FlexRadio Systems®
Software Defined Radios

White Paper

NOISE PERFORMANCE CHARACTERSITICS OF
DIRECT CONVERSION RECEIVERS

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Stephen Hicks, N5AC, AAR6AM, VP Engineering, FlexRadio Systems

HISTORY AND THE PROBLEM

Superheterodyne, or multi-conversion, receivers were invented in 1917[1] and were followed by the invention of the homodyne, or direct conversion receiver, in 1932[2]. The superheterodyne receiver has been the staple of most receivers for the last 90 years due largely to challenges in implementing a direct conversion receiver. What are the differences in these two topologies and why are there still receivers built with each topology?

In a superheterodyne of multi-conversion receiver, the desired RF signal is systematically mixed two, three or more times before being demodulated and arriving at an audio signal that can be processed by the human ear. In each of these stages, a non-linear device known as a mixer, shown schematically in Figure 1, is used. A mixer works by taking as input two frequencies, f_1 and f_2 and providing an output frequency that is typically lower than either of the input frequencies. The first of these input frequencies is the signal from the antenna which contains the desired radio signal we are attempting to decode. The second frequency, f_2, is called a local oscillator (LO) frequency. These two signals are beat against each other in the mixer resulting in both of the two original signals exiting the mixer, along with both $f_1 + f_2$ and $f_1 - f_2$. We are then able to filter out all but one of these signals, typically$f_1 - f_2$, by using RF filters on the frequency of interest. This output frequency, $f_1 - f_2$, is then called the intermediate frequency (IF). This is then done more times until the frequency is in the range that we can demodulate and use it.

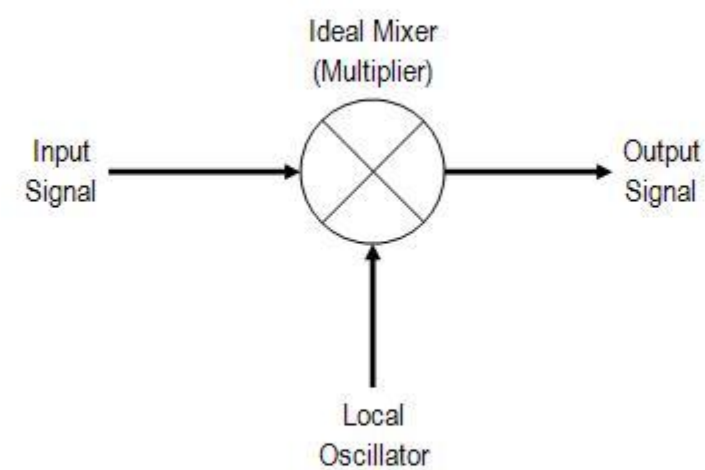

Figure 1, Ideal Mixer

[1] T. K. Sarkar (ed) *The History of Wireless*, John Wiley and Sons, 2006 ISBN 0471718149
[2] *Ibid*.

The selection of specific IF frequencies depend on the application and the range of input and out frequencies that are desired. Each mixer in the system is, by design, a nonlinear device that results in distortion of the original RF signal we are taking great care to receive. One way this can happen is through reciprocal mixing. A mixer cannot distinguish between a desired signal and an undesired signal so it mixes noise and undesired signals just as well as the desired signal. The effect of this is a mixing of not only the desired and the LO, but also of any noise in the LO against any undesired signals, desired signals against each other, etc. The end result of having a receiver with multiple IF stages is a gradual mixing of undesired noise which gets spread around the reception bandwidth of the receiver. The kind of noise produced can be seen in a two-tone intermodulation (IMD) test of a popular, respected amateur receiver shown in Figure 2.

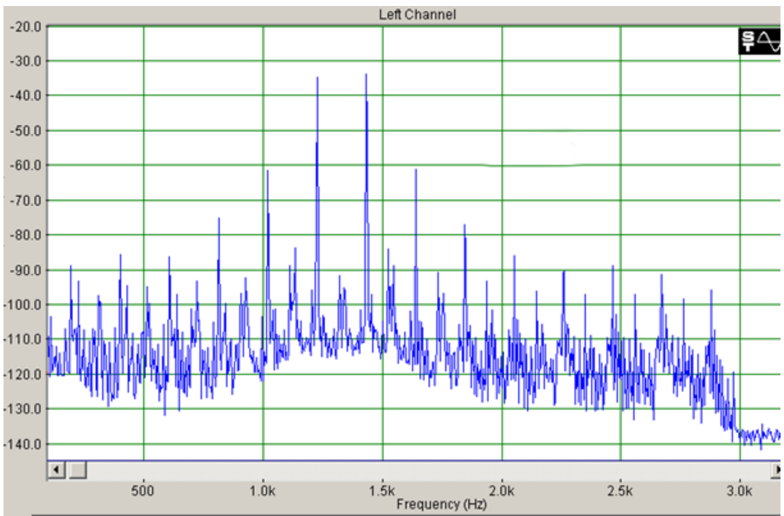

Figure 2, Mixing Noise from Superheterodyne Receiver

These undesired mixing products can cover or distort weak signals and cause fatigue to the listener in the form of “grungy” sounding noise that requires more effort from the brain to process. This latter effect is very clear if you attempt to listen to the noise in a superheterodyne receiver for a period of time and then switch to a “white noise source” such as a white noise sleep aid. Even though the pure white noise source is still noise, it has a distinctive homogenous and soft sound to it rather than a grungy, raspy sound heard in most superheterodyne receivers.

In addition, superheterodyne receivers require a filter after the mixer to remove signals that are mixed resulting in signals outside of the desired band. These signals, if not eliminated, can make the reciprocal mixing problem even worse. The typical solution to the problem is to employ the use of a crystal filter. Unfortunately, crystal filters also have nonlinearities[3,4] in them that tend to occur at the worst possible moment—when there are strong adjacent signals that vary in amplitude which cause varying drive levels on the crystal filter. Crystal filters in the IF, also known as roofing filters, have been heralded as a significant advance in radio communications in spite of the nonlinear characteristics of them. This is

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[3] D. Gordon-Smith and D. P Almond, *Anomalous Nonlinearity in Quartz Crystal Filters*, IEEE 1981
[4] Robert G. Kinsman, *A History of Crystal Filters*, 1998 IEEE International Frequency Control Symposium, IEEE 1998

because they can mean the difference in hearing and not hearing a weak signal—a strong signal can de-sense the receiver (force the AGC to lower the gain, removing the gain from a weak signal and causing it to disappear in the receiver) and elimination of this signal with a roofing filter allows the reception of the weak signal.

The very narrow RF/IF crystals also introduce group delay distortion, where slightly different frequencies encounter different time delays, manifesting as differential phase shifts. While not directly perceived or audible by the human ear, this phase distortion causes operator hearing fatigue during long sessions of listening or operating.[5]

In most commercial systems, the system can be designed such that the receive signal strength of the desired signal is of sufficient level to overcome any of these distortions and render them unimportant. This kind of a communication system is can be called a low-dynamic range communications system since the instantaneous dynamic range of the system need only be a few tens of dB. Most commercial systems are also equipped with squelch or continuous audio where the background demodulated noise is not heard, again making the problem of reciprocal mixing largely unimportant. This is in stark contrast to Amateur Radio where listening to signals at or just 10-20dB above noise level when there are other large signals near is a frequent occurrence. Amateur radio is generally considered a high-dynamic range communications medium since there are both large and small signals present at the same time and the receiver should be able to decode both in the presence of the other.

Direct Conversion Receivers

Direct conversion receivers avoid the cumulative nonlinear effects that plague superheterodyne receivers used in high-dynamic range communications systems. First, because there is no IF stage where gain in the form of Automatic Gain Control (AGC) can be employed, there can be a wide range of signals on the output of the conversion stage. Previously this was a significant technical challenge, but since the ultimate output of a direct conversion stage is baseband, the output corresponds to the same frequencies in use for high-end audio. High-end audio has received considerable engineering attention over the last few decades and very high dynamic range Analog to Digital Converters (ADCs) are available that can discern both large and weak signals at the same time—in other words the ADCs have a very high dynamic range. In the FLEX-5000, for example, we employ the use of an Asahi-Kasei Super High Performance 192kHz 24-Bit sigma-delta ADC (AK5394A)[6]. This ADC has a dynamic range of 123dB, more than enough for amateur applications. With this dynamic range, roofing filters are no longer required in the system and so with their departure also goes the nonlinearities that come with them.

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[5] Clark, R.L.; , "Phase noise measurements on vibrating crystal filters," Frequency Control, 1990., *Proceedings of the 44th Annual Symposium on* , vol., no., pp.493-497, 23-25 May 1990
doi: 10.1109/FREQ.1990.177537
URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=177537&isnumber=4483

[6] http://www.asahi-kasei.co.jp/akm/en/product/ak5394a/ak5394a_f03e.pdf

Another problem that was difficult to overcome was the rejection of images. Remember that along with the $f_1 - f_2$ signals that we receive from a conversion stage or mixer, we also receive an $f_1 + f_2$ product. In the case of a superheterodyne receiver, these signals are generally many MHz away since $f_1 - f_2$ is, itself, large. In the case of a direct conversion receiver, f_2 is picked to be the same or very near the frequency we are trying to receive. This means that $f_1 + f_2$ and $f_1 - f_2$ can both be in the same receive bandwidth. In FlexRadio products, we have two methods for suppressing these images. First, we employ the use of an I/Q Quadrature Sampling Detector (QSD). An I/Q QSD acts like a mixer, but has natural image suppression that is directly related to the balance between the I and Q local oscillator signals. The natural image suppression in an I/Q QSD results in images that are better than -40dBc or 40dB below any carrier that would produce an image. This means that a signal that is 40dB out of the noise floor could, at worst, produce an image at the noise floor.

On top of a balanced I/Q QSD, FlexRadio Systems characterizes the QSD dynamically (in real time) and adjusts the I/Q balance resulting in image suppression that can move any images to the noise floor. This technology was developed for FlexRadio Systems by Robert McGwier, PhD., N4HY, in 2006.

The results of these significant design elements can be seen in the IMD test on a FLEX-5000 receiver shown in Figure 3. Notice how the distortion caused by the mixing of signals is significantly reduced as compared to the other receiver shown in Figure 2. With the dynamic image suppression operating, image suppression exceeding 100 dB are typical, exceeding the best analog designs.

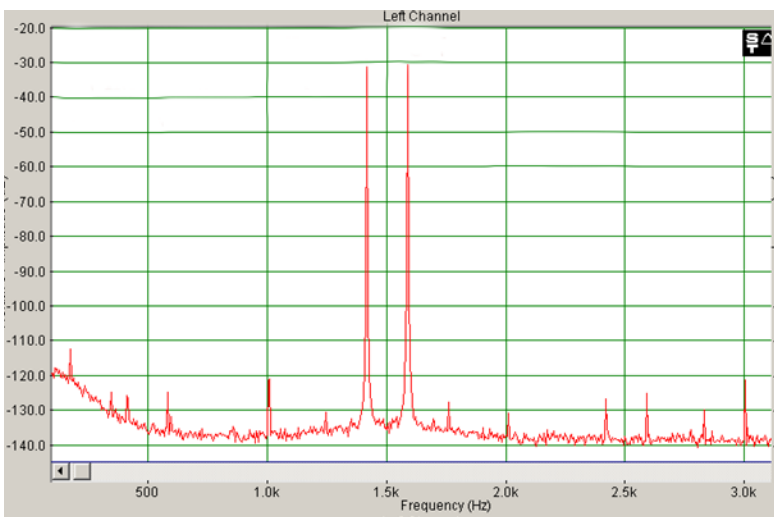

Figure 3, FLEX-5000 Mixing Noise (IMD)

Since there is only a single down-conversion or down-mixing process, from the RF band of interest direct to baseband, there is only a single opportunity for phase noise to enter the analog signal processing. If phase noise at this point is properly controlled, it sets the phase noise performance of the entire receiver, unlike the multiple down-conversions and multiple Local Oscillators in a traditional super heterodyne. Providing world class phase noise performance is inherently easier in the direct conversion radio.

By moving all of the narrow band filtering, traditionally provided by the Low IF in a super heterodyne radio into the realm of Digital Signal Processing, which are, or can be, pure mathematic processes, the digitized baseband signals can be processed, filtered and demodulated with whatever desired dynamic range, and linearity level is desired, and the DSP backend can therefore be designed so as to not add perceptible further distortion or noise beyond what exists in the analog signal entering the digitizer. With minimal analog processing in the form of a single direct conversion front end, the end result is a system with fewer opportunities and points of noise and distortion contribution.

Gain Control Considerations

A subject touched on earlier is the concept of an Automatic Gain Control or AGC. AGC was developed in the late 1920's under a few different monikers including both AGC and Automatic Volume Control (AVC) and was available in most radios by the 1930's. An analysis of these systems was published in 1928 by Karl Küpfmüller[7]. These systems use a fixed or variable delay loop and a detection mechanism to increase the gain for lower signals and decrease the gain for larger signals. It was developed to offset the ups and downs of a signal that occur in real time as propagation changes, but also prevents overload in subsequent stages of a superheterodyne receiver. The net effect is to place the signal level in a narrower, desired range, making the volume of a signal fairly constant over time. AGC itself can be a contributor to distortion if not properly implemented, but this is rarely a problem in modern receivers.

Most amateur radio receivers employ the use of an AGC circuit. An AGC system that responded continuously to the incoming signal and varied the gain all the time would do nothing but distort the input signal—the demodulator would not be able to discern differences in amplitude from moment to moment which is a requirement of most demodulators. AGC systems provide a delay in the adjustment and thus make slow changes in an attempt to avoid distortion of the incoming signal while performing their desired function. The details on how fast the AGC should respond and adjust the gain are often left to the individual operator in the case of Amateur Radio. For example, most amateur transceivers will have an AGC control that has several settings including "Fast, Medium, Slow" and "Off." These settings are all an attempt to allow the operator to tune the response of the AGC to their desired operating mode. YO3DAC provides a good description of various AGC methods in his paper, *Automatic Gain Control (AGC) in Receivers*[8].

FlexRadio Systems has employed a unique AGC system that relies on a single parameter known as Automatic Gain Control Threshold (AGC-T). This algorithm works similar to typical AGC algorithms with one major difference. In the case of the FlexRadio Systems Algorithm, a special consideration is made for signals that are weak, *but should not be amplified*. In a typical AGC system, weak signals are amplified to ensure they can be heard, but in the absence of a signal, the AGC will amplify the background noise from the receiver and loud bursts of noise are heard. Most every amateur that has used CW has attempted to run a CW QSO with AGC set on fast which can cause the AGC to "pump"—the

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[7] K. Küpfmüller, *Über die Dynamik der selbsttätigen Verstärkungsregler*, Elektrische Nachrichtentechnik, vol. 5, no. 11, pp. 459-467, 1928. (German) On the dynamics of automatic gain controllers. English translation available at http://ict.open.ac.uk/classics/2.pdf

[8] Iulian Rosu, YO3DAC/VA3IUL, *Automatic Gain Control (AGC) in Receivers*, http://www.qsl.net/va3iul/Files/Automatic_Gain_Control.pdf

AGC alternates between quickly raising the volume of noise and then when the CW signal reappears lowering the CW signal. The resulting sound of noise increasing in-between the desired signal is known as pumping and it is disturbing to the listener.

FlexRadio Systems recognized this limitation in traditional AGC systems and developed an algorithm to combat this problem. With the AGC-T setting, a threshold level below which no additional amplification will take place is set. When a signal above the threshold is received, the AGC algorithm is employed to equalize the volume level of the desired signal, just like a traditional AGC system. But when a signal or noise is below the threshold, the signal is treated as an undesirable signal and no amplification is applied. The results of this small change to the algorithm are substantial:

1) The AGC can effectively operate in the "fast" mode without bringing up the background noise during periods of inactivity. This makes a conversation more pleasant when listening and increases the contrast between periods of no speech or tone and periods when the signal is present.
2) When tuning around after a conversation, the background noise remains low since it is not amplified. This reduces operator fatigue and makes operating the radio much more pleasurable.

Achieving these results with the AGC-T algorithm in PowerSDR is very simple:

1) Tune to an area with just noise and no signal
2) Adjust the AGC-T to the default value (90)
3) Adjust the audio control (AF) until you have slightly more volume that you normally use
4) Gradually lower the threshold until noise is below the AGC-T algorithm threshold. There will be a noticeable drop in the volume level of the noise from the receiver

At this point, the AGC-T is adjusted properly and operation on the band can commence. The AGC-T will work equally well in-between elements of CW or sideband conversation as it will when tuning around the band, suppressing noise.

SUMMARY

Direct conversion receivers and the FlexRadio Systems QSD implementation in particular provide superior noise performance to a superheterodyne receiver due to the reduced opportunities for mixing noise. Combined with the ability to easily lower the noise that does remain using the AGC Threshold (AGC-T) control, FlexRadio Systems receivers achieve a noise level that is significantly lower than that of traditional superheterodyne receivers.

FOR MORE INFORMATION

For more information visit www.flexradio.com or call 512-535-4713.