RF Systems Course: RF Systems Issues I

Noise Figure of Components in Series

- For components in series can calculate the total output noise $N_{o(total)}$ and output noise due to the source $N_{o(source)}$ to determine NF

output signal S_o

$$S_o = S_i \cdot G_1 \cdot G_2 \cdot G_3$$

input noise

$$N_{i(\text{source})} = kT$$

total output noise

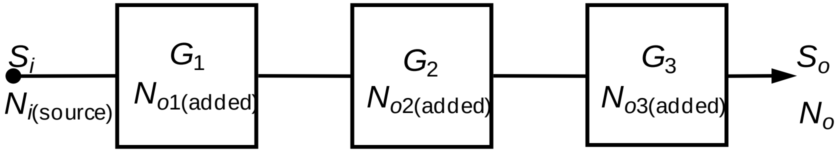
$$N_{o(\text{total})} = N_{i(\text{source})} G_1 G_2 G_3 + N_{o1(\text{added})} G_2 G_3 + N_{o2(\text{added})} G_3 + N_{o3(\text{added})}$$

output noise due to source

$$N_{o(\text{source})} = N_{i(\text{source})} G_1 G_2 G_3$$

$$F = \frac{N_{o(\text{total})}}{N_{o(\text{source})}} = 1 + \frac{N_{o1(\text{added})}}{N_{i(\text{source})} G_1} + \frac{N_{o2(\text{added})}}{N_{i(\text{source})} G_1 G_2} + \frac{N_{o3(\text{added})}}{N_{i(\text{source})} G_1 G_2 G_3} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2}$$

- formula shows how presence of gain preceding a stage causes effective NF to be reduced compared to measured NF of a stage by itself.
- typically design systems with LNA at front of the system.
- NF of each block is typically determined for case in which a standard input source (e.g., 50 Ω) is connected.



Noise Figure of Components in Series

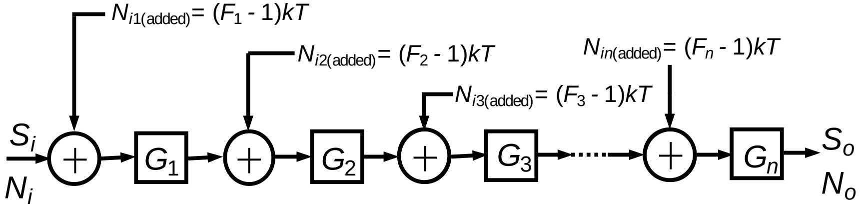
$$F=\frac{N_{o(\text{total})}}{N_{o(\text{source})}}=1+\frac{N_{o1(\text{added})}}{N_{i(\text{source})}G_1}+\frac{N_{o2(\text{added})}}{N_{i(\text{source})}G_1G_2}+\frac{N_{o3(\text{added})}}{N_{i(\text{source})}G_1G_2G_3}=F_1+\frac{F_2-1}{G_1}+\frac{F_3-1}{G_1G_2}$$

- formula can also be used to derive equivalent model of each block
- If input noise when measuring NF is

$$N_{i(\text{source})}=kT$$

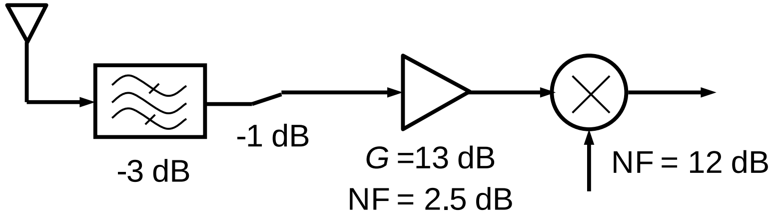
$$N_{o(\text{added})}=(F-1)N_{o(\text{source})}$$

$$N_{i(\text{added})}=(F-1)\frac{N_{o(\text{source})}}{G}=(F-1)N_{i(\text{source})}=(F-1)kT$$



Noise Figure of Components in Series

Example of Cascaded Noise Figure and Sensitivity Calculation
Find effective NF, noise floor of system shown.
Assume system needs SNR of 7 dB for a BER of 10^{-3}.
Assume system BW = 200 kHz.



Solution:

Since BW = 200 kHz, noise floor of system can be determined:

Noise Floor = $-174\ \text{dBm} + 10\log_{10}(200000) = -121\ \text{dBm}$

cascaded NF equation to determine overall system NF:

$$\text{NF}_{\text{TOTAL}}$$
$$= 3\ \text{dB} + 1\ \text{dB} + 10\log_{10}\left[10^{2.5/10} + \frac{10^{12/10} - 1}{10^{13/10}}\right]$$
$$= 3\ \text{dB} + 1\ \text{dB} + 10\log_{10}\left[1.78 + \frac{15.84 - 1}{20}\right] \approx 8\ \text{dB}$$

- if mixer has gain, possibly noise due to IF stage may be ignored.
- here we will ignore noise in IF stage.
- Since it was stated that system requires *S/N* = 7 dB, sensitivity of system can now be determined:
- Sensitivity = $-121\ \text{dBm} + 7\ \text{dB} + 8\ \text{dB} = -106\ \text{dBm}$

- Can we do better?
- smaller BW could be used. However, signal BW usually standardized -> cannot be changed.
- loss in preselect filter or switch could be reduced.
- E.g. LNA could be placed in front of one or both of these components.
- NF of the LNA could be improved.
- LNA gain could be increased reducing effect of mixer on NF.
- lower NF in mixer would also improve system NF
- If lower SNR for required BER could be tolerated, then this would also help.

Linearity of Components in Series

Starting with 2 amps in series that have unique nonlinear transfer functions

$$v_{\mathrm{o1}} = k_{a1}v_{\mathrm{i}} + k_{a2}v_{\mathrm{i}}^{2} + k_{a3}v_{\mathrm{i}}^{3}$$
$$v_{\mathrm{o2}} = k_{b1}v_{\mathrm{o1}} + k_{b2}v_{\mathrm{o1}}^{2} + k_{b3}v_{\mathrm{o1}}^{3}$$

$$v_{\mathrm{IIP3\_1}} = 2\sqrt{\frac{k_{a1}}{3\left|k_{a3}\right|}}$$

$$v_{\mathrm{IIP3\_2}} = 2\sqrt{\frac{k_{b1}}{3\left|k_{b3}\right|}}$$

$$v_{\mathrm{o2}} = k_{a1}k_{b1}v_{\mathrm{i}} + \left(k_{a2}k_{b1} + k_{a1}^{2}k_{b2}\right)v_{\mathrm{i}}^{2} + \left(k_{b1}k_{a3} + 2k_{b2}k_{a1}k_{a2} + k_{b3}k_{a1}^{3}\right)v_{\mathrm{i}}^{3} + \ldots$$

applying definition of IIP3 to overall transfer function:

$$v_{\mathrm{IIP3}} = 2\sqrt{\frac{k_{a1}k_{b1}}{3\left|k_{b1}k_{a3} + 2k_{b2}k_{a1}k_{a2} + k_{b3}k_{a1}^{3}\right|}}$$

After some math

$$\frac{1}{v_{\mathrm{IIP3}}^{2}} = \frac{1}{v_{\mathrm{IIP3\_1}}^{2}} + \frac{A_{v1}^{2}}{v_{\mathrm{IIP3\_2}}^{2}} + \frac{A_{v1}^{2}A_{v2}^{2}}{v_{\mathrm{IIP3\_3}}^{2}} + \ldots$$

assuming all blocks are matched to 50Ω in terms of power:

$$\frac{1}{IIP3} = \frac{1}{IIP3\_1} + \frac{G_1}{IIP3\_2} + \frac{G_1G_2}{IIP3\_3} + \ldots$$

1dB compression point of a cascaded system would be

$$\frac{1}{v_{\mathrm{1dB}}^{2}} = \frac{1}{v_{\mathrm{1dB\_1}}^{2}} + \frac{A_{v1}^{2}}{v_{\mathrm{1dB\_2}}^{2}} + \frac{A_{v1}^{2}A_{v2}^{2}}{v_{\mathrm{1dB\_3}}^{2}} + \ldots$$

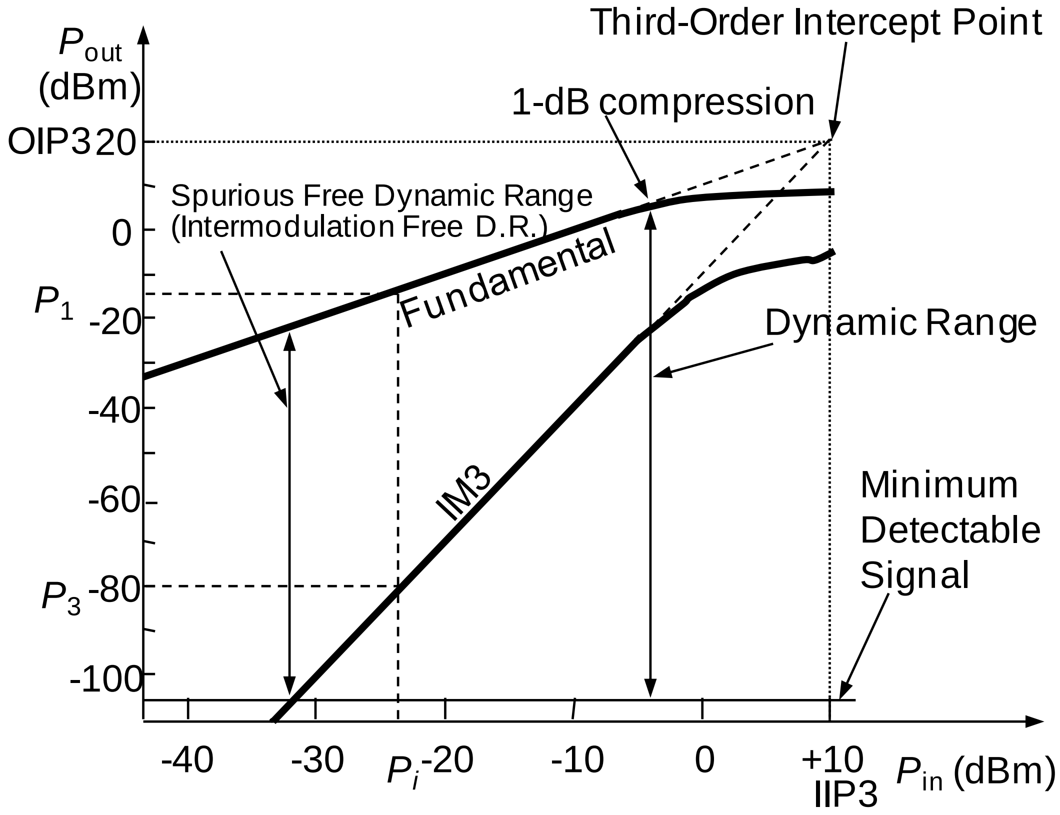
IIP2 for series blocks has a slightly different form.

$$\frac{1}{v_{\mathrm{IIP2}}} = \frac{1}{v_{\mathrm{IIP2\_1}}} + \frac{A_{v1}}{v_{\mathrm{IIP2\_2}}} + \frac{A_{v1}A_{v2}}{v_{\mathrm{IIP2\_3}}} + \ldots$$

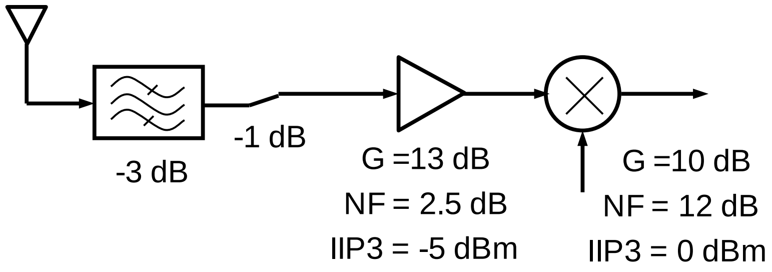
Note that unlike NF, nonlinearity is usually dominated by later stages

Dynamic Range

- Noise determines how small a signal a receiver can handle
- linearity determines how large a signal a receiver can handle.
- If operation up to the 1 dB compression point is allowed then the dynamic range is from the min detectable signal to this point.
- intermodulation components are above the min detectable signal for $P_{in} > -32$ dBm, for which $P_{out} = -23$ dBm.
- for any P_{out} between the min detectable signal of -105 dBm and -23 dBm, no intermodulation components can be seen, the so called *spurious free dynamic range* is 82 dB.



Dynamic Range?



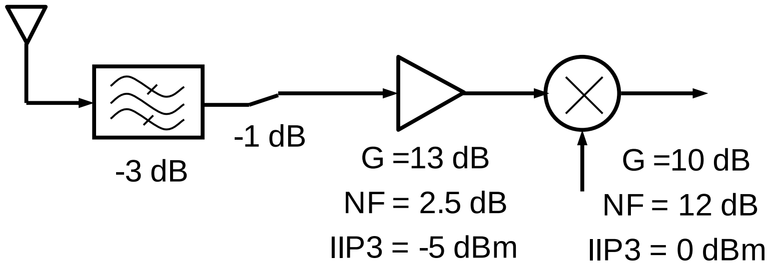
- Overall gain = 19dB
- Min detectable signal was found previously to be -106dBm
- IIP3 of LNA and mixer:

$$\frac{1}{\text{IIP3}} = \frac{1}{316.2\mu W} + \frac{20}{1mW} = 2.316 \cdot 10^4$$

$$\text{IIP3} = 43.2\mu W \Rightarrow -13.6dBm$$

- Referred to input: -13.6 + 4 = -9.6dBm
- IIP3 of mixer alone: 0-13+4 = -9dBm (very similar)
- P1dB 9.6dB lower than IIP3: -19.2dBm
- DR = -19.2 +106 = 86.8dB

Dynamic Range?



- The data transfer rate of the previous receiver can be greatly improved if we use a BW of 80 MHz rather than 200 kHz.
- What does this do to the dynamic range of the receiver?

$$\text{Noise Floor} = -174\ \text{dBm} + 10\log_{10}\left(80\cdot 10^{6}\right) = -95\ \text{dBm}$$

Assuming that the same signal to noise ratio is required:

$$\text{Sensitivity} = -95\ \text{dBm} + 7\ \text{dB} + 8\ \text{dB} = -80\ \text{dBm}$$

- Dynamaic range now: -19.2+80=60.8dB
- In order to get same DR as previous need to increase linearity by 26dB -> very hard!

Image Signals and Image Reject Filtering

- In a superhet Rx filters in RF section have task of removing image freq -> sometimes called image reject filters.
- LO reference is mixed with input to produce a signal at difference freq of LO and RF.
- A signal on other side of LO at same distance from LO will also mix down “on top” of desired freq.
- Thus, before mixing can take place, this unwanted image freq must be removed.
- important specification in a receiver is how much image rejection it has.

$$\mathrm{IR} = 10\log\left(\frac{G_{\mathrm{sig}}}{G_{\mathrm{im}}}\right)$$

- receiver must have IR large enough so that in case of largest possible image signal and weakest receive channel power, ratio of channel power to image power, once down converted, is still larger than the min required SNR.

- amount of filtering can be calculated by knowing undesired freq with respect to filter center freq, filter BW, and filter order.

$$A_{\mathrm{dB}} = \frac{n}{2} \times 20\log\left(2\frac{\Delta f}{f_{\mathrm{BW}}}\right)$$

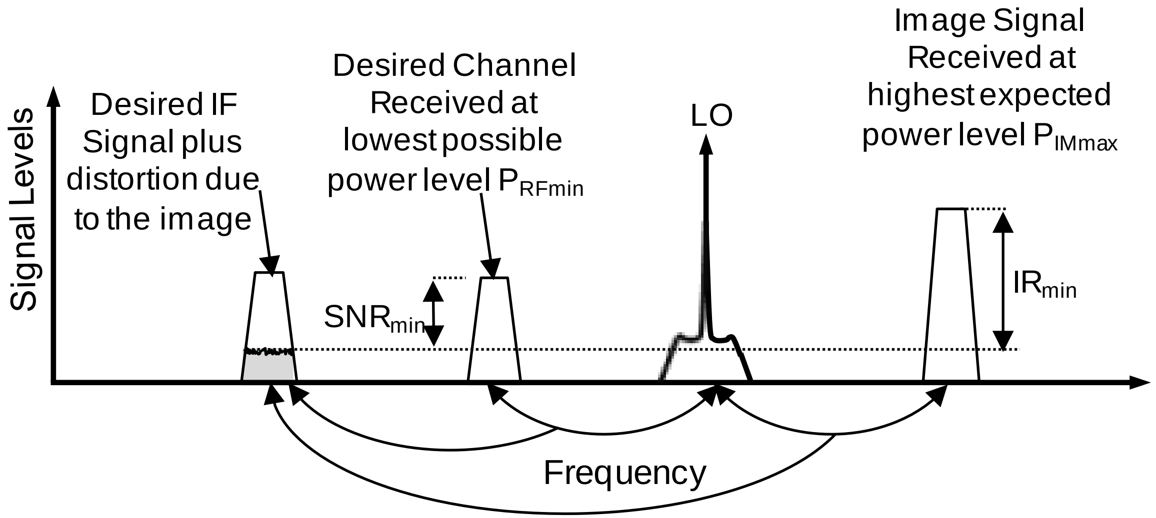
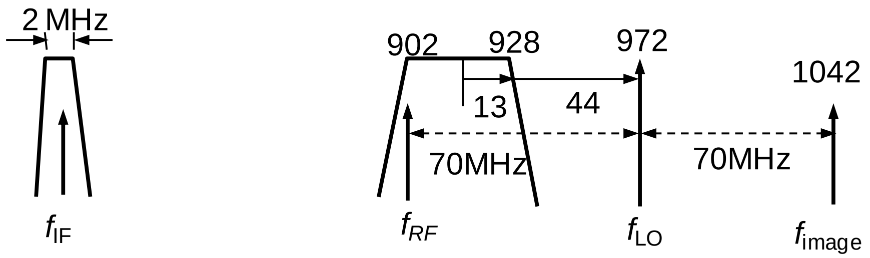


Image Reject Filtering Example

- RF 902-928MHz, 200kHz channel BW and spacing.
- IF = 70MHz.
- RF filter BW = 26MHz.
- What order filter for IR ≥ 50dB if image power is -40dBm and min signal power is -75dBm? SNR ≥ 9.5dB.
- LO is high side injected so freq is from 972 – 998MHz.
- Image is 70MHz above LO freq.
- Worst case is when image is closest to edge of RF band -> receiving channel at 902MHz.
- So for BW = 26MHz, Δf = 70+44+13= 127MHz:

$$n = \frac{2 \times A_{\mathrm{dB}}}{20 \times \log(2\Delta f \,/\, f_{\mathrm{BW}})} = 5.05$$

- BPF order has to be even so choose 6th
- Total attenuation will be 59.4dB
- So -40dBm image filter will be attenuated by more than 50dB so after filter, signal will be -90dBm.
- Gets mixed on top of desired signal at -75dBm
- So SNR from this is > 15dB -> well above requirement!

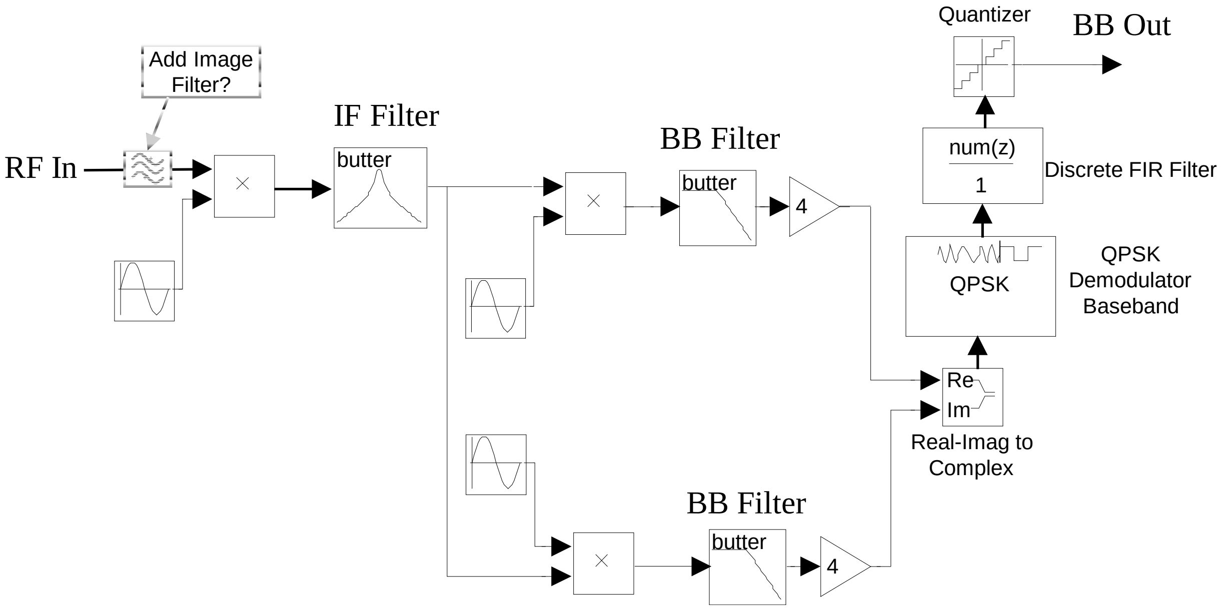


IF1 at 70MHz

RF at 902-928 MHz

Determining The Required Image Rejection in a QPSK Receiver

- QPSK receiver needs BER of 1% or better.
- RF signal = 1000 Hz, IF = 100Hz.
- data rate = 1 symbol/s.
- LO is low side injected at 900Hz.
- no nonlinearity in signal path is modeled
- IF filter is implemented as a 6th order Butterworth filter with BW = 90-110Hz.
- mixers are ideal
- At baseband I/Q filtered using 6th order Butterworth filter with BW = 1 Hz
- signals are then recombined using real/imaginary to complex number block and passed into QPSK demodulator.
- output of demodulator is sampled ten times over half a symbol period using FIR filter block and then average (which may not be an integer) is passed through an ideal quantizer to make sure output takes on value of closest symbol.
- phase of received signal is aligned with transmitted data manually by adjusting phase of IF LO signals.
- output sampling time is also adjusted manually.

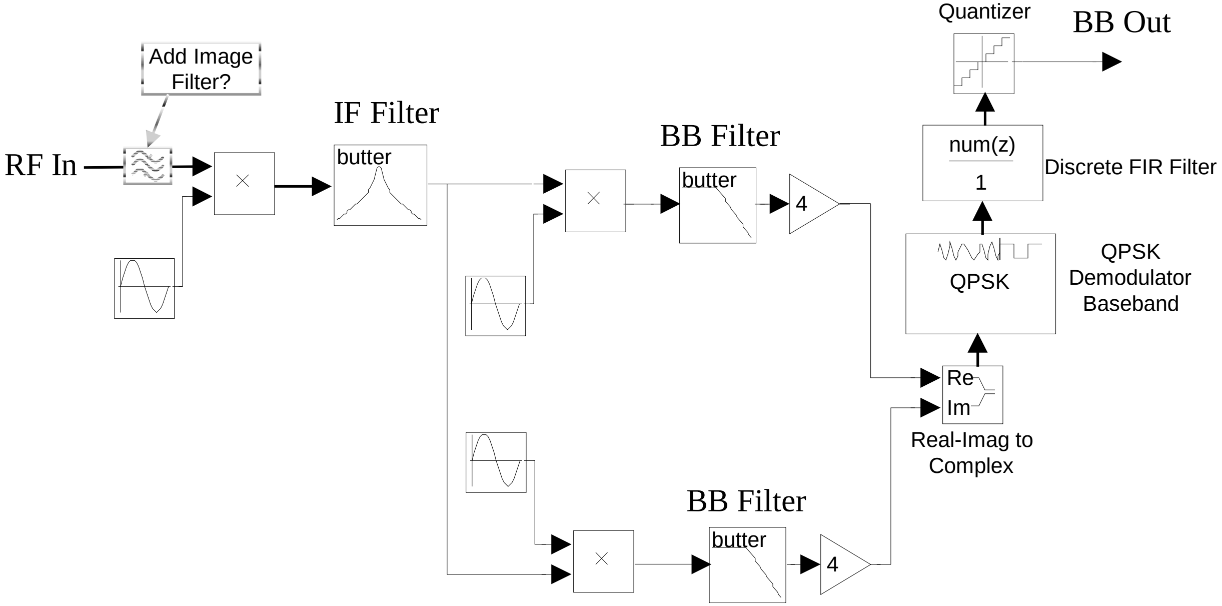


Determining The Required Image Rejection in a QPSK Receiver

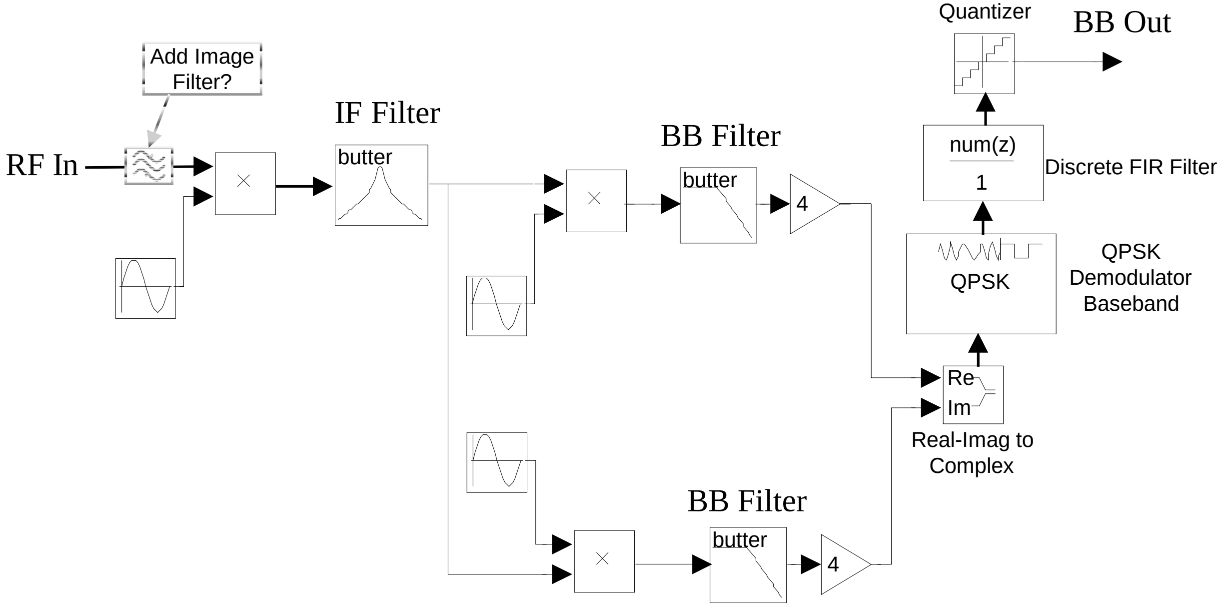
- To verify the functionality of this receiver a signal was applied to the input with varying SNR levels and BER rate was computed.
- BER can be determined easily by simply comparing bits produced by Rx with what was sent by Tx.

$$P_B\left(\frac{E_s}{N_o}\right) \approx \frac{2}{\log_2 4} \cdot Q\left(\sqrt{2\frac{E_s}{N_o}} \cdot \sin\left(\frac{\pi}{4}\right)\right)$$

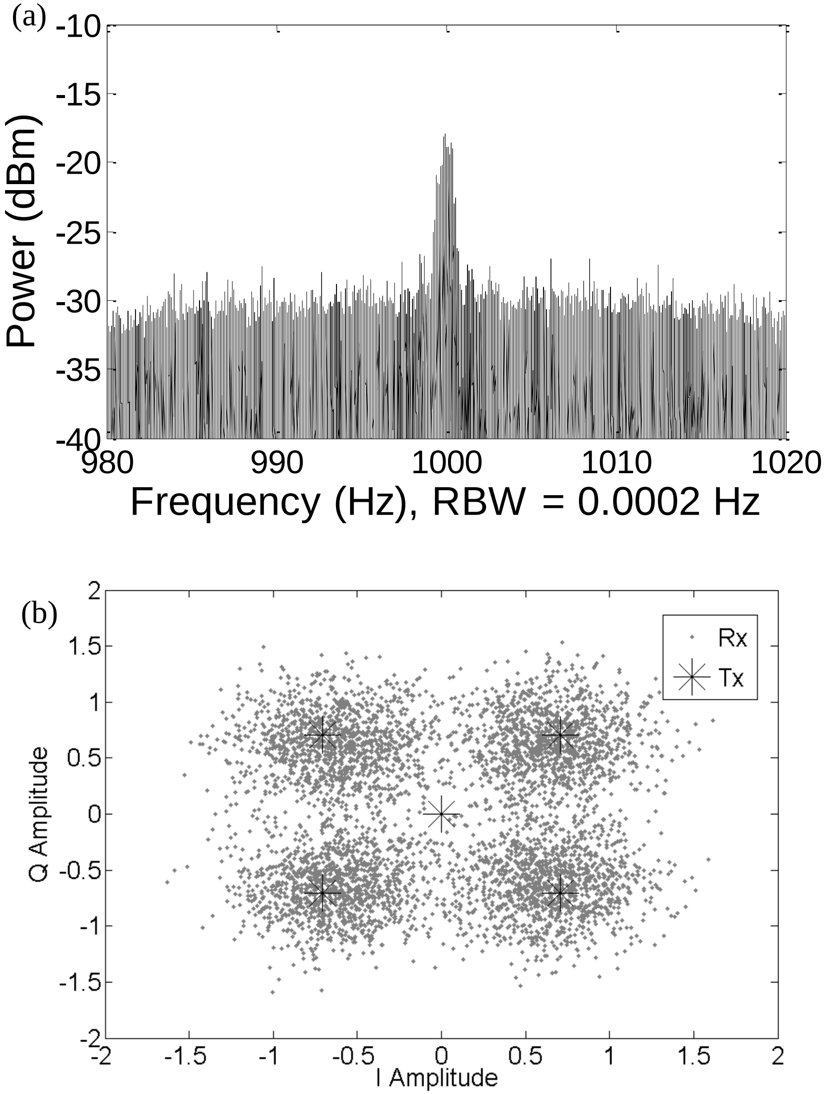
SNR	Theoretical BER	Simulated BER
5dB	3.8%	3.65%
6 dB	2.33%	2.33%
7 dB	1.28%	1.25%
8 dB	0.61%	0.48%
9 dB	0.25%	0.18%
10 dB	0.08%	0.07%



Determining The Required Image Rejection in a QPSK Receiver



SNR of 8 dB

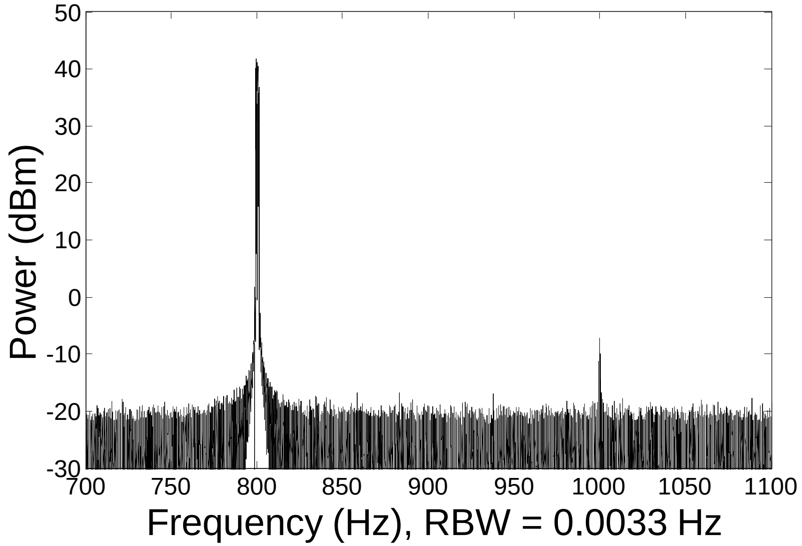


- BER = 0.48%, close to min SNR that can be tolerated and still achieve the desired 1% BER.
- if signal is received at image freq 50 dB higher than desired signal image filter will be needed.
- How much image rejection is required to maintain a BER of 1% or better?

Determining The Required Image Rejection in a QPSK Receiver

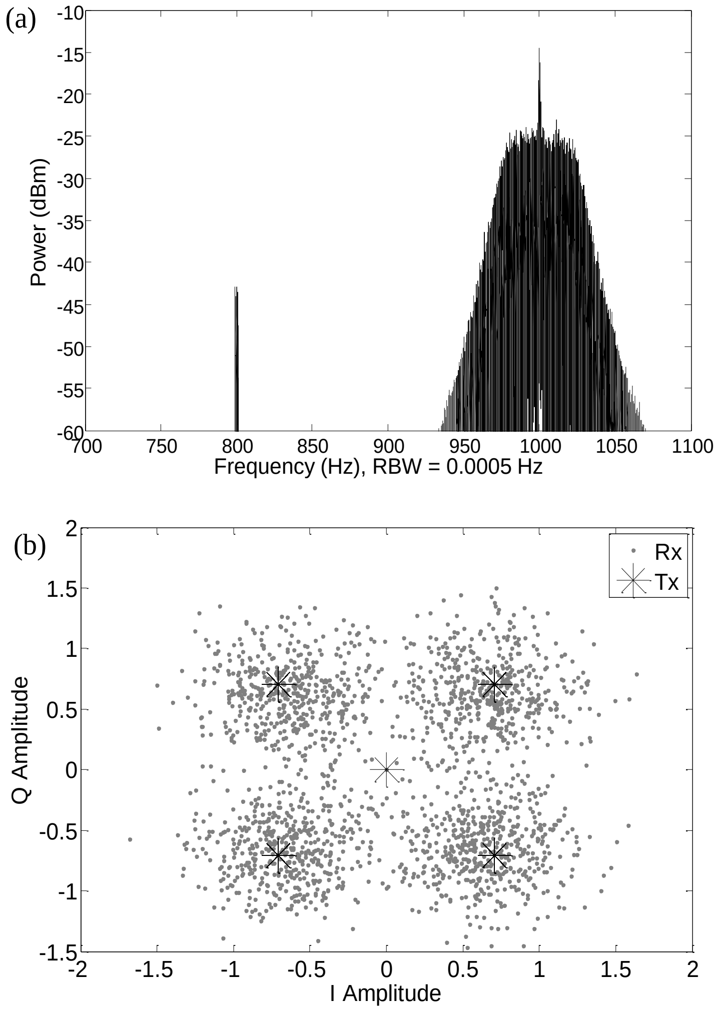
- Using Rx as it was previously designed yields a BER of 62.4% -> not functioning.
- need to attenuate image power until it is below noise floor which is 10dB below the signal power, need 60 dB of image rejection (image is 50dB higher than RF signal and needs to become at least 10dB smaller).
- assume there are 25 channels between 975Hz and 1025Hz for a total RF BW of 50Hz:

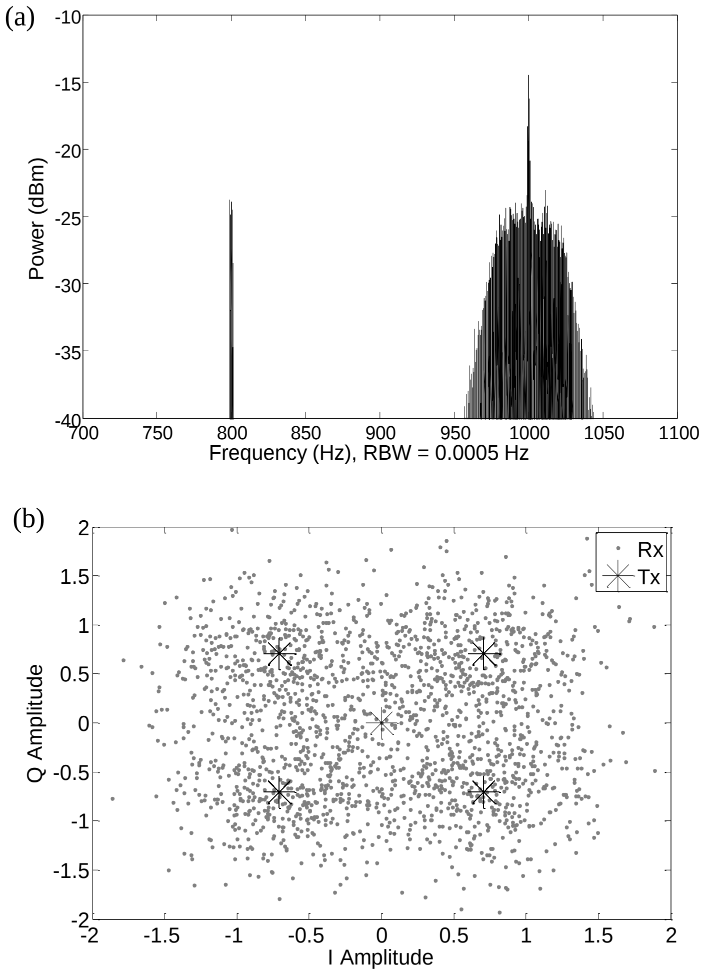
$$n = \frac{2A_{\mathrm{dB}}}{20\log\left(\frac{f_{\mathrm{ud}} - f_c}{f_{\mathrm{be}} - f_c}\right)} = \frac{2(60)}{20\log\left(\frac{800-1000}{975-1000}\right)} = 6.6$$



Determining The Required Image Rejection in a QPSK Receiver

- choose 8th order (even number).
- place into sig path and repeat sim.
- BER became 0.53% for 2000 symbols transmitted -> very close to 0.48% obtained without image.
- For comparison 6th order filter -> BER increased to 4.75% above 1% desired.
- shows 6th order not enough as predicted.





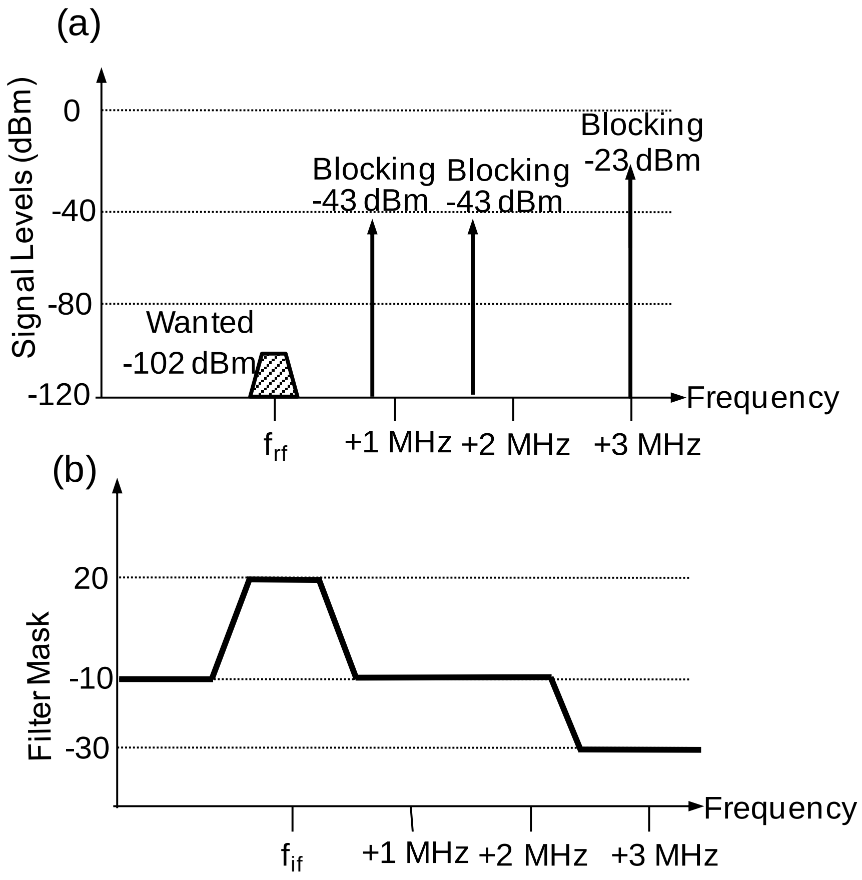
Blockers and Blocker Filtering

- Rx must be able to maintain operation in presence of other signals, often referred to as *blockers*.
- could be large amp
- could be close by in freq -> could be signals in other channels of same radio band.
- example of *near-far* problem -> occurs when desired signal is far away and one or more interfering signals are close by.
- large blocker must not saturate radio and therefore P_{1dB} must be higher than blocker power level.
- IM products of blockers can also be big problem.
- Consider case where a desired channel is detected at its min power level.
- 2 close by channels are also received at max power.
- If these signals are at freqs such that their IM3s fall on top of desired signal they will reduce SNR of desired sig -> increase BER
- circuits in radio must have high enough linearity so that this doesn’t happen.
- Once received band is down converted to an IF or baseband freq, filters may be added with a pass band narrower than whole radio band.
- strong adjacent channel signals filtered -> reduce linearity requirements of blocks after filter.

Blockers and Blocker Filtering

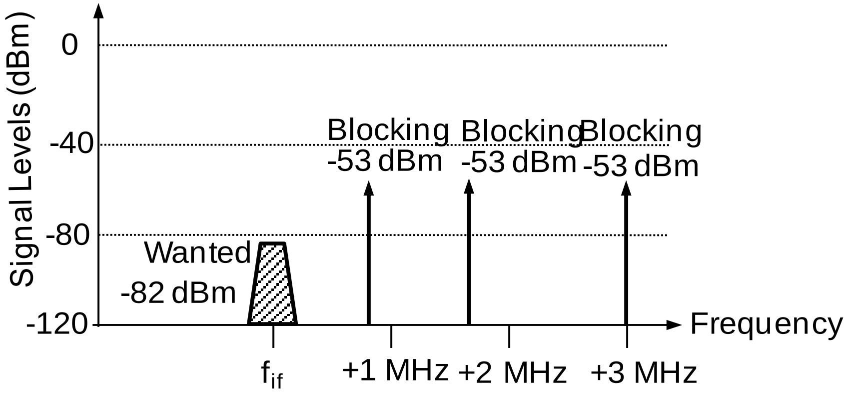
- Consider a typical blocker specification for a receiver.
- input signal = -102 dBm
- required SNR = 11 dB
- Calculate required input linearity of receiver.
- If front end has 20 dB of gain, IF filter is shown
- what is required linearity of first circuit in IF stage?

- With nonlinearity, IM3 of blockers will cause interference directly on top of signal.
- level of this disturbance must be low enough so that the signal can still be detected.
- other potential problem is that large blocker –23 dBm can cause amp to saturate.
- blocker inputs at –43 dBm will result in IM3 components which must be less than –113 dBm (referred to the input) so there is still 11 dB of SNR at the input.
- Thus, IM3 (at –113 dBm) are 70 dB below fund components (at –43 dBm).
- P_i = –43 dBm, [$P_1 - P_3$] = 70 dB -> IIP3 = -8 dBm, P_{1dB} = –18 dBm at input
- single input blocker at –23 dBm still 5 dB away from P_{1dB}
- sounds safe, however, there will now be gain through LNA/mixer.
- blocker will not be filtered until after the mixer, so one must be careful not to saturate any of the components along this path.



Blockers and Blocker Filtering

- after signal is downconverted and passed through IF filter



- signal experiences 20 dB gain,
- 2 closest blockers experience net gain of -10dB
- 3rd blocker experiences net gain of -30dB.
- If no filtering were applied to system then IIP3 of 1st IF block would need to be -8 dBm+20 dB = 12 dBm.
- With filtering, IM3 products from 2 closest blockers must be lower than -93 dBm.
- P_i = –53 dBm, [$P_1 - P_3$] = 40 dB -> IIP3 = -33 dBm, P_{1dB} = –43 dBm
- Thus it is easy to see the dramatic reduction in required linearity with the use of filters.
- P_{1dB} still 10 dB above level of any of blocking tones.

The Effect of Phase Noise and LO Spurs on SNR in a Receiver

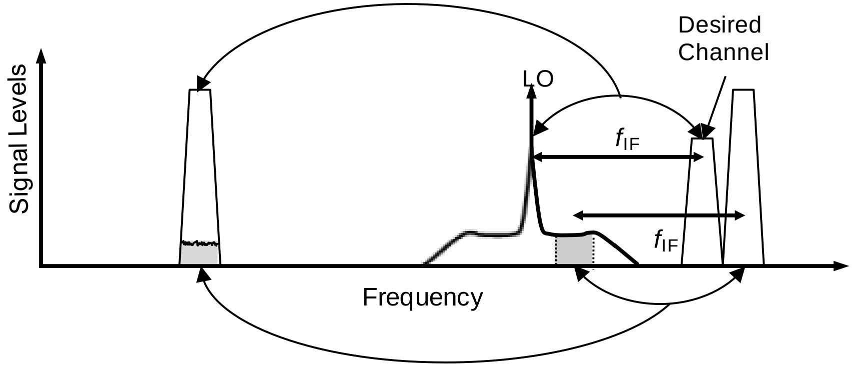
- blocking signals can cause problems in a receiver through another mechanism known as reciprocal mixing.
- For blocker at offset from desired signal, if LO also has energy at same offset from carrier, then blocking signal will be mixed directly to IF.
- to determine max phase noise allowed at an offset of adjacent channel one must know min level P_{RFmin} of desired channel, max adjacent channel power P_{ajdmax}, and SNR_{min}
- After mixing, adjacent channels must have been attenuated by at least

$$RL_{adj} = P_{adj\,\max} - \left(P_{rf\,\min} - SNR_{\min}\right)$$

- means that total power of LO across BW of adjacent channel must be lower than main carrier power by $-RL_{adj}$.
- PN across this BW must be less than

$$PN_{\max} = RL_{adj} - 10\log(BW) \quad dBc/Hz$$

- Alternatively RL_{adj} directly tells you max level of any discrete spurs over this BW.

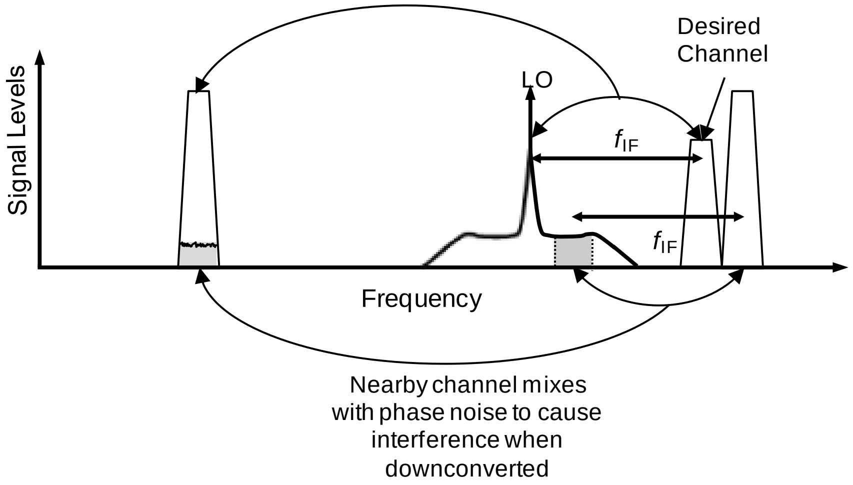


Nearby channel mixes with phase noise to cause interference when downconverted

The Effect of Phase Noise and LO Spurs on SNR in a Receiver Example

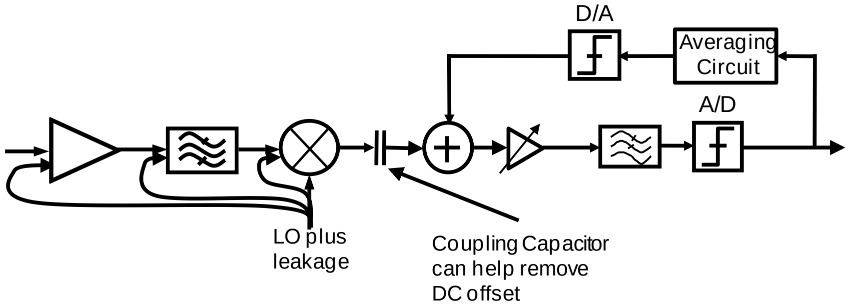
- With previous specs, (-102dBm wanted signal) calculate allowable PN in the presence of the blocking signal in the adjacent channel.
- IF BW = 200kHz.

- Tone in synth at 800kHz offset will mix with blocker at -43dBm to move it to IF.
- Blocker can be mixed with noise anywhere in the 200kHz BW.
- As previous assume SNR > 11dB -> mixed down blocker must be less than -113dBm.
- Therefore adjacent channel must be attenuated by: -43-(-113)=70dB.
- So total noise must be down by -70dB.
- As a PSD: 10log(200kHz) = 53dB.
- So PN = -70-53=-123dBc/Hz.



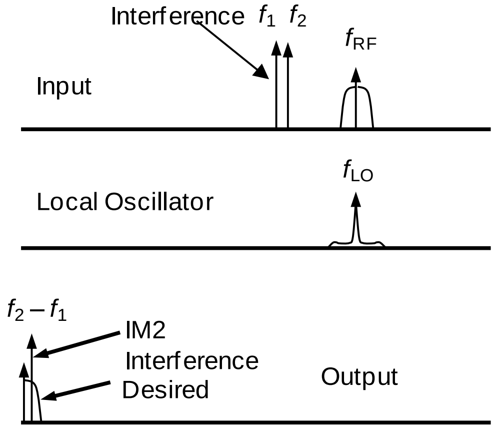
DC Offset

- DC offset caused primarily by leakage of LO into signal path.
- If LO leaks into signal path and is then mixed with itself (called self mixing), this mixing product will be at 0 freq.
- will produce DC signal or DC offset in baseband which has nothing to do with information in modulated signal.
- offset will be amplified by any gain stages in baseband and can saturate ADC if it is too large.
- DC offsets can also be caused by PA leakage and jamming signals received from antenna.
- problem is often worse in direct conversion radios where there is usually much more gain in baseband and LO is often at a much higher freq thus reducing LO isolation.
- If radio uses modulation type where there is not much information at DC (such as an OFDM signal where 1st subcarrier does not contain any information) then a blocking capacitor can be placed right before ADC.
- This will act as HPF -> will prevent DC offset from entering ADC.
- Since DC offsets are often not time variant it may also be possible to calibrate much of it out of the signal path.
- can be done by sensing DC offset in baseband and adjusting output from mixer to compensate for it.



Second-Order Nonlinearity Issues

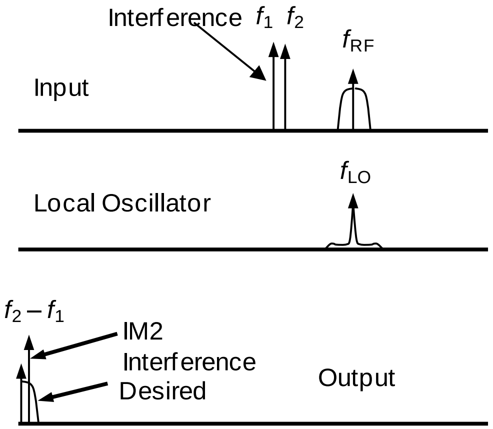
- main cause of nonlinearity is IQ mixer that down converts signal to baseband.
- Consider case where there are 2 in-band interfering signals.
- If these signals are close to each other in freq, then difference between these 2 freqs may fall into baseband BW of receiver.
- If this happens, then SNR must still be large enough to make sure that signal can be detected with sufficient BER.
- It is usually only final down-conversion stage that is the problem as prior to mixer itself, a simple ac coupling capacitor will easily filter out any low freq IM2 products produced by earlier stages in radio.
- this problem will be more important in direct down conversion radios because in these radios prior to down conversion there cannot be any filtering of in band interferers while in a superhetrodyne radio in band interferers can be filtered in the IF stage of the radio.



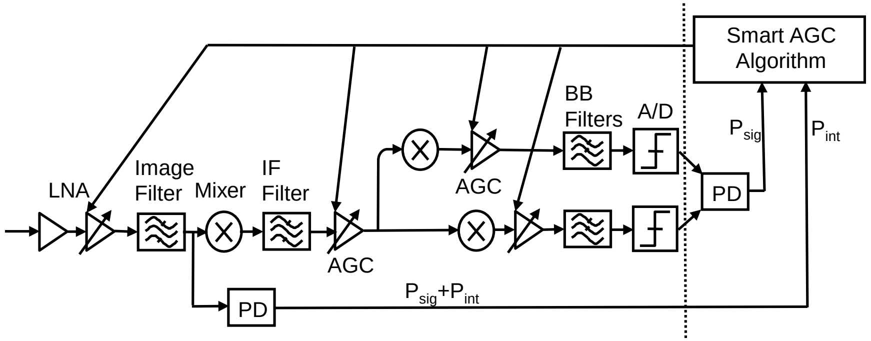
Second-Order Nonlinearity Issues: Example

- Rx trying to detect sig at 2GHz with power of -80dBm at input to mixer.
- SNR =15dB required, BW = 20MHz.
- 2 interferers present in band with power -20dBm. 2100MHz and 2110MHz.
- IIP2 needed?

- 2^{nd} order nonlinearity of mixer gives tone at 2110-2100 = 10MHz -> falls in BB BW.
- Sig is -80dBm, SNR =15dB so power in distortion must be less than -95dBm.
- P2-P1 = -20-(-95)=75dB -> IIP2 = -20dBm +75dB = 55dBm



Automatic Gain Control Issues



- To keep ADCs simple, need to keep input amp relatively constant.
- On receive side, as a bare min, radio must provide an AGC range at least equal to dynamic range of radio.
- In addition, radio gain will vary with temperature, voltage supply variations, process variations.
- additional 20 dB of gain control is required to overcome these variations.
- Normally possible to use stepped AGC (spaced ~ 3dB, maybe less), but some more sophisticated radios may require continuous AGC.
- At min detectable level receiver is set to max gain setting.
- As input power starts to rise, better to reduce gain as far towards back of radio as possible to have lowest effect on NF.
- At high power levels, better to adjust gain at front of radio thus reducing linearity requirements of parts further down the chain.
- On transmit side, AGC is often simpler.
- Even simple transmitters must have some AGC to compensate for process, temperature and supply voltage variations.
- simple stepped AGC of about 20 dB is used to make sure that required power can always be delivered to antenna.
- More sophisticated radios will use power control in Tx as well to back transmit power off if receiving radio is close
- time constant of an AGC loop in a typical GHz communication system is usually around 4-20ms.
- Usually there are 2 power detectors employed in AGC.
- One at front end of radio before filtering and it detects broad-band power.
- 2nd is after ADC and it detects in-band power.
- Subtracting the two (after adjusting for the gain) will allow signal power and interferer power to be determined.
- indicates how to start to optimize gain control.
- if signal power is strong then as a 1st step, gain can be reduced at front of radio first (LNA if it has a gain step)
- If signal is weak, but there is much interference then there is no choice but to back off gain at back end of radio to keep SNR high.
- linearity of the front end will be put to the test here.
- In order to avoid stability problems each AGC step should have some hysteresis built into it.
- This will avoid flipping back and forth due to noise when close to a transition boundary.

Frequency Planning Issues

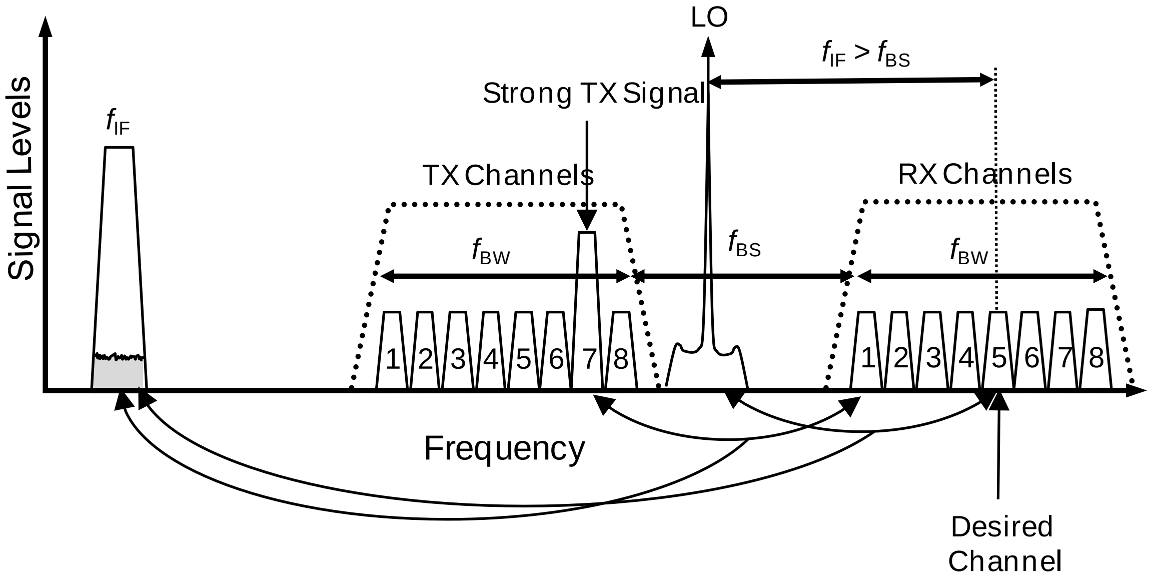
- freqs must be carefully chosen in a full duplex transceiver where transmit and receive tones will be present at same time.
- problem is that often these signals or harmonics of these signals can mix together and if mixing products fall into receive band or transmit band then this can reduce SNR and cause decreased BER performance.
- choice of 1st LO is often the first thing to consider.
- Often in a full duplex transceiver desirable to share LO between receive path and transmit path.
- once receive-side IF freq is determined, transmit-side IF freq will also be determined by default.
- In half-duplex transceiver, often LO will still be shared between 2 paths and often out of convenience IF freq will be same in both paths.
- To set LO freq must first determine receiver IF freq which is more important of 2 IF freqs.
- involves a number of tradeoffs and considerations.
- Choosing a low IF will be good for IF filter design which may otherwise have a high Q requirement.
- However, low IF will make image filter harder to design so some compromise between these two requirements is required.
- In band interference between a strong transmit tone and receive band is also a major consideration.
- Tx channels are potentially more troublesome than other random interfering signals because of a limited ability to filter them.
- After all Tx band is likely close in freq to Rx band and these freqs have to pass through any filter shared by both Tx and Rx paths.
- problem can be avoided by making IF freq less than the band spacing between TX and RX bands, so

$$f_{IF} < f_{BS}$$

Frequency Planning Issues

$$f_{IF} < f_{BS}$$

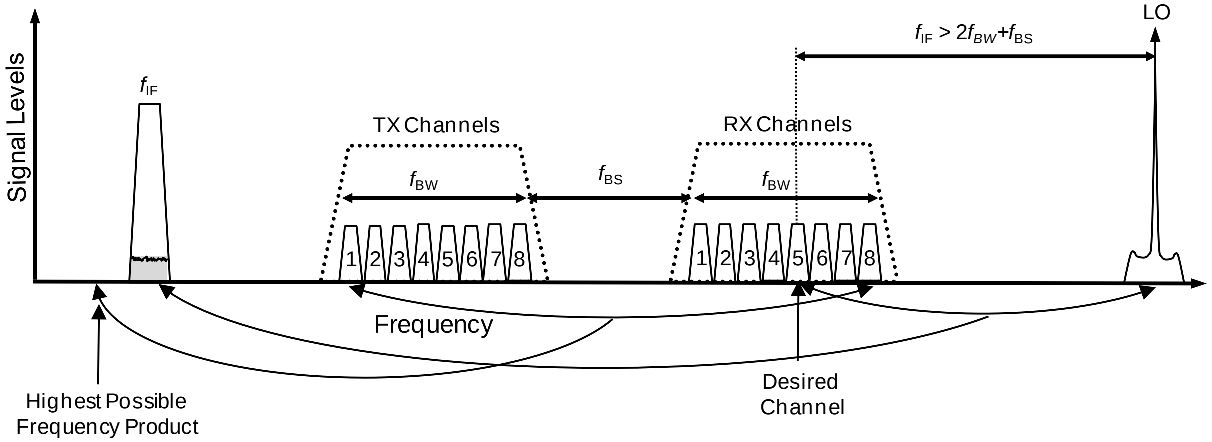
- If IF freq is chosen larger than this value, nearby TX signal could act as an LO signal and mix an undesired RX channel on top of desired channel at IF



Frequency Planning Issues

If there is a need to make IF higher than band separation, then IF should be larger than

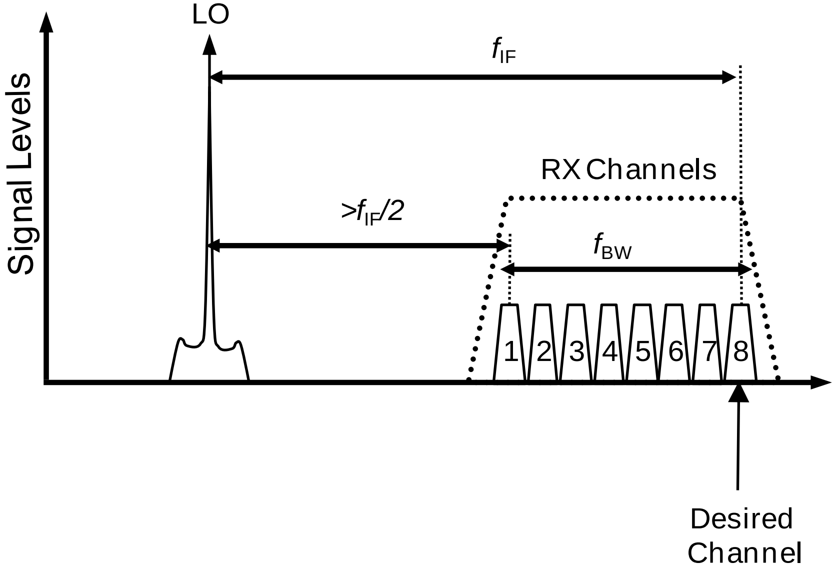
$$f_{IF} > 2 f_{BW} + f_{BS}$$



Frequency Planning Issues

- Another effect that sets a lower limit on the IF frequency is the IF/2 problem.
- In this case another unwanted channel is mixed down to half the IF frequency.
- At this point a second-order nonlinearity can mix this term on top of the IF itself.
- Since these in band channels cannot be filtered it is desirable to set the IF frequency so this cannot happen.
- To make sure this can't happen the IF must satisfy

$$f_{IF} > 2 f_{BW}$$



Dealing with Spurs in Freq Planning

- Interaction of different signals and their harmonics inside a radio is inevitable, however one thing you can do is try and mitigate how many potentially harmful unwanted signals fall onto particularly sensitive freq bands.
- In general all signals present and their harmonics must be considered.
- For RF signals it may be sufficient to consider only first 8 to 12 harmonics, with IF signals you may have to consider up to 14 to 20 harmonics and with a reference signal (typically 40MHz or less) 30-40 harmonics may be necessary.
- These signals can all mix with one another.
- Generally it is low freq mixing products that must be considered.
- Thus for any two fundamental tones in the radio f_a and f_b we are interested in

$$f_{spur} = mf_a, nf_b, mf_a \pm nf_b$$

Once all spurs have been located then we need to find out if any fall into:

1) The receive band.
2) The transmit band.
3) The image band.
4) The IF band.
5) The IF/2 band.
6) Close to either the RF or IF LO frequencies.

Any tones falling onto a signal path freq has possibility of jamming the radio.
We are also concerned with signals that fall onto or close to LO freqs.
Tones at or near these freqs could increase PN or worse, pull LO off freq.