Wideband Receiver for Communications Receiver or Spectrum Analysis Usage: A Comparison of Superheterodyne to Quadrature Down Conversion

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There are many different system architectures which can be used in the design of High Frequency wideband receivers for communications or spectrum analysis usage. In general, however, the higher the required RF frequency and the wider the bandwidth required, the more demanding and complex the design will be.
Hence, a 400 to 6000 MHz receiver design will be a much more difficult task than an AM broadcast band receiver covering .540 to 1.610 MHz.

Virtually all radio signals which are desired to be received must first be converted from a high frequency radio signal (RF) into a much lower frequency Baseband (BB) signal.

Some examples are:

- A 2400 MHz Bluetooth radio signal (RF) used for hands free Cellular Radio applications must be down converted to a 300-3000 Hz Baseband (BB) audio signal.
- A 512 MHz TV radio signal (RF) must be down converted to a 2 - 6 MHz Baseband (BB) video signal.
- A 5800 MHz Wireless Local Area Network (WLAN) radio signal (RF) for mobile laptop\tablet communications must be down converted to a 20 MHz Baseband (BB) data stream.

One of the major problems in receiver design is dealing with undesired RF signals at the antenna input which can interfere with and obscure the proper reception of the desired signals. This is generically referred to as the Selectivity or Undesired Signal(s) Rejection characteristic(s) of the radio. And as mentioned, higher operating frequency and bandwidth compounds this problem.

Unfortunately, the conversion process from RF to Baseband “opens the door” to allowing certain types of potentially undesired signals into the receiver signal path and causing interference.

Hence, some means of reducing or eliminating these undesired RF signals must be utilized in a radio receiver in order that the Baseband (BB) signals can be properly decoded.

This paper will show that for many applications, Quadrature Down Conversion may be the best choice with respect to cost, size and design effort. In some cases, Superheterodyne Down Conversion may still be the performance winner, however.

In all the following discussions and diagrams, signal boosting RF Low Noise Amplifiers (LNAs) right after the antenna have not been included, as they are necessary for almost all types of receivers.
It is assumed that any of these receivers would in practice have LNA’s that have been designed for sufficient linearity and stability, such that they do not generate interference products (Intermodulation Distortion) nor oscillations.

Superheterodyne Down Converter Receiver

In the most common class of radio receivers, the Superheterodyne Receiver has historically been the topology of choice, largely because of its superior ability to prevent undesired signals from interfering with desired signals.
A Superheterodyne receiver can provide a high degree of rejection of unwanted signals, while being able to provide a high degree of selection for desired signals. (Selectivity is the degree to which a receiver will pass desired signals well, while rejecting undesired signals.)

It does this by utilizing a series of filters and frequency translation circuits (Mixers and Oscillators) in the RF signal path.
Typically in a Superheterodyne radio receiver, the RF signal is first converted to an Intermediate Frequency (IF) signal, filtered, and then the IF is converted to Baseband and filtered again. Often times there will be more than one Intermediate Frequency and filter, but at a minimum there will always be at least one.

The figure below shows a basic Superheterodyne topology:

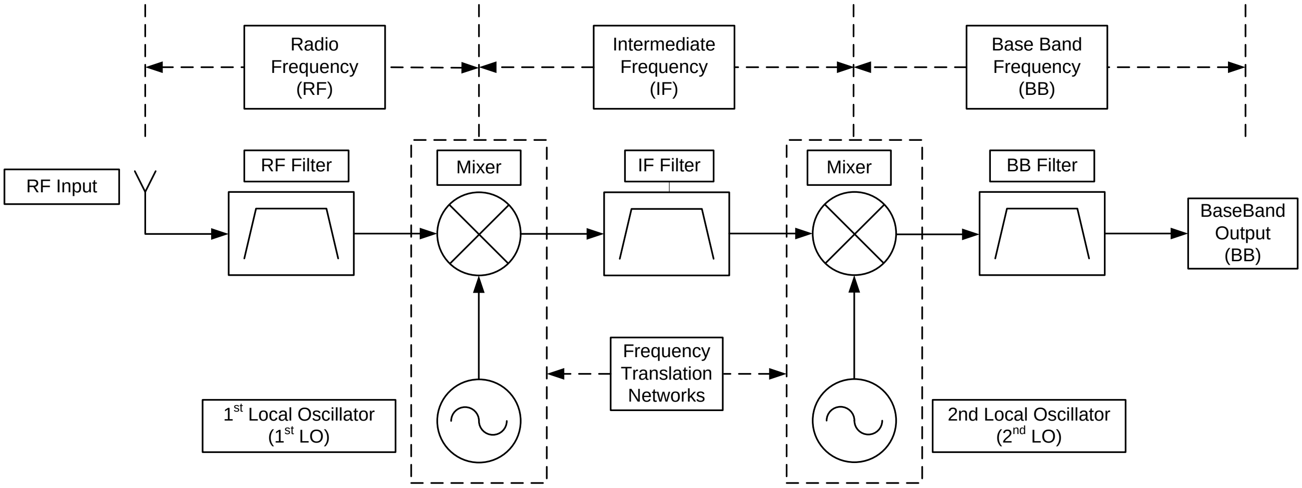

Figure 1

One major source of undesired signals which can get into the radio signal path due to the conversion process is called the Image Frequency(s), F_i.

In the conversion process, there are 2 signals which can be converted to the Intermediate Frequency (*IF*) in a receiver:

- The Desired signal F_d
- The Undesired Image signal, F_i

The Image Frequency(s) translate to the same exact Intermediate (*IF*) frequency(s) as the RF Desired signal (F_d), and both F_d and F_i are present in the IF. Once the Image Frequency has converted to IF, there is no way to remove it, and if it's magnitude is on par with the Desired F_d, it will block F_d from further processing, and the receiver is impaired.

In a Superheterodyne receiver, the Undesired signal F_d due to the Image signal F_i occurs when $F_i = F_d + (2 \text{ x } IF)$, when the Local Oscillator signal (F_{lo}) is higher in frequency than the Desired Signal F_d:

With $F_{lo} > F_d$: $F_i = F_d + (2 \text{ x } IF)$

The example below illustrates how two different signals, a desired and an undesired Image signal, can end up in the *IF* at the same exact frequency, on top of each other. The undesired, being the stronger signal, will block the desired signal.

F_d = 900 MHz (Desired Signal)
IF = 200 MHz
F_{lo} = 1100 MHz ($F_{lo} > F_d$)
$F_i = F_d + (2 \text{ x } IF) = 900 + (2 \text{ x } 200) = 1300$ *MHz* (Undesired Image frequency)

The picture below illustrates this; note that there are two 200 MHz signals in the middle of the *IF* passband:

- One due to the desired down converted **900 MHz signal F_d**
- One due to the undesired down converted **Image signal at 1300 MHz, F_i**

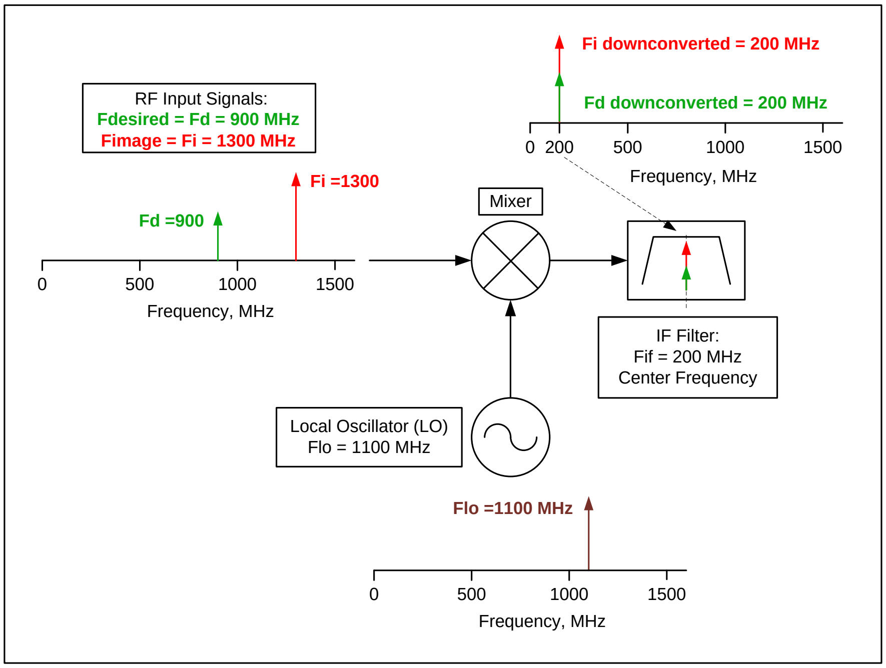

Figure 2

The usual solution to this problem is to choose the First IF Frequency to be higher than the highest Desired Frequency F_d. This then places the Image Frequency F_i very high, and out of band, where it can be filtered off and rejected.

The next example is that of a practical wide RF Bandwidth 400-6000 MHz Superheterodyne Receiver :
F_d = 400-6000 MHz.
1st *IF* = 8000 MHz ($IF > F_d$; 8000 > 6000 MHz)
Bandwidth = 2% = .02 x 8000 MHz = 160 MHz
1st *LO* = F_d + 1st *IF* = [(400 – 6000 MHz) + 8000 MHz] = 8400 – 14,000 MHz.
F_i = Image Frequency range = (F_d + 2 x 1st *IF*) = (400 – 6000) + (2 x 8000) = 16,400 – 22,000 MHz. This is very far removed from the highest frequency F_d (22,000 > 6000 MHz), so it can be relatively easily filtered and rejected.
2nd *IF* = 380 MHz, chosen to be below the desired lowest F_d signal: (380 < 400 MHz)
3rd *IF* = 10 MHz, chosen to get the Baseband signal within range of the ADC.

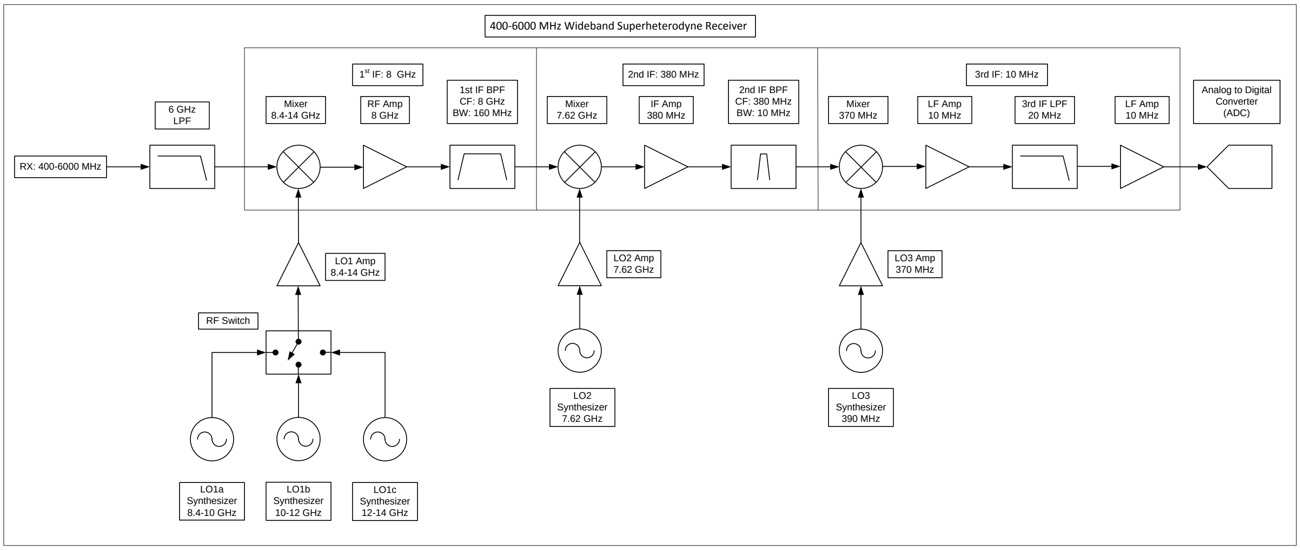

Figure 3

While this is great for selectivity and rejection of the Image frequencies, it creates Engineering and cost issues:

1. The 1St *IF* Filter must be VERY high in frequency, while maintaining a fairly narrow pass band of just a few % wide.
   This can be very expensive and\or large, depending upon the filter technology required for the very high frequency and narrow bandwidth; typically large cavity resonators might be required.

2. Since the 1st *IF* Frequency is very high, it means that the first Local Oscillator (*LO1*) must be very high as well, since the *LO* Frequency $LO = F_d + Fi_f$. This causes several issues:
   - Higher Frequency\Wider Bandwidth Local Oscillators typically are more difficult to design and costly.

- Minimizing important noise characteristics (referred to as Phase Noise) is problematic, and often requires that multiple Oscillators be used to cover the entire desired range. Here, 3 different *LO1's (L01a, LO1b, LO1c*) would be required to cover the 8.4-14 GHz range
- Maintaining the ability to change frequency rapidly can be difficult.

3. More sections of down conversion must be used, in order to down convert the high 1st IF to a low enough Base Band frequency that can be used to extract the desired signal, using Analog to Digital Converters (ADC's).

4. As the number of IF's grow, so do the accompanying loss of the extra filters and converter (mixer) circuits. This additional loss must be offset by adding gain amplifiers, which must simultaneously be high gain at high frequency, low noise, and linear.

5. The 2nd *IF* frequency must be chosen so that it does not fall within the desired 400-6000 MHz range, F_d.
   If it were within the F_d range, say 600 MHz, then a strong signal at 600 MHz at the RF input could easily leak into the 600 MHz *IF*, and block any desired signals from passing. Forcing this filter to be out of the F_d range (400-6000 MHz) has implications for the choice of *LO3* and the 3rd *IF* filter, and could prove costly.

Quadrature Down Conversion Receiver

Quadrature Down Conversion is a technique that mitigates the Image Frequency(s) problem by using phase cancellation techniques to cancel the Image frequency(s), rather than the Superheterodyne method of rejecting them with filtering.
The RF input Frequency signals F_{in} are converted directly to Baseband; there are no IF stages or Band pass filters required.
The Quadrature Down Conversion process does place the undesired Image frequency signal in the Baseband path where it could cause interference of the Desired signal, except that there are phase shifts added to the signals, which, along with DSP processing, ultimately allows the Image signals to be cancelled, leaving only the Desired Signals.
The Image Frequency in a Quadrature Down Converter is equal to (2 x *LO* Frequency) - Desired Frequency:

$$F_i = (2 \times F_{lo}) - F_d$$

The figure below shows the most basic Quadrature Down Conversion topology:

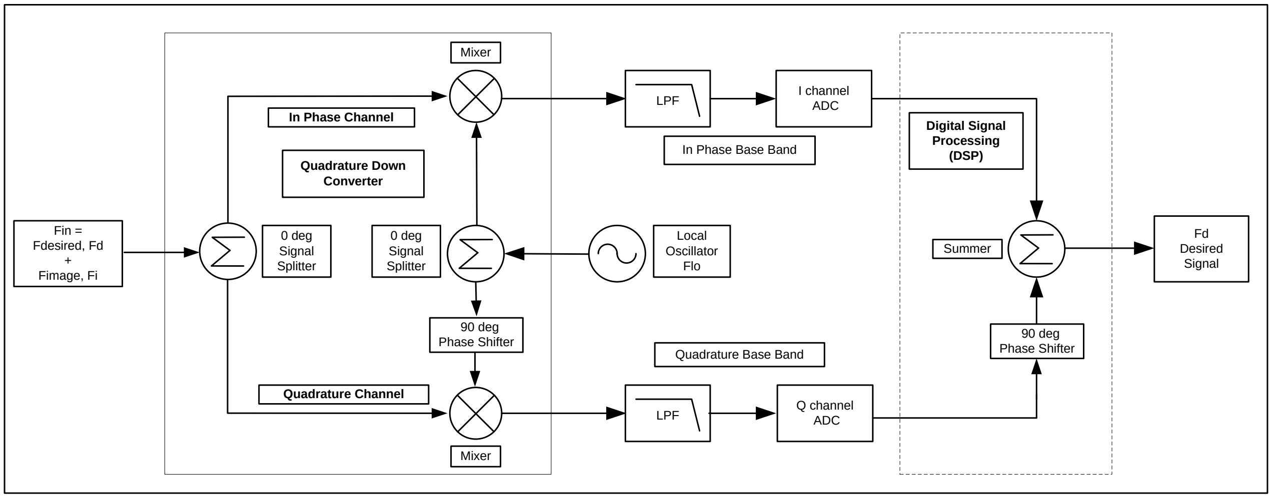

Figure 4

Quadrature Down Conversion is accomplished by:

1. First passing the RF input signal (F_{in}) through a Quadrature Down Converter, which:
    - Splits Fin into 2 channels: an In Phase Channel and a Quadrature Channel.
    - Down converts both channels directly to Baseband
    - Further, adds the following phase shifts to the channels:
        - Quadrature Channel:
            - Desired Signal F_d = F_{in} + 90 degrees
            - Undesired Image signal F_i = F_{in} - 90 degrees
        - In Phase Channel: No phase shift added to either F_d or F_i

    One important requirement is that this is typically accomplished, in part, by creating two versions of the LO signal with 90 degrees phase difference.

2. After low pass filtering the Baseband In Phase and Quadrature Channel signals, they are then sampled by independent Analog to Digital Converters (ADCs).

3. Digital Signal Processing (DSP) then operates on these 2 channels:
   - Quadrature channel receives another 90 Degree phase shift
   - In Phase Fi channel receives no further phase shift.
   - The 2 channels are then added together.

4. The resultant from combining the 2 channels is that the Image Signal F_i has been cancelled, and the Desired Signal F_d has been enhanced. Hence, rejection of the Image Signals has been accomplished without filtering.

5. The Desired Base Band Signal F_d will be passed for any further processing such as demodulation.

The following example illustrates how two different signals, a desired and an undesired Image signal, will be processed in a Quadrature Down Converter.
At the output, the Image Frequency F_i signal will have been removed by phase cancellation,
and the Desired signal F_d will be preserved and passed on for further processing, such as demodulation.

Desired Signal Frequency: F_d **= 1005 MHz**
Local Oscillator Frequency: F_{lo} = 1000 MHz
Undesired Image Frequency: F_i **= 995 MHz** [$Fi = (2 \times F_{lo}) - F_d = (2 \times 1000) - 1005 = 995$ MHz]
Base Band Frequency: 5 MHz

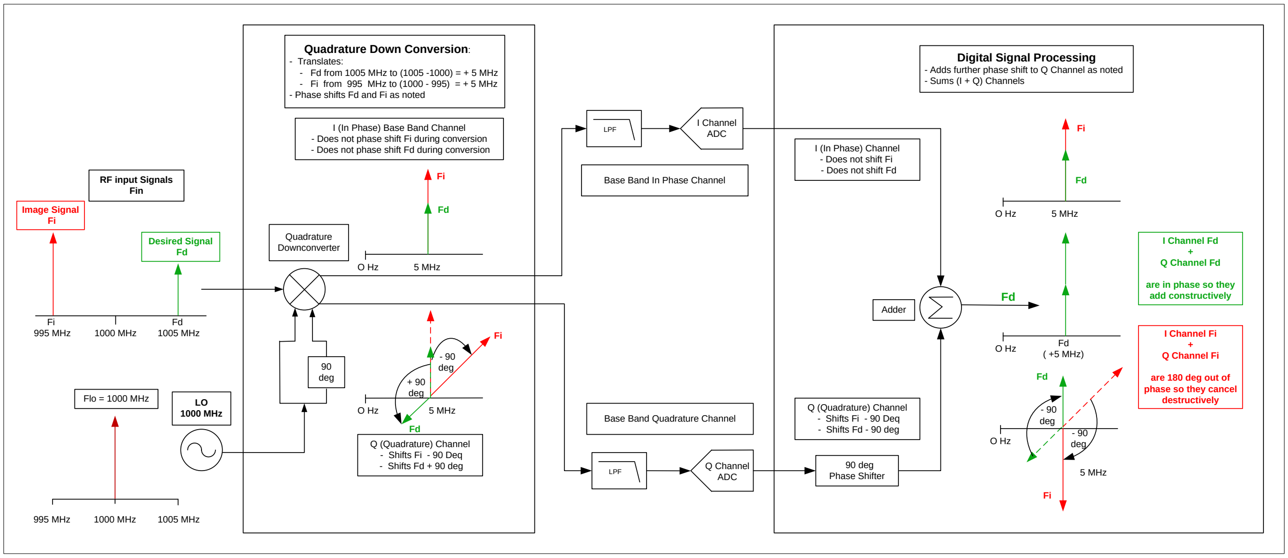

Figure 5

The next example is that of a practical wide RF Bandwidth 400-6000 MHz Quadrature Down Conversion Receiver.

Desired Signal: F_d = 400-6000 MHz. , same as for the Superheterodyne example.
Base Band Bandwidth: 10 MHz, same as for the Superheterodyne example.

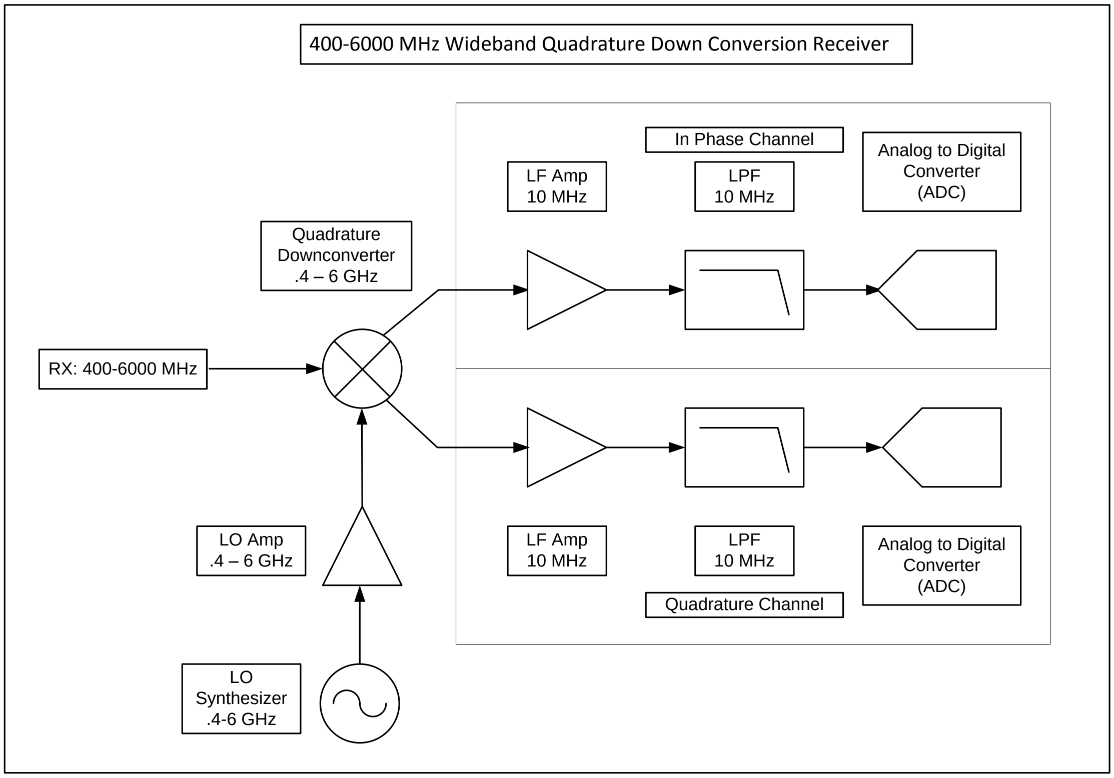

Figure 6

Note the relative simplicity, as compared to the Superheterodyne 400-6000 MHz Receiver.

The main issues that need to be addressed (and can be addressed adequately) are:

1. The degree of Undesired Signal rejection entirely depends on how well the In Phase and Quadrature Channels are balanced, with respect to Amplitude and Phase differences. In order to maintain adequate rejection, these channels must be compensated continuously with correction networks, typically implemented in the DSP.
   This typically means:
   a. DSP algorithms must be developed to continuously perform this correction.
   b. A 2nd Synthesizer covering the same range (400-6000 MHz) may need to be added to be used as a reference source that the DSP correction algorithms use to perform the compensation. However, there are no special requirements on this source, such as phase noise, which make it a cost driver.

2. The LO Synthesizer is operating on or near the same frequency as the Desired Signal, as it should. This does allow for the possibility of leakage from the LO Synthesizer through the Quadrature Down Converter to the RF input.
   If a Quadrature Demodulator with poor LO to RF isolation is used, this receiver could unintentionally broadcast a strong enough signal that might interfere with other nearby co-located radios on the same frequency.
   Note, though, that this is mitigated by the reverse isolation of any RF LNA added before the Converter.

3. Quadrature Down Conversion is susceptible to down converting harmonics of the desired signal, $2F_d$, $3F_d$, etc.
   These signals could block the reception of a desired weaker signal at F_d. The designer must make sure that both the Quadrature Down Converter circuit, RF LNA and LO amplifier (if needed) all have appropriate 2nd Order Intercept point linearity characteristics. Additionally, the synthesizer needs to exhibit decent 2nd harmonic output levels.
   Sometimes relatively inexpensive Harmonic Low Pass Filters may need to be added in front of the Quadrature Down converters, if the receiver is to be operated in environments where strong stations operating at a harmonic of a desired weak level signal is located.

RF Down Converters Cost\size Comparison:
Wideband 400-6000 MHz Superheterodyne vs Quadrature Converters

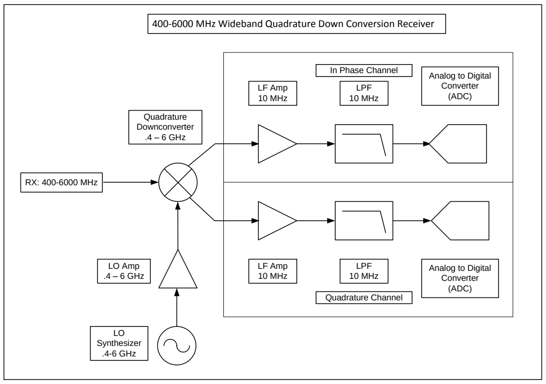

Figure 7
Quadrature Down Converter

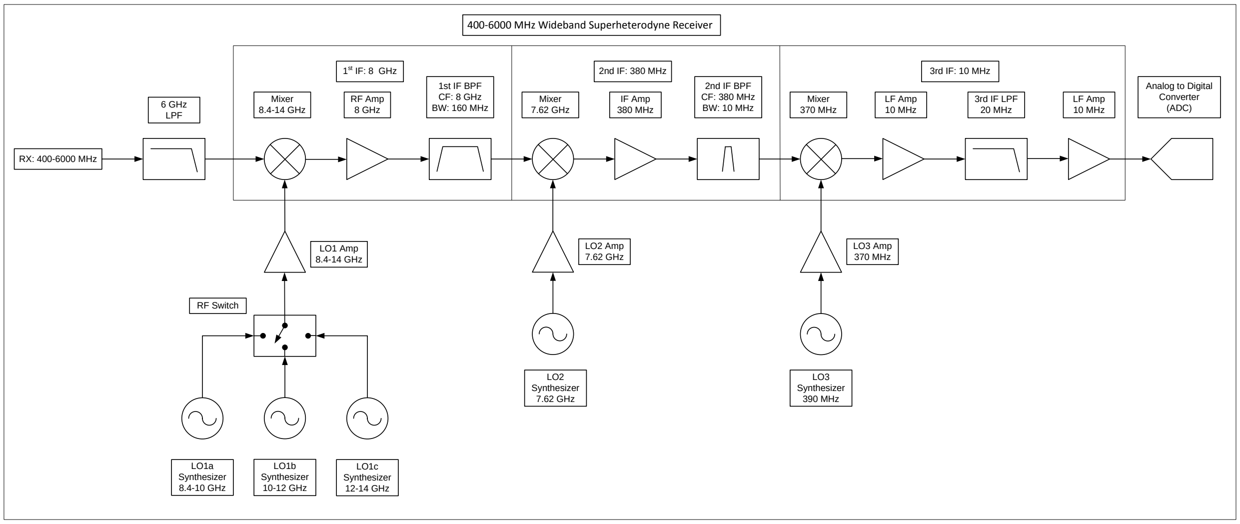

Figure 8
Superheterodyne Down Converter

Bold Red = most expensive components
Red = expensive components

Receiver Type	Superheterodyne	Quadrature
Mixers	8.4-14 GHz (Double Balanced)	.4 - 6 GHz (I\Q Demodulators)
Frequency Synthesizers\LO Sources	**8.4 - 10 GHz** **10 - 12 GHz** **12 - 14 GHz** **7.54 GHz** 390 MHz	**.4 - 6 GHz (Main LO)** .4 - 6 GHz Calibration Oscillator
RF\IF Amplifiers	8 GHz 460 MHz 70 MHz	
LO Amplifiers	**8.4 - 14 GHz** 460 MHz 70 MHz	.4 - 6 GHz
RF Low Pass Filters	6 GHz	Possiblly need Harmonic LPFs
RF Band Pass Filters	**8 GHz, 160 MHz BW** 460 MHz, 20 MHz BW 70 MHz, 20 MHz BW	
Base Band Low Pass Filters		10 MHz 10 MHz
Analog to Digital Converters (input Frequency)	70 MHz	10 MHz 10 MHz
RF Switches	**8.4 - 14 GHz**	.4 - 6 GHz .4 - 6 GHz

Figure 9

Relative Cost Comparison, Superheterodyne vs Quadrature Wideband Receivers