Chapter 2

Receiver Design Considerations

2.1 General Considerations

In wireless communication environment, the most important constraint is the limited spectrum allocated to each user. This constraint translates to a limited rate of information, mandating the use of sophisticated techniques and also impacts the design of the RF section. As shown in figure 2.1, the transmitter must employ narrowband modulation, amplification, and filtering to avoid leakage to adjacent channels and the receiver must be able to process the desired channel while sufficiently rejecting strong neighboring interferers [8].

In case of large in-band interferers accompany the received signal even after the front-end BPF, the nonlinearity of the following stages particularly that of the low-noise amplifier and the mixer, becomes important. These nonlinearities yield intermodulation products that fall in the desired channel.
These products not only distorting the amplitude, but also corrupt the zero-crossing points of the desired signal.

Figure 2.1 Front end of a wireless transceiver

Another important concern in the design of receivers is the dynamic range of the signals. With multipath fading and path loss, the required dynamic range for the received signal is typically 85 dB. As the minimum detectable signal is in the microvolt range, not only the input noise of the receiver but also cross-talk becomes critical in case of transceiver structure.

In recent generations of RF transceivers, the power amplifier is periodically turned ON and OFF to save power. However, the large current
Chapter 2  Receiver Design Considerations

drawn by the power amplifier introduces noise in the power supplies and may change the battery voltage by several hundred millivolts. For this reason, noise immunity and supply rejection become important.

Therefore, a receiver not only required to fight with external noise but also with the internal distortions. For effective removal of internal distortion, understanding the performance of receiver, in terms of noise and nonlinearities, is crucial. This chapter addresses the above topics. Apart from showing trends in receiver architectures, in particular, increase in their integration scale and the challenges associated with reduction of the system component count are highlighted.

2.2 Type of receiver architecture

The main task of wireless receivers is detection of the incoming desired modulated signals. To achieve this goal, wireless receivers have to perform several functions, including tuning to the wanted signal carrier frequency, filtering out the undesired signals present at the receiver input and amplification of the wanted signal to compensate for power losses occurring during transmission.

In the receive path, preselect RF filters - either stand-alone or as part of duplexers - are used to suppress potentially large signals far outside of the desired channel. They are followed by a low noise amplifier, which increases the amplitude of weak received signals for further processing. Its name stems from the fact that as per Friis formula, its noise contribution has to be as
small as possible. RF signals are then translated down in frequency by mixers. After channel selection filtering, the transmitted information is recovered.

Receiver architectures can be classified into two major groups: heterodyne and homodyne receivers. The names are derived from the Greek roots hetero for different, homo for the same and dyne for power. A distinguishing feature is the value of the LO frequency in relation to the RF frequency of the desired signal.

### 2.2.1 Heterodyne Receiver Architecture

The heterodyne receiver was for long time dominating receiver architecture in most wireless applications due to its superior selectivity and immunity to interfering signals.

![Superheterodyne Receiver – Architecture](image1.png)

(a) Superheterodyne Receiver – Architecture

![Superheterodyne Receiver – Spectra](image2.png)

(b) Superheterodyne Receiver – Spectra

**Figure 2.2 Superheterodyne receiver**

A heterodyne receiver translates the desired input signal from the RF frequency to one or more preselected intermediate frequencies before demodulation. A block diagram of the superheterodyne receiver with one intermediate frequency is shown in figure 2.2(a). The channel selection is performed by means of an IF filter having a fixed transfer characteristic. After
additional amplification, the IF signal is shifted to baseband using a quadrature down-converter as shown in figure 2.2b [9]. The gain and phase quadrature mismatches are usually not important in this stage since the operating frequencies are low. Here, the desired channel is translated to much lower frequencies so as to relax the Q required of the channel-select filter. Therefore, selectivity and sensitivity of this receiver architecture is very high.

This architecture is suffering from a very serious problem called as Problem of Image. In a heterodyne architecture, the bands symmetrically located above and below the LO frequency are down-converted to the same center frequency. To avoid folding of interfering signals residing on the other side of the LO frequency to the common IF frequency, either a RF filter with sharp edges or a separate image-reject filter is required, which is shown in figure 2.2(a).

Despite its superior performance, the superheterodyne architecture is not suitable for monolithic integration because of presence of several expensive and bulky RF/IF filters. Since the IF filter has a fixed pass-band, optimized for a given wireless system, separate filters are necessary for multi-mode operation. This translates into large area and cost because many components are necessary and signal routing becomes complicated. An external image reject filter requires using a stand-alone LNA stage or additional pins for connecting output of an integrated LNA and input of an integrated RF mixer with the image reject filter. Extra pins are also required for connection to an IF filter [10].
2.2.2 Direct Conversion Receiver / Homodyne Receiver Architecture

Direct conversion receiver is also known as Homodyne receiver or Zero-IF receiver. The DCR was developed in 1932 by a team of British scientists searching for a design to surpass the superheterodyne. Not only did it have superior performance due to the single conversion stage, but it also had reduced circuit complexity and power consumption. The simplification of performing only a single frequency conversion reduces the basic circuit complexity but other issues arise, for instance, regarding dynamic range and various types of distortion. Despite of all these benefits due to technical challenges and non-availability of today’s high level technology made this technique rather impractical around the time of its invention. Rapid development in VLSI technology regain the interest of various researchers in development and analysis of DCR[1-9].

A zero-IF receiver translates the desired RF signal directly to baseband for information recovery. Figure 2.3(a) shows its block diagram, while an example of signal spectra before and after demodulation is shown in figure 2.3(b) [11]. The quadrature down-converter performs the same function as the last stage of the superheterodyne receiver [figure 2.2(a)], but it usually operates at substantially higher frequencies. The channel selection is done with low-pass filters, which are much easier to integrate than band-pass filters.
The conceptually simple homodyne architecture presents a number of challenges, like gain and phase quadrature mismatches, undesired low-frequency distortion and DC-offsets.

### 2.2.3 Low-IF Receiver Architecture

To reduce the impact of both low-frequency distortion and DC-offsets, low-IF receiver architecture can be employed [12-13]. It can be viewed as a special case of the homodyne architecture. No image reject filters are needed so the low-IF architecture has the same benefits in terms of reduced component count as the standard homodyne architecture.

Channel selection in low-IF receivers can be performed in two ways. In the first method, the mirror signal is first suppressed by means of complex pass-band filters, centered around the IF frequency, as shown in figure 2.4(a).
Such filters can be easily built from baseband prototypes using a poly-phase filtering technique. After suppression of the mirror signal, the final downconversion can be performed by multiplication with a sine, which is usually carried out in the digital domain [figure 2.4(b)]. The second downconversion stage does not require quadrature LO signals.

Alternatively, a real baseband filter can be used to filter out all but adjacent channels [figure 2.4(c)]. Next, a sophisticated quadrature mixing is carried out with four multipliers, an adder and a subtractor, which effectively calculates a real part of a product of two complex signals. Using this technique, spectrum of the complex IF signal is moved in one direction only, as shown in figure 2.4(d). Final channel filtering is performed at baseband using
real low-pass filters. The same technique has been applied in a so-called wideband-IF receiver [14].

The advantage of low-IF receivers in comparison to zero-IF receivers is that there is no DC-offset problem as it can be removed before the desired signal is shifted to DC. Low-frequency distortion is also attenuated.

The main challenge in a practical application of the low-IF receiver topology is the performance of image signal suppression, which can be insufficient due to I/Q imbalances. Additionally, if the channel selection is performed in the digital domain, high-performance analog-to-digital converters are needed to resolve a weak desired signal with sufficient number of bits while digitizing a strong mirror signal at the same time.

### 2.2.4 Image-Reject Receiver

Enforced by the trends to reduce the cost and size of the RF front-end, alternative heterodyne architectures have been proposed. The trade-offs governing the use of image-reject filters in heterodyne architectures have motivated RF designers to seek other techniques of suppressing the image. Image reject filters can be removed by employing image reject receivers based on Hartley or Weaver architecture but at the expense of additional power consumption [15].
(1) Hartley Architecture

An image-reject architecture originating from a single-sideband (SSB) modulator introduced by Hartley [16] is illustrated in figure 2.5. Hartley’s circuit, mixes the RF input with the quadrature phases of the local oscillator, low-pass filters the resulting signals, and shifts one by $90^\circ$ before adding them together.

![Heartly Image Reject Architecture](image)

**Figure 2.5  Heartly Image Reject Architecture**

A critical issue in the Hartley architecture is the gain mismatch resulting from the $90^\circ$ phase shift operation. In addition other matching requirements in this topology are still much more stringent than those in...
homodyne receivers. Monolithic implementation of the Hartley architecture entails other issues as well. Detailed analysis is presented in [4].

(2) **Weaver Architecture**

In heartly architecture, critical problem is to achieve $90^\circ$ phase shift over entire channel bandwidth. This problem is solved in weaver architecture by shifting carrier signal by $90^\circ$ phase shift. In the Hartley architecture, we noted that quadrature downconversion followed by a $90^\circ$ phase shift produces in the two paths the same polarities for the desired signal and opposite polarities for the image. Illustrated in figure 2.6, the Weaver architecture [17] replaces the $90^\circ$ stage by a second quadrature mixing operation to perform essentially the same function.

![Weaver Architecture Diagram](image)

**Figure 2.6** *Weaver Image Reject Architecture*
Numerous papers showing implementations of a direct conversion concept for cellular applications exist, clearly confirming the widespread interest in the homodyne architecture. Direct conversion receivers for the GSM system are documented in [18-22]. Receiver implementations based on a direct conversion architecture for CDMA applications are shown in [23-24], while direct conversion receivers for WCDMA UMTS are presented in [25-32]. Direct conversion architecture is also preferable for multi-mode solutions. Examples of dual-mode GSM-WCDMA receivers can be found in [33-35]. Due to entirely different system requirements of GSM and WCDMA standards, a low-IF topology is often preferred for GSM while a normal homodyne architecture is used for WCDMA.

Thus DCR is choice of the today’s designer due to low component count. But distortions affect its performance. To eliminate the effect of distortions, sources of distortions should be investigated in detail. In next section, distortions in direct conversion receiver are described in detail.

### 2.3 Distortions in Direct conversion receiver

Direct translation of the spectrum to zero frequency entails a number of issues that do not exist or are not as serious in a heterodyne receiver. These distortions are described below:
2.3.1 DC Offsets

Since in a direct conversion receiver the down-converted band extends to zero frequency, extraneous offset voltages can corrupt the signal and, more importantly, saturate the following stages. To understand the origin and impact of offsets, consider the receiver shown in figure 2.7 [36], where the LPF is followed by an amplifier and an A/D converter.

![Figure 2.7 DC-offset generation due to Self-mixing](image)

(a) Self-mixing of LO signal  
(b) Self-mixing of a strong interferer

The isolation between the LO port and the inputs of the mixer and the LNA is not infinite; that is, a finite amount of feed through exists from the LO port to points A and B [figure 2.7(a)]. Called "LO leakage," this effect arises from capacitive and substrate coupling and, if the LO signal is provided externally, bond wire coupling. The leakage signal appearing at the inputs of the LNA and the mixer is now mixed with the LO signal, thus producing a DC component at point C. This phenomenon is called "self-mixing." A similar effect occurs if a large interferer leaks from the LNA or mixer input to the LO port and is multiplied by itself [figure 2.7(b)].

The problem of offset is exacerbated if self-mixing varies with time. This occurs when the LO signal leaks to the antenna and is radiated and
subsequently reflected from moving objects back to the receiver. For example, when a car moves at a high speed, the reflections may change rapidly. Under these conditions, it may be difficult to distinguish the time-varying offset from the actual signal.

We should also note that the problem of offset is much less severe in heterodyne architectures. Since the first LO frequency is not equal to the input carrier frequency, self-mixing may arise only for interferers [figure 2.7(b)], and DC offsets thus generated can be removed because the IF signal is far from zero frequency. Furthermore, in analog FM systems the second IF is nonzero and in digital modulation systems signal amplification and (partial) channel filtering at the first IF simplify the removal of the offset after the second downconversion.

2.3.2 I/Q Mismatch

Direct conversion receiver incorporates quadrature mixing. This requires shifting either the RF signal or the LO output by 90°. Shifting the RF signal generally entails severe noise-power-gain trade-offs, making it more desirable to use the topology in which LO signal is shifted 90°. In either case, the errors in the nominally 90° phase shift, and mismatches between the amplitudes of the I and Q signals corrupt the down-converted signal constellation, thereby raising the bit error rate. Note that, as shown in figure 2.8, all sections in the I and Q paths contribute gain and phase error.
Figure 2.9 shows the resulting signal constellation. This effect can be better seen by examining the down-converted QPSK signals in the time domain [figure 2.10]. Gain error simply appears as a non-unity scale factor in the amplitude. Phase imbalance, on the other hand, corrupts each channel by a fraction of the data pulses in the other channel; in essence degrading the signal-to-noise ratio if the I and Q data streams are uncorrelated.

**Figure 2.8**  \( I/Q \) mismatch contributions by various stages

**Figure 2.9**  Effect of \( I/Q \) mismatch on QPSK signal constellation
Figure 2.10 Effect of I/Q mismatch on a demodulated QPSK waveform

While heterodyne receiver may also employ I/Q downconversion in the last stage, their mismatch requirements are much more relaxed. This is for two reasons. First, since the frequency at which I and Q phases are separated is about one to two orders of magnitude lower than that in homodyne counterparts, the two paths are much less sensitive to mismatches in parasitics. Also, in IC design, the lower frequency allows the use of large devices to improve the matching without excessive power dissipation. Second, in heterodyne receivers, the signal is amplified by approximately 50 to 60 dB before I/Q separation, requiring only one or two more stages afterwards. By contrast, each channel of a DCR incorporates several stages of gain and filtering, each of which contributes mismatches. We should also note that heterodyne receiver can perform the I/Q separation in the digital domain to avoid mismatch issues whereas DCR cannot. The problem of I/Q mismatch has been an obstacle in discrete implementations, but it tends to improve as monolithic integration embraces more sections of DCR. Furthermore, since mismatches vary negligibly with time, signal processing techniques may be utilized to correct the points in the constellation.
2.3.3 Even-Order Distortion

Even-order nonlinearity is an important RF imperfection in all wireless receivers. In heterodyne receivers, it manifests itself through half-IF spurious responses. Careful frequency planning, including proper selection of the IF frequency, is required to protect the receiver from such distortion. In DCR, even-order nonlinearity is responsible for low-frequency even-order intermodulation distortion, which effectively increases the noise floor of the direct conversion receiver.

Suppose, as illustrated in figure 2.11, two strong interferers close to the channel of interest experience a nonlinearity such as \( y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) \) in the LNA [6]. If \( x(t) = A_1 \cos \omega_1(t) + A_2 \cos \omega_2(t) \) then \( y(t) \) contains a term, \( \alpha_2 A_1 A_2 \cos(\omega_1 - \omega_2)t \), indicating that two high-frequency interferers generate a low-frequency beat in the presence of even-order distortion. Upon multiplication by \( \cos \omega_{LO} t \) in an ideal mixer, such a term is translated to high frequencies and hence becomes unimportant. In reality, however, mixers exhibit a finite direct feed through from the RF input to the IF output. This is because, mixers typically suffer from some asymmetry and their operation can be viewed as \( v_{RF}(t)(a + A \cos \omega_{LO} t) \), where \( a \) is a constant. Thus, a fraction of \( v_{RF}(t) \) appears at the output with no frequency translation. In typical differential mixers, the beat signal is attenuated by only 30 to 40 dB as it couples to the output.
Figure 2.11 Effect of even-order distortion on interferers

Such distortion can be reduced by sufficient filtering of interferers before they reach the nonlinear components of the RF front end. However, highly selective RF filtering is not welcome in modern transceivers. In many practical wireless receivers, downconversion mixers are main contributors to even order distortion as shown in figure 2.12[10]. This is due to the fact that low-frequency even-order distortion products generated in the LNA are normally filtered out by AC coupling or band-pass filtering between the LNA and the downconversion mixer.

Figure 2.12 Spectral aliasing in DCR due to even-order intermodulation distortion

Sufficient filtering of interferers before the active part of the receiver RF front end is required. However, this approach lies in contradiction to the
current trends aimed at reduction of the component count of mobile transceivers. In particular, certain RF filtering stages like interstage surface-acoustic wave filters in CDMA receivers are not welcome, not only because of their size and cost but also because they degrade receiver sensitivity by introducing in-band loss. Furthermore, tunable band-pass RF filters are preferred in multi-band transceivers instead of a bank of fixed band RF filters, as they occupy less space. Since tunable filters usually have poorer attenuation in their stop bands, they provide less attenuation of out-of-band interferers. Therefore, second order intermodulation distortion is a serious issue in modern receiver design and techniques of its mitigation have to be provided to fulfill system requirements.

### 2.3.4 Flicker Noise

Since the down-converted spectrum extends to zero frequency, the $1/f$ noise of devices substantially corrupts the signal, a severe problem in MOS implementations. For this reason, it is desirable to achieve a relatively high gain in the RF range, for example, through the use of active mixers rather than passive mixers. The effect of flicker noise can be reduced by a combination of techniques. As the stages following the mixer operate at relatively low frequencies, they can incorporate very large devices to minimize the magnitude of the flicker noise [36]. In addition, if DC free coding is employed, the down-converted signal and hence the noise can be high-pass filtered.
2.3.5 LO Leakage

In addition to introducing DC offsets, leakage of the LO signal to the antenna and radiation there from creates interference in the band of other receivers using the same wireless standard [4]. The design of the wireless standard and the regulations of the Federal Communications Commission (FCC) impose upper bounds on the amount of in-band LO radiation, typically between -50 dBm and -80 dBm.