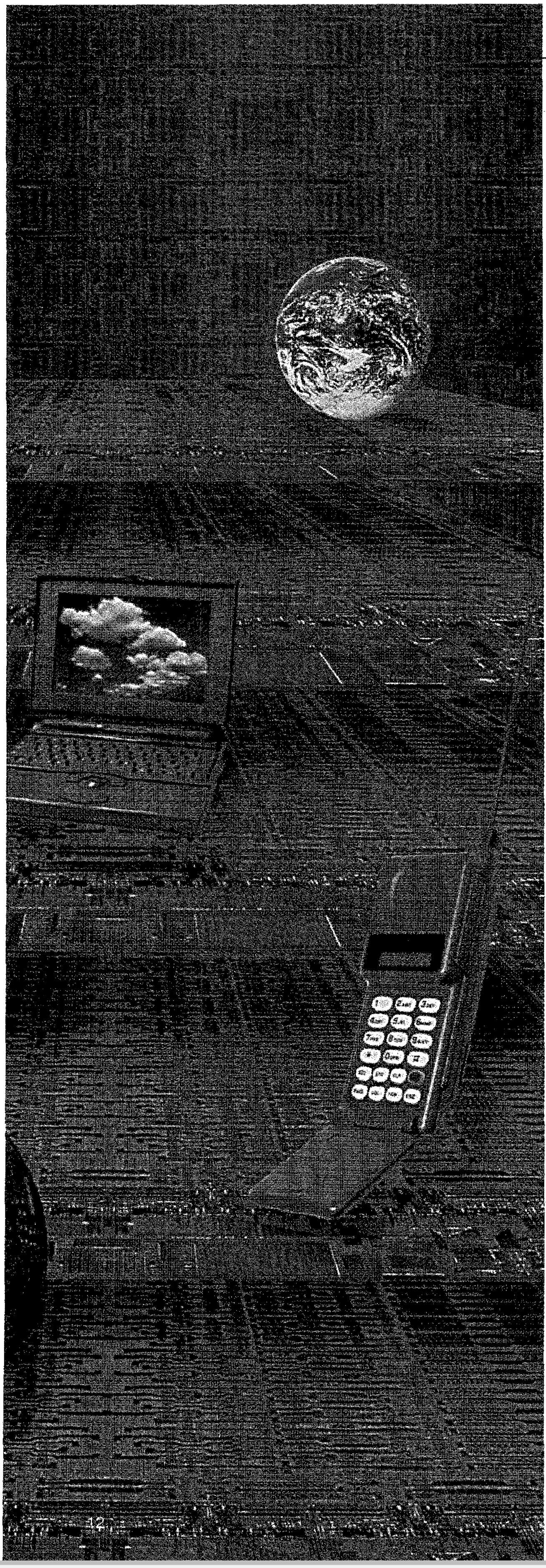

Challenges in Portable RF Transceiver Design

Behzad Razavi

As wireless products such as cellular phones become an everyday part of people's lives, the need for higher performance at lower costs becomes even more important. Overcoming the challenges involved in the design of radio-frequency (RF) transceivers can help meet this need. This article provides an overview of RF electronics in portable transceivers and describes design issues as well as current work toward achieving both high performance and low cost. To understand the implications in the design of RF integrated circuits (ICs) we look at the properties of the mobile communications environment. We then study receiver and transmitter architectures and their viability in present IC technologies. An example of an RF transceiver is given and the design of transceiver building blocks is discussed. We conclude by looking at future directions in RF design.

Wireless Communication Development

Wireless technology came to existence in 1901 when Guglielmo Marconi successfully transmitted radio signals across the Atlantic Ocean. The consequences and prospects of this demonstration were simply overwhelming; the possibility of replacing telegraph and telephone communications with wave transmission through the "ether" portrayed an exciting future. However, while two-way wireless communication did soon materialize in the military, wireless transmission in daily life remained limited to one-way radio and television broadcasting by large, expensive stations. Ordinary, two-way phone conversations would still go over wires for many decades. The invention of the transistor, the development of Shannon's information theory, and the conception of the cellular system — all at Bell Laboratories

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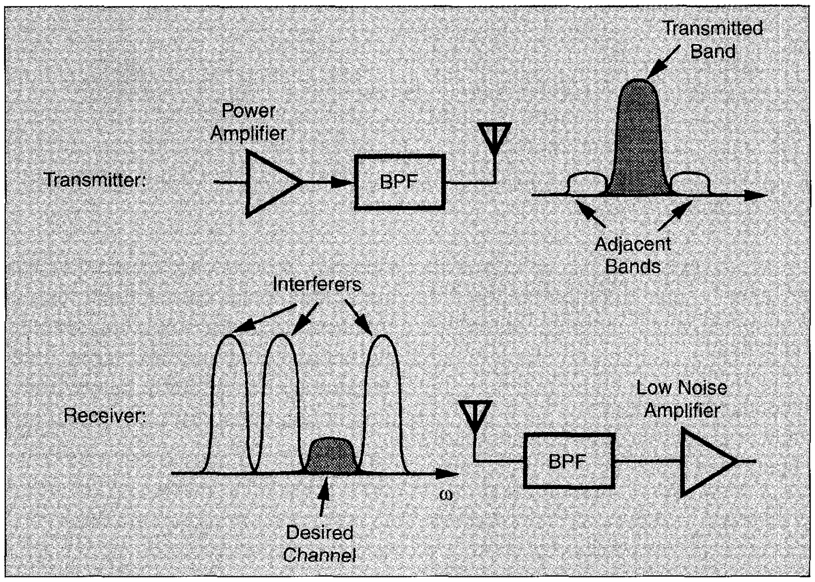
— paved the way for affordable mobile communications, as originally implemented in car phones and eventually realized in portable cellular phones (cell phones).

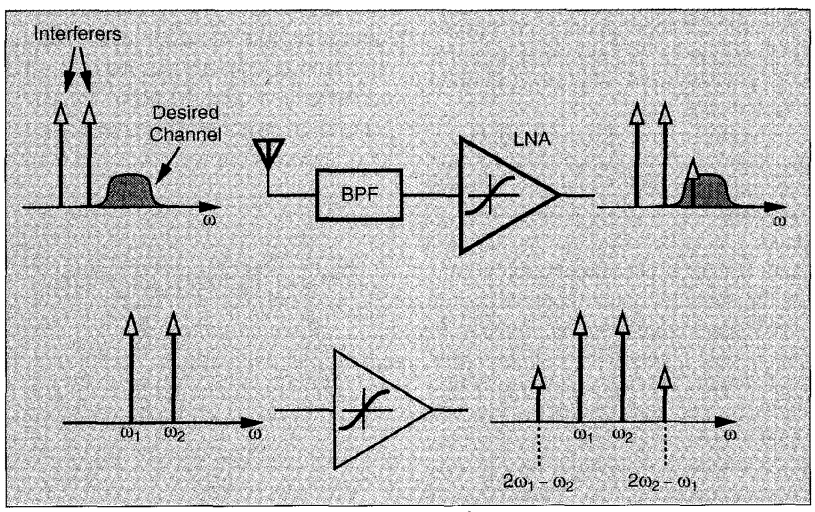
But, why the sudden surge in wireless electronics? Market surveys show that in the United States more than 20,000 people join the cellular phone system *every day*, motivating competitive manufacturers to provide phone sets with increasingly higher performance and lower cost. In fact, the present goal is to reduce both the power consumption and price of cell phones by 30% every year — although it is not clear for how long this rate can be sustained. A more glorious prospect, however, lies in the power of two-way wireless communication when it is introduced in other facets of our lives: home phones, computers, facsimile, and television.

While an immediate objective of the wireless industry is to combine cordless and cellular phones to allow seamless communications virtually everywhere, the long-term plan is to produce an "omnipotent" wireless terminal that can handle voice, data, and video as well as provide computing power. Other luxury items such as the global positioning system (GPS) are also likely to become available through this terminal sometime in the future. Personal communication services (PCS) are almost here.

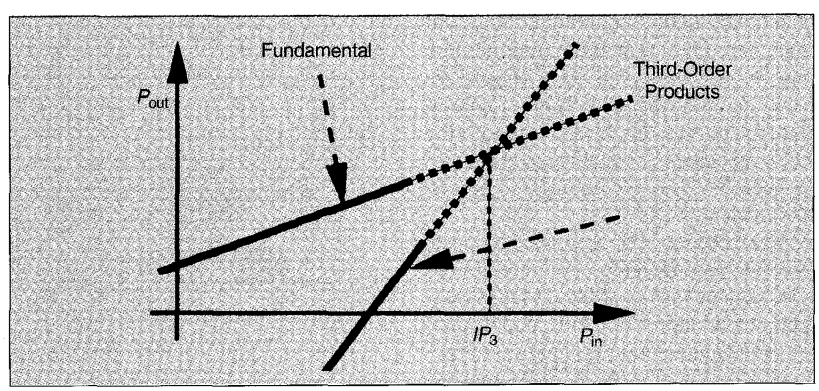
Today's pocket phones contain more than one million transistors, with only a very small fraction operating in the RF range and the rest performing low-frequency baseband signal processing. However, the RF section is still the design bottleneck of the entire system. This is primarily for three reasons. First, while digital circuits directly benefit from advances in integrated-circuit (IC) technologies, RF (analog) circuits do not benefit as much because they suffer from many more trade-offs and often require external components (such as inductors) that are difficult to bring onto the chip even in modern fabrication processes. Second, in contrast to other types of analog circuits, proper RF design demands a solid understanding of many areas that are not directly related to integrated circuits, e.g., microwave theory, communication theory, analog and digital modulation, transceiver architectures, etc. Each of these disciplines has been under development for many decades, making it difficult for an IC designer to acquire the necessary knowledge in a short time. Third, computer-aided analysis and synthesis tools for RF are still in their infancy,



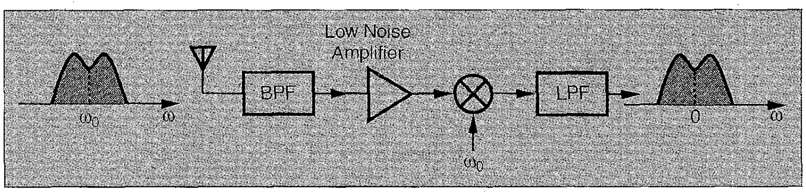
1. Simple RF front end.



2. Effect of third-order nonlinearity in LNA.



3. Definition of third-order intercept point.



4. Simple homodyne receiver.

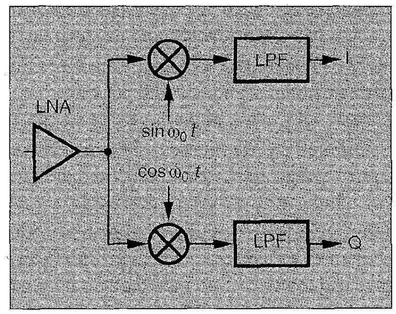
forcing the designer to rely on experience and intuition to predict the performance. For these reasons, RF IC designers have been a rare species.

Wireless Environment

The wireless communications environment, especially in urban areas, is often called "hostile" because it imposes severe constraints upon the transceiver design. Perhaps the most important constraint is the limited spectrum allocated by regulatory organizations to wireless users. From Shannon's theorem, this translates to a limited rate of information, mandating the use of sophisticated techniques such as coding, compression, and bandwidth-efficient modulation, even for voice signals.

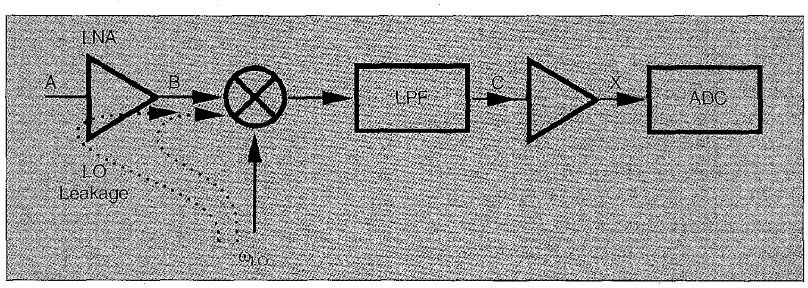
The narrow bandwidth available to each user also impacts the design of the RF front end. As depicted in Fig. 1, the transmitter must employ narrowband amplification and filtering to avoid "leakage" to adjacent bands, and the receiver must be able to process the desired channel while sufficiently rejecting strong neighboring channels. To gain a better feeling about the latter issue, we note that if the front-end bandpass filter (BPF) in a 900-MHz receiver is to provide 60 dB of rejection at 45 kHz from the center of the channel, then the equivalent Q of the filter is on the order of 10^7, a value difficult to achieve even in surface acoustic wave (SAW) filters. Since typical filters exhibit a trade-off between the loss and the Q and since in receiving very small signals the loss must be minimized, the out-of-channel rejection of the front-end filters is usually insufficient, requiring further filtering in the following stages (typically at lower center frequencies). This will be clarified later in this article.

The existence of large unwanted signals in the vicinity of the band of interest even after filtering creates difficulties in the design of the following circuits, in particular the front-end low-noise amplifier (LNA). As shown in Fig. 2, if the LNA exhibits nonlinearity, then the "intermodulation products" of two strong unwanted signals may appear in the desired band, thereby corrupting the reception. As a simple example, we note that if the input/output static characteristic of the LNA is approximated as $y(t) = \alpha_1 x(t) + \alpha_2 x^2(t) + \alpha_3 x^3(t)$ and $x(t) = A_1 \cos\omega_1 t + A_2 \cos\omega_2 t$, then the cubic term yields components at $2\omega_1 - \omega_2$ and $2\omega_2 - \omega_1$, either of which may fall in the band. The standard approach to quantifying this effect is to choose $A_1 = A_2$ and, using extrapolation, calculate the input power that results in equal magnitudes for the fundamental components and the intermodulation products (Fig. 3). Such value of input power is called the "third-order intercept point" (IP_3). It is interesting to note that this type of nonlinearity is important even if the signal carries information in its phase or frequency rather than in its amplitude.

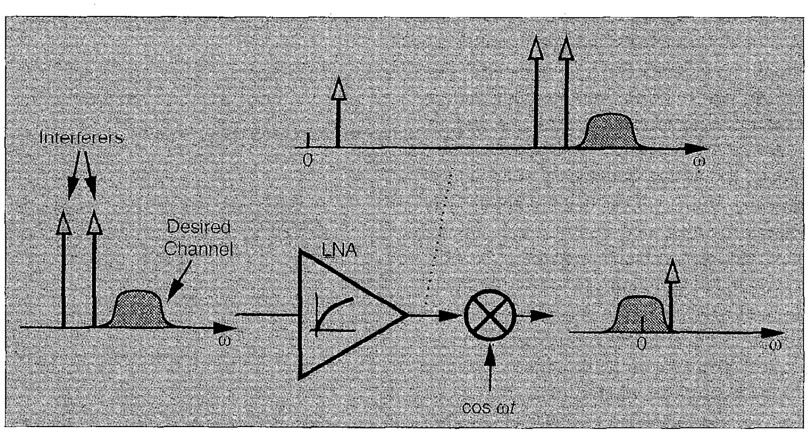


5. Homodyne receiver with quadrature downconversion.

Another important issue in the design of wireless receivers is the dynamic range of the input signal. Typically around 100 dB (a factor of 100,000 for voltage quantities), the dynamic rage is limited by a lower bound due to noise and an upper bound due to nonlinearities and saturation. The minimum detectable signal in today's handsets is in the vicinity of –110 dBm (≈0.71 μV_{rms} in a 50-Ω system), thus demanding very low noise in the receive path. For the upper bound, the receiver must achieve a high



6. LO leakage to input.



7. Effect of second-order distortion.

linearity so as to minimize intermodulation products. Also, saturation effects at high input levels often mandate the use of gain control in various parts of receivers.

Receiver Architectures

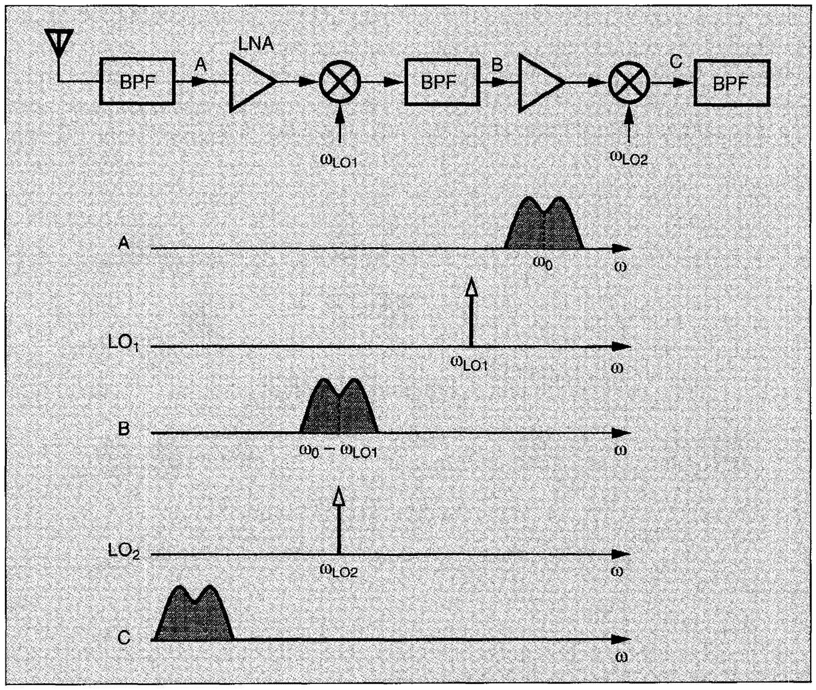
Complexity, cost, power dissipation, and the number of external components have been the primary criteria in selecting receiver architectures. As IC technologies evolve, architectures that once seemed impractical may return because, when they are implemented in today's advanced processes, their advantages outweigh their drawbacks.

Homodyne Architecture

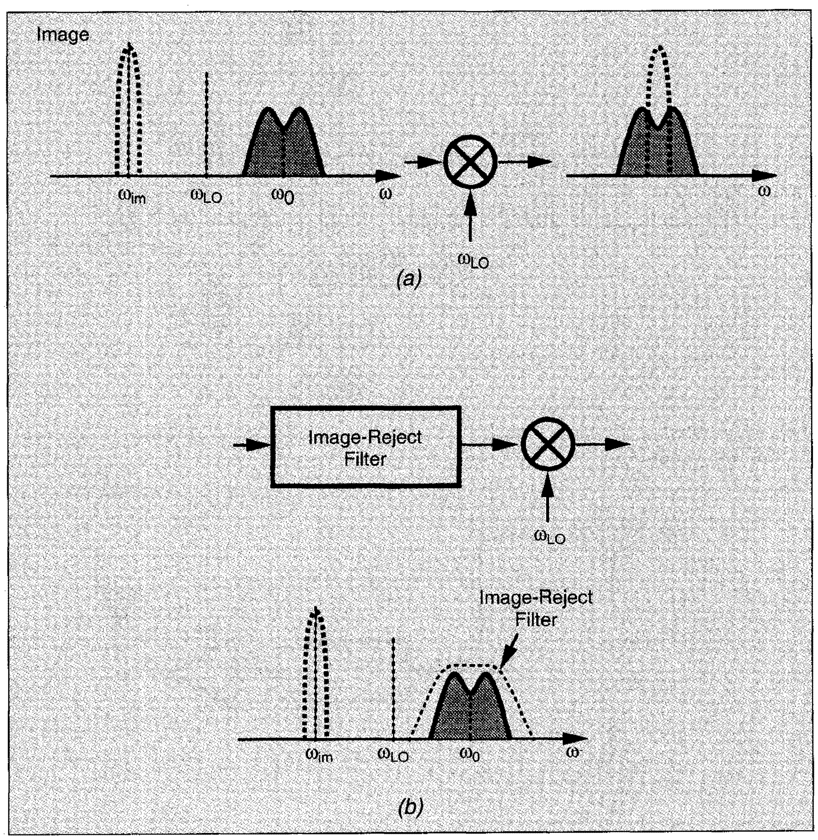
Also called "direct conversion" architecture, the homodyne receiver is the natural topology for downconverting a signal from RF to baseband. The idea is simply to mix the RF signal with a local oscillator (LO) output and low-pass filter the result such that the center of the band of interest is translated *directly* to zero frequency (Fig. 4). Because of its typically high noise, the mixer is usually preceded by an LNA. Also, in phase and frequency modulation schemes, the RF signal is mixed with both the LO output and its quadrature so as to provide phase information (Fig. 5).

The simplicity of the homodyne architecture makes it attractive for compact, efficient implementation of RF receivers [1, 2]. However, several issues have impeded its widespread use. We briefly describe these issues and their impact on the design of related ICs.

DC Offsets. Since in a homodyne receiver the downconverted band extends to the vicinity of the 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 more realistic circuit shown in Fig. 6. Here, the mixer is followed by a low-pass filter, a post-amplifier, and an analog-to-digital converter (ADC). We make two observations: (1) The isolation between the LO and RF ports of the mixer is not perfect; due to capacitive coupling and, if the LO signal is supplied externally, bond wire coupling, a finite amount of feedthrough exists from the LO port to points A and B. This effect is called "LO leakage." The leakage signal appearing at the input of the LNA is amplified and mixed with the LO signal, thus producing a DC component at point C. This phenomenon is



8. Heterodyne architecture.



9. (a) Problem of image, (b) image rejection by filtering.

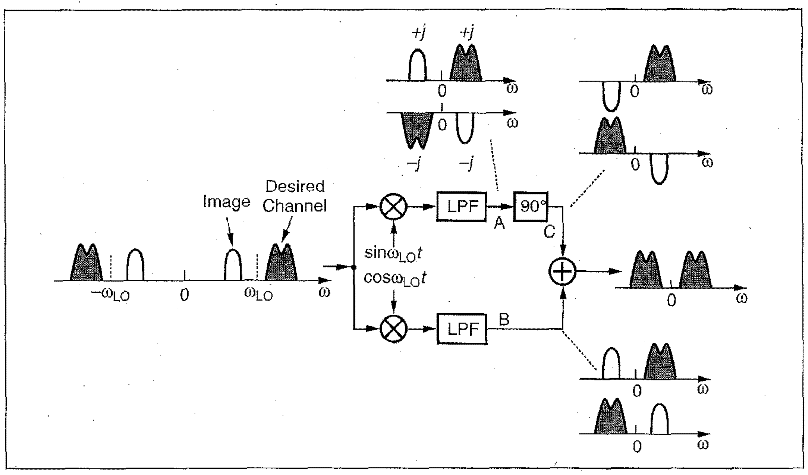
called "self-mixing." (2) The total gain from the antenna to point X is typically around 100 dB so that the microvolt input signal reaches a level that can be digitized by a low-cost ADC. Of this gain, approximately 25 to 30 dB is contributed by the LNA/mixer combination.

With the above observations and noting that the LO power is typically around 0 dBm (approximately 0.6 V_{pp}), and the LO leakage to point A on the order of –60 dB, we infer that the DC component at the output of the mixer due to self-mixing is roughly equal to 0 dBm –60 dB + 30 dB = –30 dBm, corresponding to a level of 10 mV. We also note that the signal level at this point can be as low as 25μV_{rms}. Thus, if directly amplified by the remaining gain of 70 dB, the DC component saturates the following circuits, prohibiting the amplification of the desired signal.

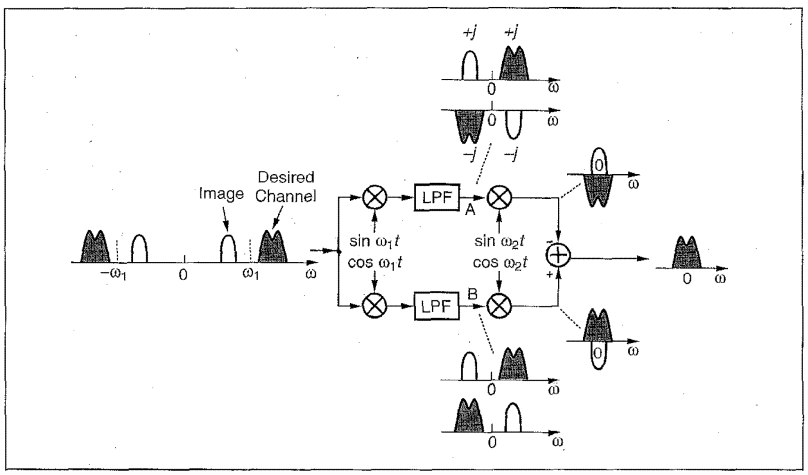
While high-pass filtering (i.e., AC coupling) may seem the solution here, in most of today's modulation schemes the spectrum contains information at frequencies as low as a few tens of hertz, mandating a very low corner frequency in the filter. In addition to difficulties in implementing such a filter in IC form, a more fundamental problem is its slow response, an important issue if the offset varies quickly. This occurs, for example, when a car moves at a high speed and the LO leakage reflections from the surrounding objects change the offset rapidly.

For these reasons, homodyne receivers require sophisticated offset-cancellation techniques. In [3], for example, the offset in the analog signal path is reduced by feeding information from the baseband digital signal processor (DSP). Alternatively, modulation schemes can be sought that contain negligible energy below a few kilohertz [4].

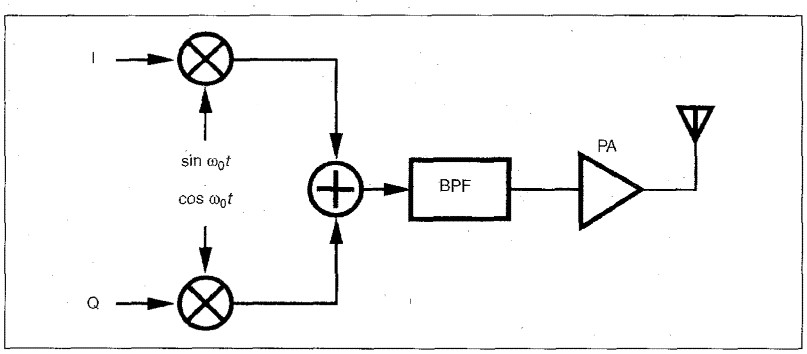
Even-Order Distortion. While third-order mixing was considered as a source of interference in Fig. 2, even-order distortion also becomes problematic in homodyne downconversion. As depicted in Fig. 7, if two strong interferers close to the channel of interest experience a nonlinearity such as $y(t) = \alpha_1 x(t) + \alpha_2 x^2(t)$, then they are translated to a *low* frequency before the mixing operation and the result passes through the mixer with finite attenuation. This is because, in the presence of mismatches that degrade the symmetry of the mixer, the mixing operation can be viewed as $x(t)(a + A \cos \omega t)$, indicating that a fraction of $x(t)$ appears at the output without frequency translation. A similar effect occurs if the LO output duty cycle deviates from 50%. Another issue is that the second harmonic of the input signal (due to the square term in the above equation) is mixed with the second harmonic of the LO output, thereby appearing in the baseband and interfering with the actual signal [5]. For these reasons, even-or-



10. Image rejection using single-sideband mixing.



11. Weaver architecture.



12. Direct conversion transmitter.

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