# CIRCUITS AND SYSTEMS FOR RADIOFREQUENCY AND TELECOMMUNICATIONS

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## Summary

This chapter describes architectures and circuits for telecommunication systems using as reference the structure of a radio receiver, which includes most of the functional units

found in any telecommunication equipments. An Introduction discusses motivation and relevance of the circuits presented in the chapter. Then Section 2 describes the functional architectures, starting from classic heterodyne, with a discussion on image rejection solutions, direct conversion (ZIF) and software-defined radio (SDR). The following sections describe the various modules, with circuit details: RF amplifiers and Mixers with related problems of nonlinearity in Section 3; Phase Lock Loops and signal sources with synthesizers and DDS in Section 4. The migration of electronic systems towards digital solutions includes telecommunication equipments, which move more and more functions to digital circuits. The processing chain must therefore include Analog-to-Digital and Digital-to-Analog functions, with characteristic suited for each application. Section 5 describes ADC and DAC units and circuits, focusing on the architectures which allow us to achieve the performance required in telecommunication, such as mixed DACs, residue and pipeline ADCs, with discussion of parameters and tradeoffs.

## 1. Introduction

Telecommunication systems use a variety of functional units, built with different types of electronic circuits, both analog and digital. The overall range covers several aspects of electronics, and many circuits found in a telecommunication systems are used also by other types of electronic equipment: amplifiers, power management, sensor and actuator interfaces, AD and DA converters. In telecommunication systems however these units have specific requirements: for instance, a radio system must handle high frequency signals towards the antennas, and baseband (audio, video) at the other side. In many cases, the transmitter needs some power for the Radio Frequency output, and must therefore use high-efficiency power handling techniques and circuits. The receiver must face problems related with low-level signals and noise. The signal processing units are migrating from analog towards digital circuits, based on microprocessors, Digital Signal Processors (DSP), or programmable logic devices.

This analog-to-digital shift is common to all electronic systems, but in the case of telecommunication equipment is further pushed for portable units, which exploit technology developments to achieve size and power reduction, and total integration, from baseband to RF interfaces. The move towards fully integrated System On Chip (SOC) is made possible also by architecture innovations. Bulk components (such as large inductors) and filters which require critical devices, are replaced by signal processing, with algorithm complexity which can be afforded only by digital techniques.

This chapter is focused on architectures and electronic circuits specific for telecommunication systems. The structure of a radio receiver is used as general reference frame, since it includes a representative variety of functional units, and the circuits used can be found also in other telecommunication equipment, such as those used for wireline connections.

The next section (Section 2) is at "system" level, and describes the functional architectures used in current radio receivers and transmitters. The starting point is the classic heterodyne, with evolution to direct conversion (ZIF) and software-defined radio

(SDR). The following sections have a "circuit" flavor: they describe the circuit details of the various modules previously defined at the architectural level. The functional units addressed include RF amplifiers, Mixers, Phase Lock Loops and other signal sources. The last section addresses Analog-to-Digital and Digital-to-Analog conversion circuits, focusing on the architectures which allow us to achieve the performance required in telecommunication applications.

## 2. Radio Systems Architecture

This section describes architectures for radio receivers and transmitters, starting from the classic heterodyne, based on frequency translation, continuing to digital and Software Radio. The section is focused on description of functions (block diagrams); more detailed analysis and examples of circuit schematics for the various units are in the following sections.

### 2.1. Heterodyne Radio Receivers

A radio receiver is a system which takes Radio Frequency (RF) signals collected by an antenna, and extracts the information embedded in one of the “channels” (e.g. a specific radio station, with carrier $\omega_a$). The functional diagram of a radio receiver is in Figure 1.

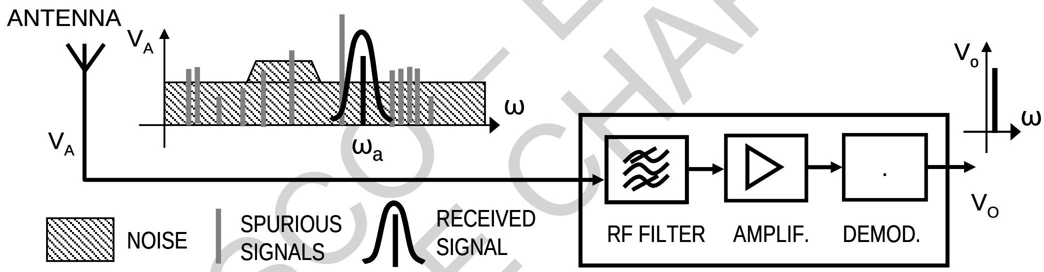


Figure 1. Functional diagram of radio receivers.
The input signal $V_A$ (from the antenna) contains the useful signal ($\omega_a$ spectral line), plus many types of noise and spurious signals. The filter selects the desired channel. The receiver output signal $V_O$ should be a copy of the original modulation, with low noise and distortion.

The useful signal is embedded in a variety of RF signals, originated by other channels, interferences (EMI), and noise. The receiver must SELECT and AMPLIFY the required signal (with TUNING capability to receive different channels). Information is extracted from RF signal by a DEMODULATOR. A system architecture which can carry out conveniently these functions is the HETERODYNE, shown in Figure 2.

The product of two sine signals, with frequencies respectively $\omega_a$ and $\omega_o$, gives two terms in the frequency domain, respectively a sum beat, with frequency $\omega_s = \omega_a + \omega_o$, and a difference beat with frequency $\omega_d = \omega_o - \omega_a$. Multiplying a signal with spectrum

$X(\omega)$ by a sine wave with frequency $\omega_o$, translates the spectrum to $X(\omega+\omega_o)$ and $X(\omega-\omega_o)$.

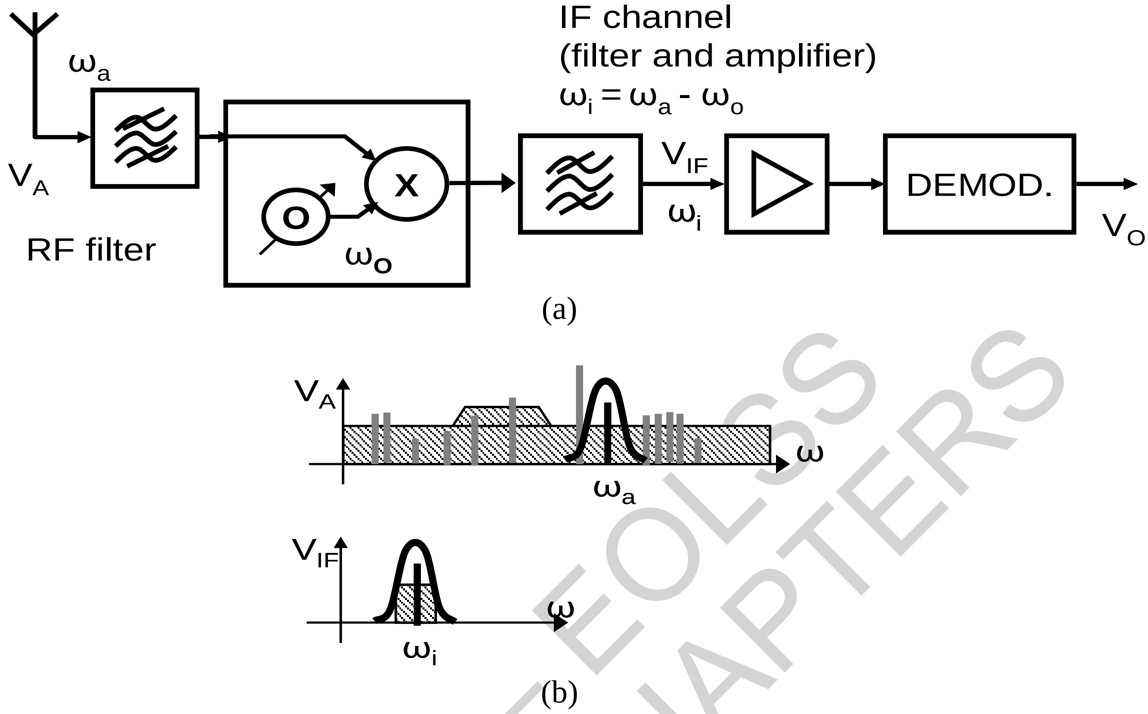


Figure 2. Heterodyne architecture.
The input signal is shifted in the frequency domain by the mixer $X$ to an Intermediate Frequency (IF) $\omega_i = \omega_a - \omega_o - \omega_i$ is fixed, and tuning is achieved shifting the frequency $\omega_o$ of the local oscillator O.
a) Block diagram;
b) Signal spectrum: the wanted signal $\omega_a$ is isolated by the IF bandpass filter.

In the heterodyne the product operation is performed by a MIXER circuit, and one of the beats (e.g. the difference beat $\omega_i = \omega_a - \omega_o$) is filtered, amplified, and demodulated in the Intermediate Frequency (IF) chain. To receive other channels the system moves the local oscillator frequency $\omega_o$ to a new value $\omega_{o2}$, and the mixer brings to IF a different RF signal $\omega_{a2} = \omega_{o2} + \omega_i$. All the units in the IF chain (after the Mixer) operate at the fixed frequency $\omega_i$; the band-pass transfer function in the IF chain isolates the single channels. Frequency translation and IF filtering have the same effect as a narrow band-pass filter (with IF bandwidth) has on the RF signal. When LO frequency is changed (tuning), the effect is the same as a shifting the mask of this filter to a new frequency.

The same approach – frequency translation by beats – is used also for radio transmitters: modulated signals are generated at baseband frequency, than translated to RF band by mixing baseband with the carrier, and amplified as required.

### 2.2. The Image Frequency

The signal at $\omega_i$ actually comes from two RF signal: $\omega_a = \omega_o - \omega_i$ and $\omega_b = \omega_o + \omega_i$; both $\omega_a$ and $\omega_b$ are moved to the same IF frequency $\omega_i$ and can proceed in the IF chain (Figure 3). If the signal we want to receive is $\omega_a$, the other one ($\omega_b$) is the IMAGE frequency and must be removed. The image comes from other channels or noise, and can be stronger than the useful signal, causing interference and blocking (the high level of image signal drives amplifiers or mixer into saturation).

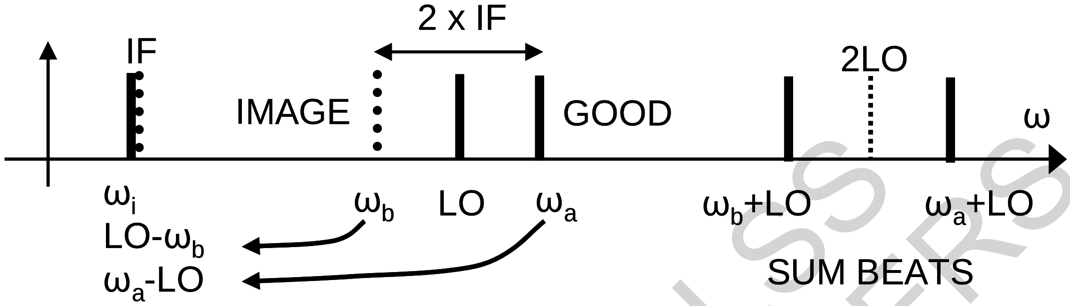


Figure 3. Image frequency.
The mixer generates sum and difference beats. Sum beats can be easily filtered; difference beats are both folded to IF, and the image component ($\omega_b$ -*LO*) is not removed by IF filter.

Removing the image is a major problem in the heterodyne receivers, solved either using RF filters before the mixer, often combined with multiple-conversions, or using image cancellation mixer, based on separate processing of the In-phase/Quadrature (I/Q) components.

A pass-band filter on RF, with bandwidth including all channels to be received, can block the image. The distance between $\omega_a$ and $\omega_b$ is twice the IF value, therefore a "high IF" makes more easy good-signal / image separation. On the other hand, channel separation requires narrowband filter in the IF chain, more easy to achieve with "low IF". The double conversion heterodyne (Figure 4) brings together the benefits of high IF (easy image rejection) and low IF (good channel isolation).

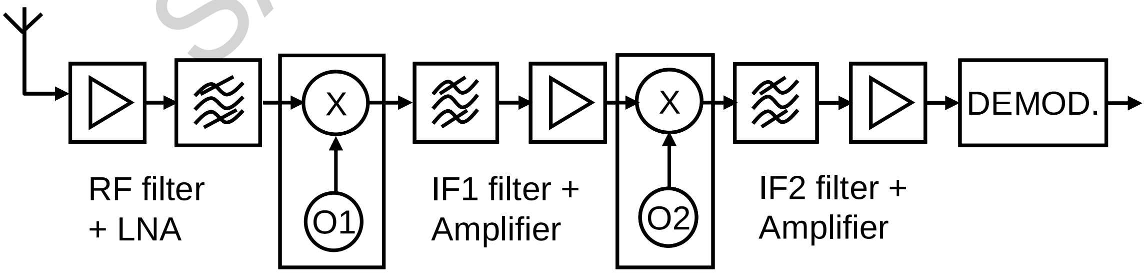


Figure 4. Double conversion heterodyne.
IF1 (high) keeps wide separation between signal and image (blocked by the RF filter). IF2 (low) has narrowband filters for channel separation.

## 2.3. Image Rejection Mixers

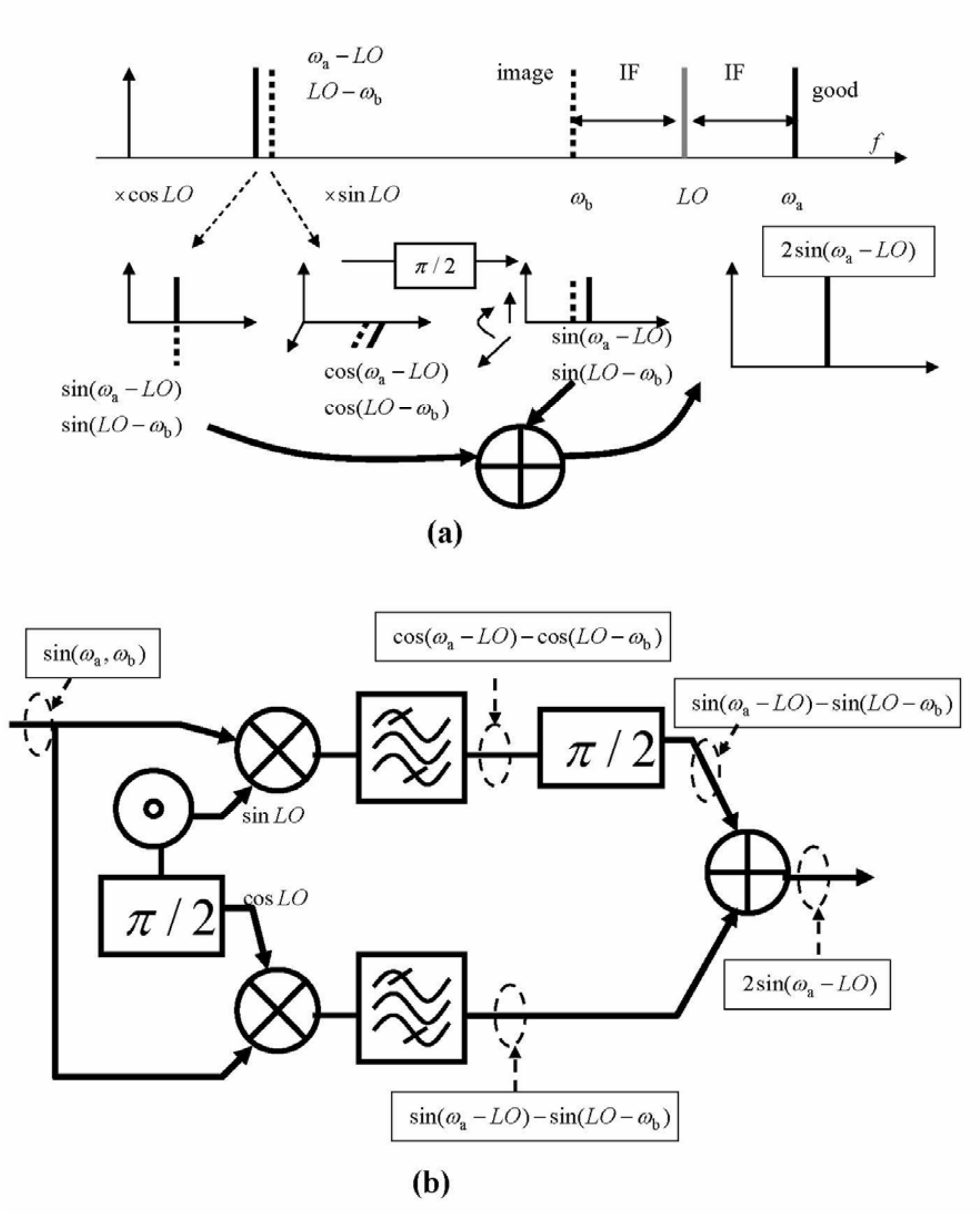


Figure 5. I/Q processing for image cancellation.
a) Sequence of operations
b) Block diagram of the I/Q image rejection mixer.

Separate processing of In-Phase and Quadrature (I/Q) signals allows us to cancel the image signal, by applying the processing steps described in Figure 5.

1) The RF signal includes two components: $\omega_a$ (good signal) and $\omega_b$ (unwanted image);

2) Two mixers multiply RF signal respectively by I (sine) and Q (cosine) components of LO. After each mixer the IF signal includes both $\omega_a$ (the "good" one) and $\omega_b$ (the image), overlapped to the same IF frequency, but with different phase rotation.
3) A $\pi/2$ phase shift is applied to one path, so image components have opposite polarity in the two branches.
4) The two paths are added; $\omega_b$ components have opposite phase and cancel each other; only $\omega_a$ (the good signal) survives.

Image rejection mixers release the specifications of RF and IF band-pass filters. A drawback is the need for tight matching of gain and phase shift in the two branches, to achieve good cancellation.

### 2.4. Zero-IF Architectures

In DIRECT CONVERSION or HOMODYNE, or Zero-IF (ZIF) receivers, the LO has the same frequency as the desired channel, and the "good" signal is moved to DC. ZIF use low-pass filters in the IF chain, more easy to design and build than band-pass inside an IC, making the ZIF architecture suitable for total integration (Systems On Chip : SOC). Critical issues are:

- Offset: DC is a signal, and high-pass filters to remove offset and DC unbalances are not allowed.
- LO to RF leakage in the mixer: it causes a DC beat, which cannot be isolated from the DC coming from actual RF, since they are overlapped on the same frequency band.

Image is the same signal spectrum flipped on the frequency axis around DC, and cannot be removed by filters; image cancellation by I/Q processing becomes mandatory.

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**Biographical Sketch**

**Dante Del Corso** received the Master Degree in Electronic Engineering from Politecnio di Torino in 1070. Since 1986 he is Full Professor of Electronics at the Politecnico di Torino. He coordinated research and design activities for several national and international projects. He received the "Research" award from AEI in 1972, "Informatics" award from Sperry-Univac in 1982 (both with other researchers), "Meritorious Service Certificate" from IEEE-CS in 1994, and IEEE-CS "Golden Core" in 1996. Editor in Chief of IEEE MICRO magazine from 1991 to 1994. Member of the IEEE-CS Publication Board (till 1998), of the Editorial Boards of IEEE MICRO (till 2005), of Neural Processing Newsletters, of the Journal of Engineering Science and Technology Review, and of the JTC1/SC36 ISO-IEC committee (learning technologies). From 1995 to 2008 director of the Multimedia Laboratory of Politecnico and COREP (LAMP). Coordinator of the EU 5th framework IST project "3DE: Design, Development, and Delivery Electronic Environment for Educational MultiMedia" (2000 to 2003). Currently coordinator of the Degree Programmes in Electronic Engineering, for BSc and Masters levels of Politecnico di Torino.
D. Del Corso carried out research and design activities on analog and digital circuits, multiprocessor architectures and buses, high speed interconnections, architectures for Artificial Neural Networks based on pulse-stream circuits, aerospace electronic systems, and in the development of methodologies for design of interactive multimedia educational packages. D. Del Corso is author or co-author of about 160 papers and 8 books and CD-ROMs in the fields of analog and digital electronics, multiprocessor architectures, and use of ICT in education.