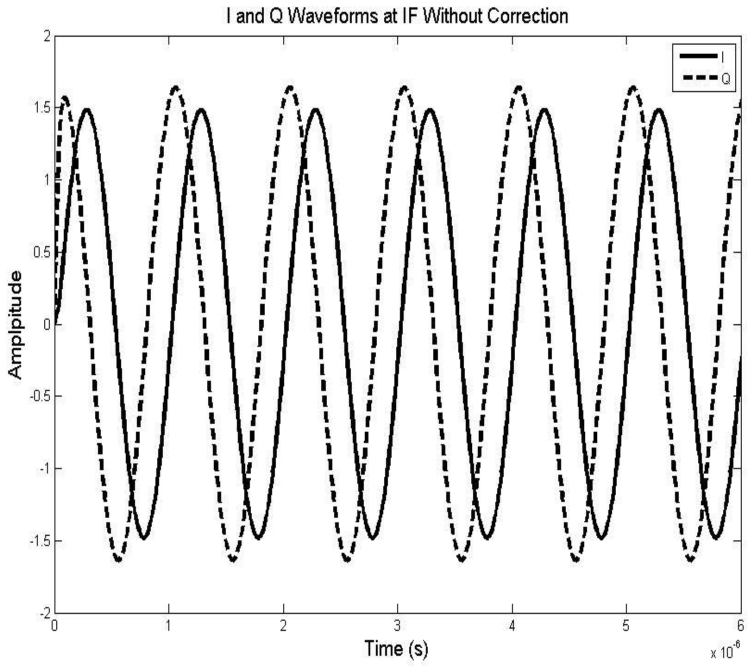
Low IF Transceiver Example

- A low IF receiver receives 101MHz RF signal and converts it to 1MHz IF using 100MHz LO
- There are errors in the RF part of the circuit.
- These need to be corrected within the BBSP part of the radio.
- Simulate the system and determine the correction coefficients needed.

- First test signal at 101MHz is fed into receiver and IF signals are observed in simulation.
- Clearly these waveforms are not well balanced.
- The actual amp and phase mismatch could be found from this graph, but it can also be found from baseband signals just as the processor would do.
- Reading the baseband output data it is found that: I_d = -0.445, Q_d = 1.488, I_{im} = 0.151, Q_{im} = -0.0326.
- amplitude and phase mismatch can be found to be:

$$\Delta A = \frac{-2(Q_d Q_{im} + I_d I_{im})}{I_d^{\,2} + Q_d^{\,2}} = \frac{-2(1.488 \cdot -0.0326 + -0.445 \cdot 0.151)}{(-0.445)^2 + 1.488^2} = 0.096$$

$$\phi_e = 2\tan^{-1}\left[\frac{Q_d I_{im} - I_d Q_{im}}{Q_d^{\,2} + I_d^{\,2}}\right] = 2\tan^{-1}\left[\frac{1.488 \cdot 0.151 - 0.445 \cdot 0.0326}{0.445^2 + 1.488^2}\right] = 9.96°$$



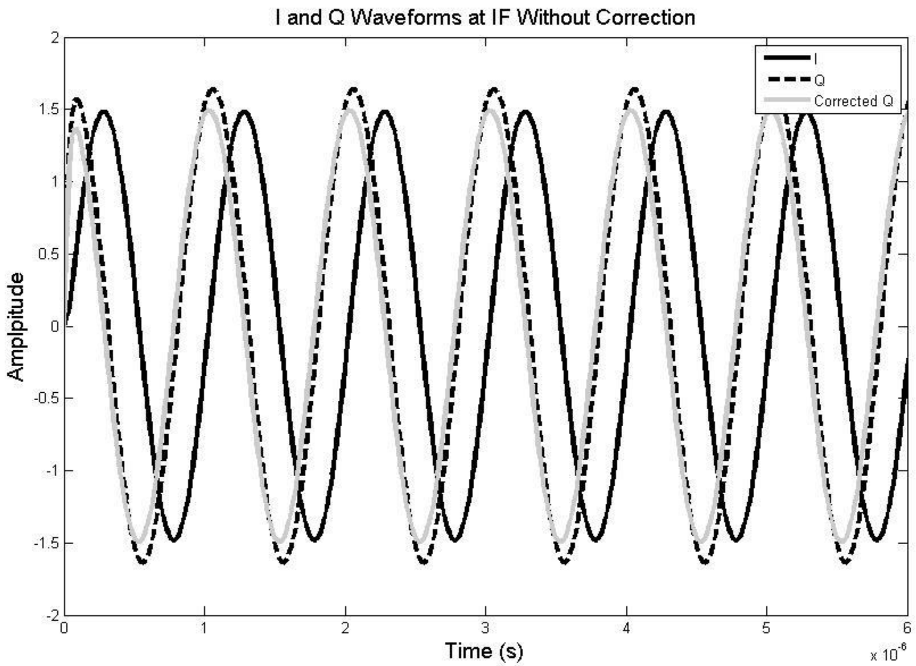
Now that the imbalance is known for this radio, compensation can be calculated as:

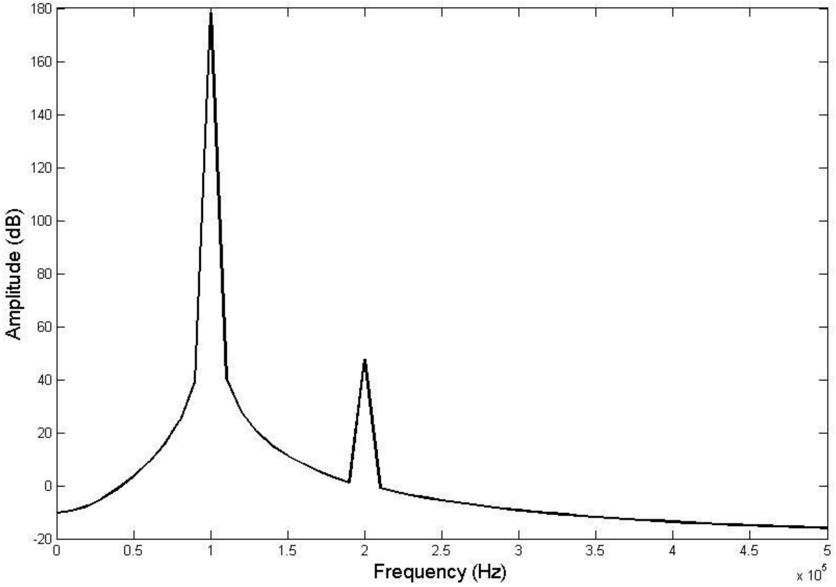
$$\alpha = \frac{1}{(1+\Delta A)\cos(\phi_e)} = \frac{1}{(1+0.096)\cos(9.96°)} = 0.926$$

$$\beta = -\tan(\phi_e) = -\tan(9.96°) = -0.176$$

Low IF Transceiver Example

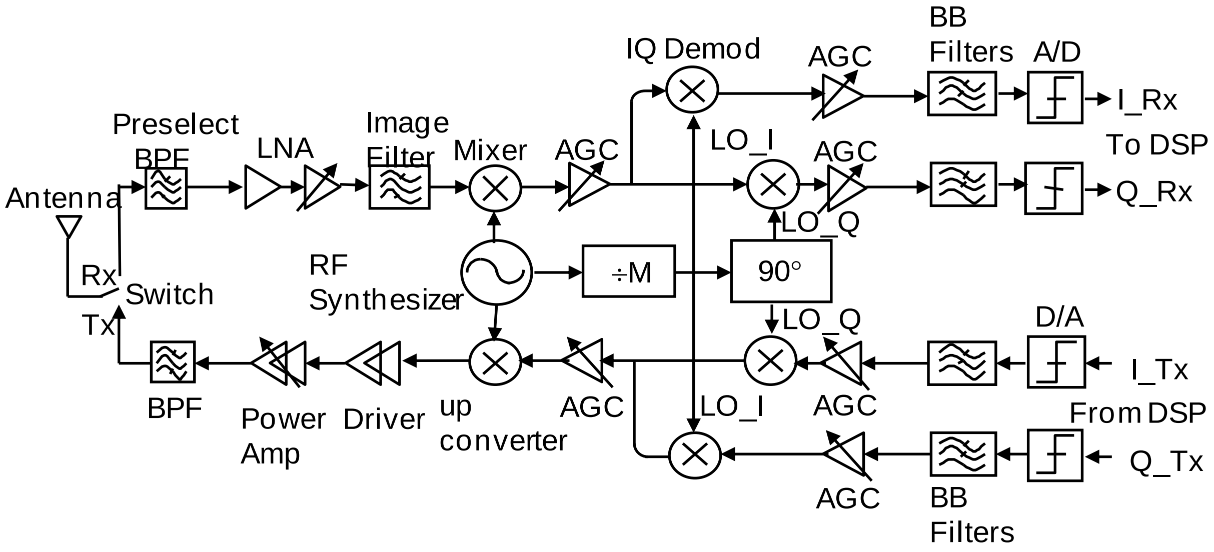
- These numbers are now added to Rx to correct the signal.
- simulation is run once more and both I_{im} and Q_{im} are now very close to 0 showing that correction was successful.
- can also be seen by looking at IF signals again and noting Q path after correction.
- In order to test sideband rejection of this receiver, a signal at 101.1MHz representing a desired 100kHz output and a signal at 98.8MHz representing an undesired 200kHz output signal was applied to the input.
- This figure shows nearly perfect image rejection.
- Note that sim of this receiver is almost ideal except for modeled imperfections explicitly stated in the RF section.





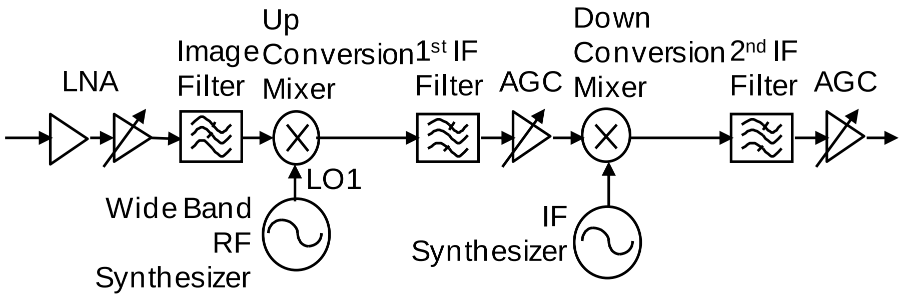
Walking IF Transceiver

- compromise between superheterodyne and direct-conversion transceiver
- This architecture derives IF LO by dividing the RF LO by some fixed number.
- IF freq is not fixed but “walks” in step with a fraction of the freq of RF LO.
- This transceiver with walking IF still has many of advantages of superhet radio (although it is not possible to filter as well at IF), but removes need for extra synthesizer, potentially reducing layout area and power dissipation.



An Up Conversion Down Conversion Receiver Architecture

- variation of superhet that can be used when Rx is expected to handle a wide band of input signals
- input signal is amplified by a broad band LNA and then low pass filtered to remove noise at image and then up converted to a fixed IF freq above band of Rx signals.
- then filtered to remove numerous unwanted channels and potentially provide image rejection and then down converted either to a second lower frequency IF or directly to base band.
- Applications include cable tuners for TV applications or AM radios.
- advantage of dual conversion architecture -> eliminates need for expensive external tracking filters to provide necessary image rejection at RF front-end.
- using a down converter would mean that for certain channels, image would be centered on another channel.
- placing a filter in front end that provided image rejection would require that filter to be tunable depending on what channel Rx was trying to receive.
- Implementing such filters is difficult using IC technology.
- Another problem with down converting wide BW signals -> harmonics of synthesizer may fall on other channels, down converting them on top of desired channel.
- Using this architecture moves images and VCO harmonics out of the receive band.



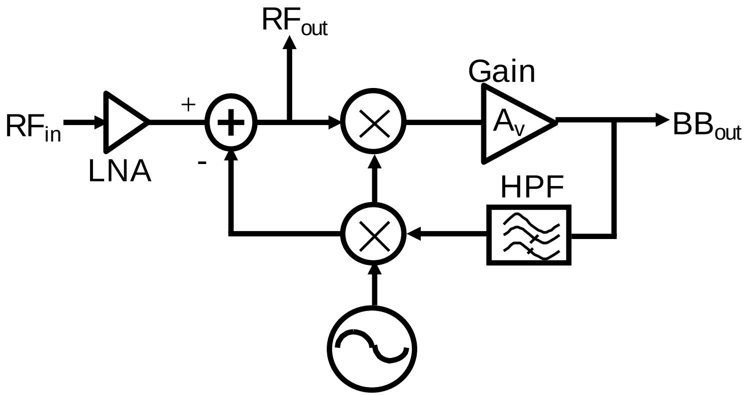
An Up Conversion Down Conversion Receiver Architecture Example

- In a cable tuner, RF front-end must not only exhibit low noise but it must also have high linearity and be broadband.
- must handle up to 135 interfering RF channels at +15 dBmV over a freq range from 47 to 870MHz.
- Determine a basic receiver freq plan to handle this situation.

- Solution:
- Since this is a wideband input, an up conversion down conversion architecture is chosen.
- 1^{st} IF freq chosen to be 1890MHz, (the European DECT frequency) to eliminate inband lower order beat products between 1^{st} and 2^{nd} VCO on chip and to keep filter cost low due to its high volume usage.
- To tune to this IF freq, high-side LO is chosen for wideband RF freq synthesizer (1936 to 2760MHz), places image freq range from 3826 to 4650MHz.
- front-end filter can easily reject this 1^{st} image.
- main purpose of RF front-end is to convert incoming band of RF signals to a single IF freq such that channel selectivity can be achieved by subsequent filtering.
- After 1^{st} IF filter only a few channels will remain, this will greatly reduce linearity requirement of 2^{nd} mixer block.
- 2^{nd} LO freq can be a fixed number.
- Choosing a low side injected LO sets freq of this synthesizer at 1840MHz to provide a 2^{nd} IF freq of 50MHz.

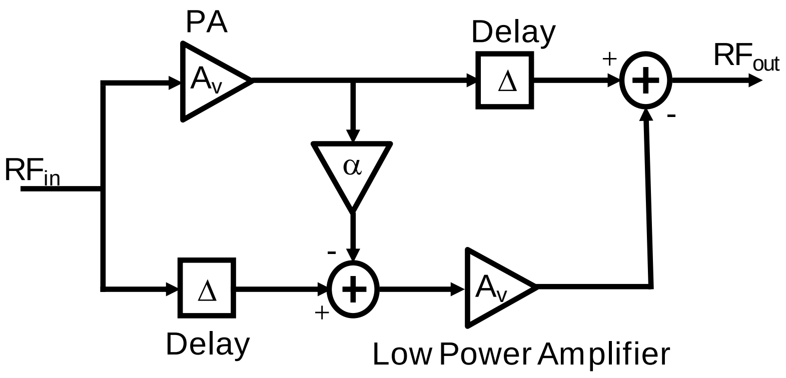
Channel Selection at RF

- All architectures considered so far do not perform any channel selection at RF.
- building tunable bandpass filters at RF freqs difficult.
- there are alternative architectures in RF front end to provide channel selection before down conversion.
- RF signal is mixed with an LO centered at desired channel.
- down converted signal is amplified and applied to a HPF.
- The job of HPF is to remove desired channel from overall waveform.
- Then signal is mixed back to RF freq and applied to a summing block.
- after summing block difference of incoming signal and incoming signal's unwanted channels is passed forward.
- This is a negative feedback loop and therefore through feedback loop will try and keep signals at RF_{out} node as small as possible in any freq band in which loop has gain.
- corrected RF_{out} signal could then be passed through a more conventional down conversion stage to an IF, or if a direction conversion radio is desired then output of system may be taken at BB_{out} instead.



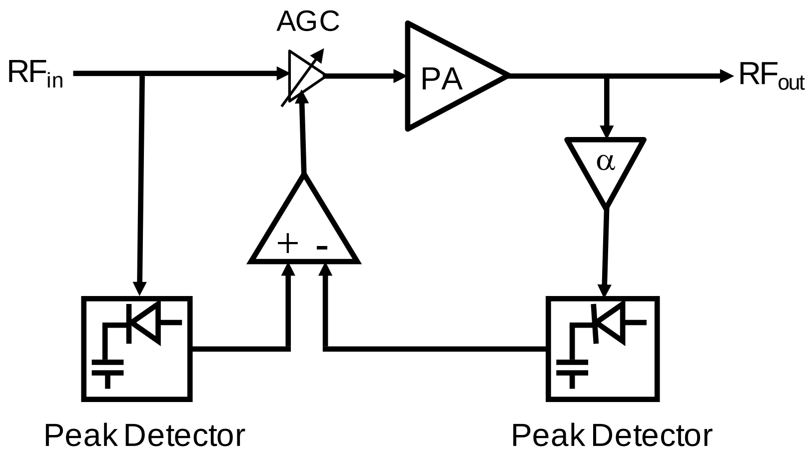
Transmitter Linearity Techniques

- feed forward linearization.
- additional blocks placed around RF PA to reduce distortion components.
- output of main PA is sensed by attenuator with a loss of α.
- α normally set to be equal to $1/A_v$.
- output of this attenuator is subtracted from a delayed version of input.
- delay is included to make sure that phases are aligned.
- idea is that output of lower summing block now includes only distortion components with main (desired) signal removed.
- result is passed through a low power amp and then subtracted from main output.
- gain of the low power amp should match main PA gain.
- After addition resulting output should contain desired signal with no distortion.



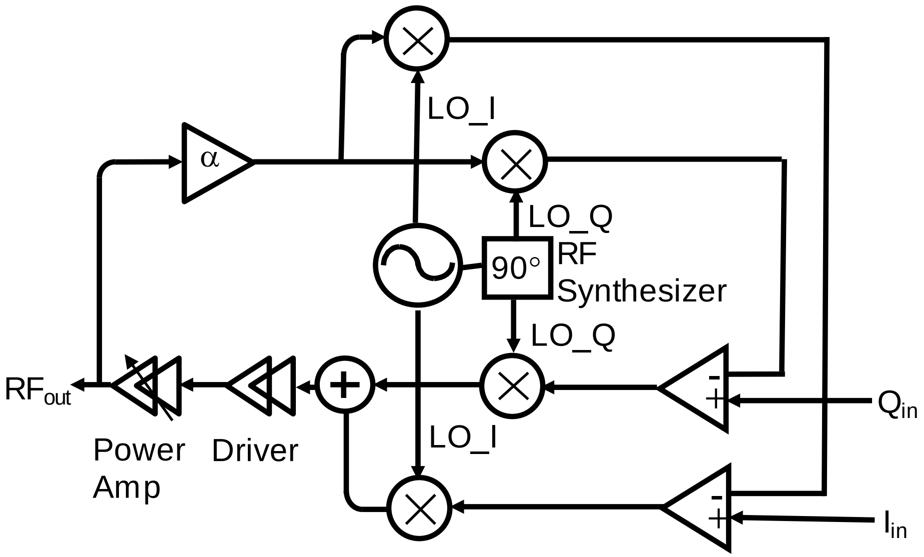
Transmitter Linearity Techniques

- feed forward technique can work very well, but depends on gains of the amps to be matched, low power amp to be linear, delays to match.
- If any of these parameters are wrong or incorrectly tuned, amount of distortion cancellation will decrease.
- feedback linearization:
- at RF there is often significant phase shift associated with obtaining desired gain and this poses stability problems for feedback systems.
- For this reason, direct RF feedback is not usually employed.
- more complicated architectures need to be used
- output of PA is sensed and attenuated and then passed through a peak detector.
- compared against input which is also passed through a peak detector.
- result is amplified and used to control the gain of Tx.
- relative phases of input and output are not compared -> correction provided by not perfect, but in many cases it is possible to provide a few crucial dB of needed linearity to a transmitter.



Transmitter Linearity Techniques

- Another feedback loop often used in transmitters is a Cartesian feedback loop.
- Here the output of the PA is attenuated and passed through a down converter.
- Amplifiers then perform the feedback comparison at the IF or baseband rather than at RF.
- This technique requires more complex circuitry then the previous architecture, but it can provide superior linearization as well.



Multiple Input Multiple Output (MIMO)

- The idea of having several radios either at the receiver or at the transmitter or both allows greater transmission range at the same transmitted power level and for the same data rate.
- Or with MIMO architectures, system SNR requirement can be relaxed for a given data rate.
- conventional single-input-single-output (SISO) 1x1 link is compared to various MIMO systems such as a 1x2 selection diversity link (spatially separated receiver or transmitter antennas to select the strongest signal), a 4x4 link that uses composite beam forming (CBF) technology and maximal ratio combining, and a vector CBF (VCBF) link.
- it can be seen that at data rate of 54Mbps, the SNR required for a 4x4 link is 16.5dB lower than that required by a 1x1 link, clearly demonstrating the advantages of MIMO architectures.