Preface

In the last decade wireless communications engineering has seen outstanding progress, making merged, enhanced and novel applications in the area of mobile phones, wireless networks, sensors and television feasible. Technologies have developed from hybrid systems to highly integrated solutions in silicon, SiGe, GaAs and InP. By aggressive scaling of device dimensions below 0.1 μm and employing advanced technologies such as SOI, strained silicon and low-k, circuits with operation frequencies and bandwidths up to approximately 100 GHz can now be fabricated. However, especially in silicon, the restrictions inherent in scaling make circuit engineering a demanding task. Examples of these drawbacks are the limited high frequency signal power, leakage effects and significant parasitics in passive devices. Enhanced circuit topologies and design techniques have to be applied to achieve maximum performance. In this context, designers must have profound skills in the following areas: circuit theory, IC technologies, communications standards, system design, measurement techniques, etc. The aim of this book is to address all these multidisciplinary issues in a compact and comprehensive form and in a single volume. Suitable for students, engineers and scientists, the manuscript provides the necessary theoretical background together with cookbook-like optimisation strategies and state-of-the-art design examples. Each chapter is accompanied by tutorial questions repeating the key issues of the treated subjects.

The manuscript is organised as follows: Chapter 1 preludes with an introduction concerned with the exciting history of integrated circuits, technologies and wireless communications. Moreover, an overview of the IC circuit design flow, tools, applications and markets is given. Chapter 2 reviews the key architectures of wireless systems. In Chap. 3 we study S-parameters and the Smith chart being instrumental for small signal circuit analyses and optimisations. Important RF basics including gain, stability, linearity and noise are treated in Chap. 4. Transistors and passive devices are discussed in Chaps. 5 and 6. Key circuit design techniques and components such as LNAs, PAs, VCOs, synthesisers, mixers, amplitude control elements and phase shifter are elaborated in Chaps. 7–14. Measurement methods and setups are outlined in Chap. 15.

Most of the subjects treated in this book are taught in lectures at the Dresden University of Technology (TUD) in Germany. Lecturers who might be interested in using the material of this manuscript for teaching purposes are encouraged to contact the author. An exchange of experiences is welcome.

This is the second edition of this book. However, the manuscript may still exhibit some unclear phrasings or errors awaiting to be discovered by careful readers like you! I would be very pleased to receive appropriate comments.

This book would not have been possible without the constructive impact of several great colleagues.

I have benefited very much from my teachers Prof. Dr. H. Jäckel, ETH Zürich, Prof. Dr. W. Bächtold, ETH Zürich, Dr. U. Lott, Founder of AnaPico Zürich, and Prof. Dr. H. Schumacher, University of Ulm. Moreover, I would like to thank Prof. Dr. G. Böck, University of Berlin, and Prof. Dr. Dr. habil. R. Weigel, Friedrich Alexander University of Erlangen-Nuremberg, for their support and nice collaboration in several projects. For his fruitful efforts concerning IBM/ETH Zürich CASE (Center For Advanced Silicon Electronics), I would like to acknowledge Dr. M. Schmatz at the IBM Zürich Research Laboratory. A big thank you goes to the members of his group, who are Dr. M. Kossel, Dr. T. Morf, Dr. T. Toifl, Dr. C. Menolfi, and Dr. J. Weiss for sharing their excellent expertise in high-speed circuit design. For the constructive teamwork in my former RFIC group at ETH Zürich, I would like to thank D. Barras, G. von Büren, J. Carls, Dr. C. Kromer, L. C. Rodoni, G. Sialm, and S. Wehrli. The joint afterwork parties were always very funny. I would like to express my gratitude to H. Benedickter and M. Lanz, both with ETH Zürich, for their very valuable help concerning challenging measurements and circuit assembling.

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A large debt of gratitude is owed to my wonderful parents Margit and Wolfgang Ellinger. Finally, and most importantly, I want to express my deep appreciation to my inspiration and girl friend Karin Mächler for her unlimited patience and support. I'm very delighted to dedicate the book to her.

Most of this book has been written during my holidays in Brazil (Porto Galinhas and Fortaleza) and Spain (Canary Islands and Mallorca). These gorgeous locations gave me a fruitful balance and relaxation during the writing of the manuscript.

Since my student days I have found high-speed analogue and RF circuit design very interesting and enthralling. If this book succeeds in inspiring the same enthusiasm in others, then the efforts of its compilation have borne the desired fruit.

Frank Ellinger
Dresden, Germany
April 2008

2 Transceiver Architectures

There is no ingenuity without passion.
Theodor Mommsen, University of Leipzig

Consumer markets demand miniaturised and low-cost transceivers with low power consumption and weight. These goals mandate the consequent integration of all functions and devices on a minimum number of ICs, ideally on one single chip without requiring any external components. However, this is not as trivial as replacing the external elements by on-chip components. Due to significant performance differences between the on-chip and off-chip components, complete overhauls of the transceiver architecture may be necessary. Over the last few years there has been a trend to relocate functions and modulation schemes from the analogue to the digital domain. Reasons are higher flexibility, simpler portability regarding new technologies and standards, and robustness against interferers and noise. A transceiver consists of a receiver and a transmitter. The architecture and key characteristics of different types of receivers and transmitters are covered in this chapter, helping the designer to choose the optimum for a specific application. For detailed information, the reader is encouraged to study the specific literature [Raz03, Meh01, Raz98, Raz96, Spr02].

2.1 Receiver

The main function of a receiver is the demodulation of a wanted signal in the presence of undesired interferers and noise. Due to the strong attenuation during air transmission, the RF signal has to be amplified and recovered. Taking into account scenarios with varying attenuation, a wide dynamic range is required for the detection of signals with high data-rates. To be treated in Sect. 4.5, the dynamic range is determined by noise as the lower bound, and nonlinearities caused by saturation effects as the upper limit.

Due to strongly increasing data traffic, the associated frequency bandwidths are limited. To support a high number of users, these frequency bands are divided into narrow channels typically having a bandwidth in the range of 100 kHz to 100 MHz. Filters with high out-of-band attenuation are required to select those narrow channels. Unfortunately, this high off-band attenuation increases the complexity of filters requiring an increased number of elements. The quality factor

Q of these components must be large to minimise the attenuation of the desired signal.

Power consumption is an important issue for receivers. Even if there is no active communication, receivers can't be switched off completely. They have to detect when a transmitter requests a data transmission and subsequently must switch on the receiver chain by means of a wake-up circuit. Consequently, if not active, a receiver has to be operated in a standby mode, where the DC power is reduced. Nevertheless, accumulation of the drawn DC power over a long stand-by-time can result in significant power consumption. Thus, mobile receivers must have a low power consumption in the stand-by mode.

In the following, we discuss the most important concepts used for wireless communication.

2.1.1 Regenerative Receiver

Regenerative receivers have been a great milestone in radio history since they provided sensitivity and selectivity far beyond that available by the former crystal radio. In 1914, at the age of 21, while he was a student in college, Edwin Armstrong invented the first regenerative radio [Arm14]. The idea behind the enhanced performance was the careful control of the positive feedback between the antenna input and the triode output as depicted in Fig. 2.1. Due to the constructive combining of signal power at the input and the subsequent amplification relatively high gain and output power has been achieved. The feedback allows the generation of negative resistance within the devices leading to controlled instability and oscillation with maximum amplitude at a specific frequency.

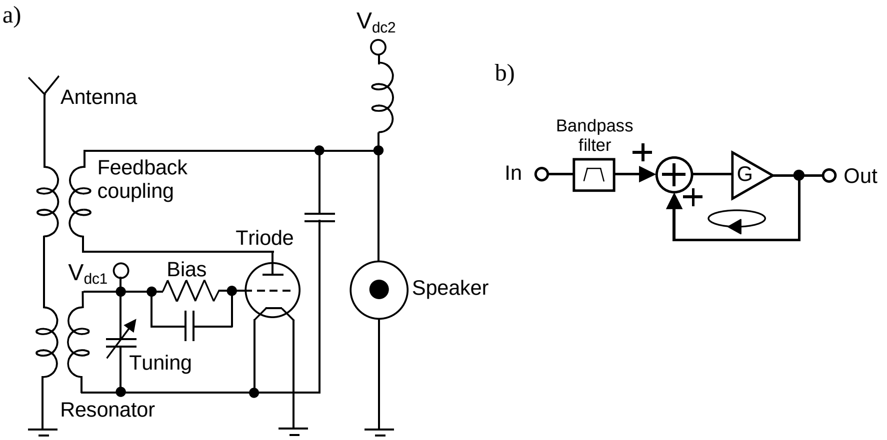

Fig. 2.1a,b. Regenerative receiver: **a** simplified schematics; **b** first order illustration

A patent was filed in 1922 by Armstrong for the principle called the super-regenerative receiver. To prevent the devices from getting saturated and stuck in a previous signal period, the circuit is periodically shut down by an additional quench oscillator. This circuit opens and closes the connection between the resonator and the active device. Due to the high performance, only a few components are required making the super-regenerative receiver a low cost solution, which is still employed today for low data rate applications such as walkie-talkies.

2.1.2 Super-heterodyne Receiver

In 1917, Armstrong invented a further receiver principle, which is still used for a majority of wireless systems. It is the super-heterodyne topology as illustrated in Fig. 2.2. In the literature we frequently find the shortcut simply named heterodyne. At the same time and independently from Armstrong, a similar architecture was proposed by Walter Schottky.

The signal is received by the antenna, coarse filtered by a bandpass filter, amplified by an LNA and converted down to an intermediate frequency (IF) by means of a mixer fed by a local oscillator (LO) signal. The demanding channel filter is employed at IF frequency, followed by an analogue to digital converter and a digital signal processor performing the demodulation and the data decoding. As discussed in Sect. 10.1 and verified by trigonometry, the mixer acts as a signal multiplier yielding

$$\omega_{IF} = \omega_{RF} - \omega_{LO} \tag{2.1}$$

after proper filtering where we assume that $\omega_{RF} > \omega_{LO}$. The demodulation, channel filtering and a part of the amplification can now be performed at the low IF frequency. This relaxes the demands for the components, which typically exhibit raised performance at lowered frequencies. The LO frequency is tuned to fix the IF frequency at varying RF frequency. Consequently, the filter frequency remains constant simplifying the filter complexity.

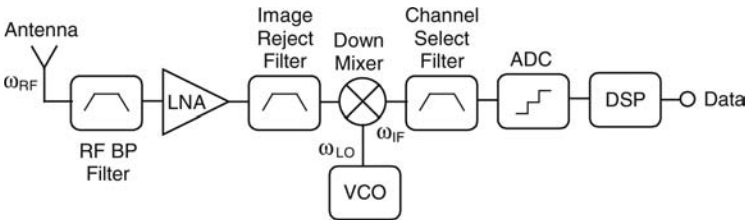

Fig. 2.2. Simplified architecture of the super-heterodyne receiver with single down-conversion, BP: Bandpass, LNA: Low Noise Amplifier, VCO: Voltage Controlled Oscillator, ADC: Analogue Digital Converter, DSP: Digital Signal Processor

On one hand, the in-band loss of filters has to be minimised demanding for low order filters with weak resonances. On the other hand, high selectivity with strong attenuation towards interferers requires high filter orders and high out-of-band attenuation slopes. The requirements for the later parameter depend on the distance between the desired and the unwanted signal frequency related to the desired frequency component. Before and after down-conversion the relation yields $\frac{\omega_{RF}-\omega_{RF*}}{\omega_{RF}}$ and $\frac{\omega_{IF}-\omega_{IF*}}{\omega_{IF}}$, respectively, with potential interferes labelled by *. Since frequency distances are preserved during frequency conversion, we get $\omega_{RF}-\omega_{RF*}=\omega_{IF}-\omega_{IF*}$. By recalling that $\omega_{IF} \ll \omega_{RF}$, we can conclude that down conversion significantly relaxes the demands for the filter with respect to the out-of-band attenuation. Let us review an example with a desired signal at ω_{RF}=15.0 GHz and an undesired interferer at ω_{RF*}=14.4 GHz. The relative frequency difference $\omega_{RF}-\omega_{RF*}$ is only 4 % of ω_{RF}. Therefore, filtering of the interferer is challenging. After down-conversion with ω_{LO}=13.5 GHz, we get ω_{IF}=1.5 GHz and ω_{IF*}=0.9 GHz, respectively. Now, the frequency difference with respect to ω_{IF} is 40 %, which is by a factor of 10 beyond that without frequency conversion. This is illustrated in Fig. 2.3a for filters with the same selectivity at the IF and the RF frequency. By depicting the frequency axis in logarithmic scale, the attenuation slope of the filters appears equal. At IF, the undesired interferer is completely filtered, whereas it can't be entirely filtered at RF.

A severe problem may arise at the undesired image frequency of the RF signal denoted by RFi. Suppose frequencies symmetrically located above and below the LO frequency as illustrated in Fig. 2.3b. In this case, the RF and RFi frequencies are converted to exactly the same IF frequency given by

$$\omega_{IF}=\omega_{RF}-\omega_{LO} \tag{2.2}$$

as wanted, and the component

$$\omega_{IF}=\omega_{LO}-\omega_{RFi} \tag{2.3}$$

incorporating undesired content associated with ω_{RFi}. After mixing, there is no way to separate the original signal and the undesired image signal. In a worst-case scenario, the power of an interferer can be well above the one of the desired signal. Thus, an image rejection filter is required in front of the mixer.

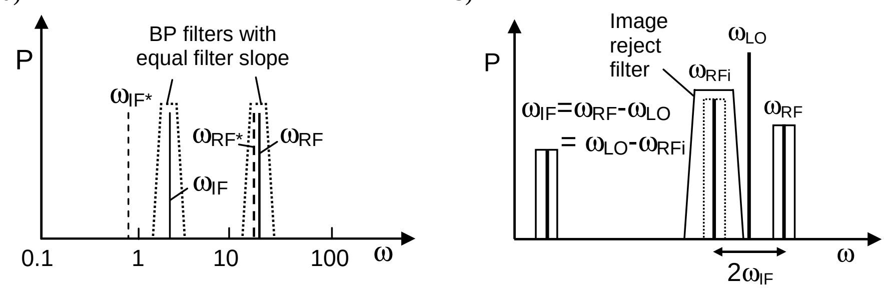

Fig. 2.3a,b. Filtering: **a** of undesired interferer denoted by * at IF and RF using same filter selectivity, BP: Bandpass; **b** of undesired image frequency ω_{RFi}, ω_{RFi} and desired RF frequency ω_{RF} are converted to the same intermediate frequency ω_{IF}

The frequency difference between the desired RF signal and the undesired image signal RFi is given by $2\omega_{IF}$. From this point of view, a large IF frequency is favourable to relax the requirements for the image rejection filter. Unfortunately, this is in contradiction with the requirements for the channel selection filter. Therefore, a reasonable trade-off concerning the IF frequency has to be found for the super-heterodyne receiver with single down conversion.

This tradeoff can be mitigated by using the dual super-heterodyne topology as illustrated in Fig. 2.4. Two different IF frequencies are used. Image rejection is carried out at high IF, whereas channel selection is accomplished at low IF, thereby relaxing the requirements for both filters simultaneously. A constant frequency can be used for the demanding first VCO. Frequency tuning can be performed by the second VCO operating at lower frequency. Unfortunately, two mixers and two oscillators are required increasing the circuit complexity, power consumption and costs.

Nevertheless, systems with narrow channel distances and low IF frequencies typically need image reject filters comprising elements with Q factors well above 100. Such a performance is not feasible with on-chip elements. In this case, external SAW (Surface Acoustic Wave) filters are used. The parasitic off-chip connection, e.g. by bonding wires is not severe given that the IF frequency is below several GHz. Due to filter and connection constraints, the interface impedance between the output of the filters and the input of the active circuits must be around 50 Ω limiting the exploitation of the active device gain, which typically increases with raised load impedance.

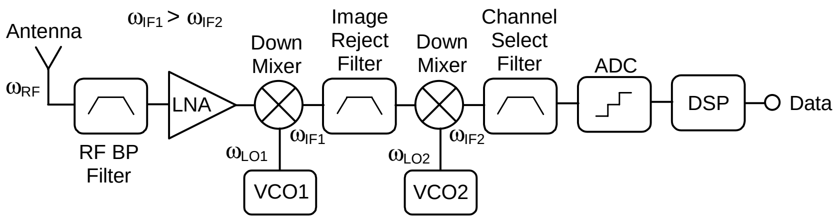

Fig. 2.4. Simplified architecture of super-heterodyne receiver with double down-conversion

The RF band filter preceding the LNA operates as coarse filter and rejects strong interferers, which may saturate the receiver. A certain level of filtering can be achieved by narrowband design of the LNA. Due to their high Q-factors, off-chip filters allow enhanced performance compared to on-chip realisations. However, they consume much more circuit size. Moreover, low loss connections are challenging at high frequencies. For these RF filters, low resistive losses are very important since they directly add to the system noise figure. According to the equation of Friis, see Eq. (4.29), the noise contribution of the filters located after the LNA do not have a significant noise contribution as long as the LNA gain is high.

2.1.3 Image Rejection

The problems associated with the image rejection have motivated designers to invent smart techniques for the rejection of the image frequency without requiring sophisticated filters. Such techniques are especially useful for applications where the desired RF and the undesired image signal are so close in frequency that conventional filtering is not possible. Among the most often used approaches are the Hartley and Weaver image reject techniques developed in 1928 and 1956, respectively.

These techniques are based on the idea of producing two paths having the same polarity for the desired signal, and the opposite polarity for the undesired image signal. Subsequent combining of the paths recovers the desired signal and cancels the image signal.

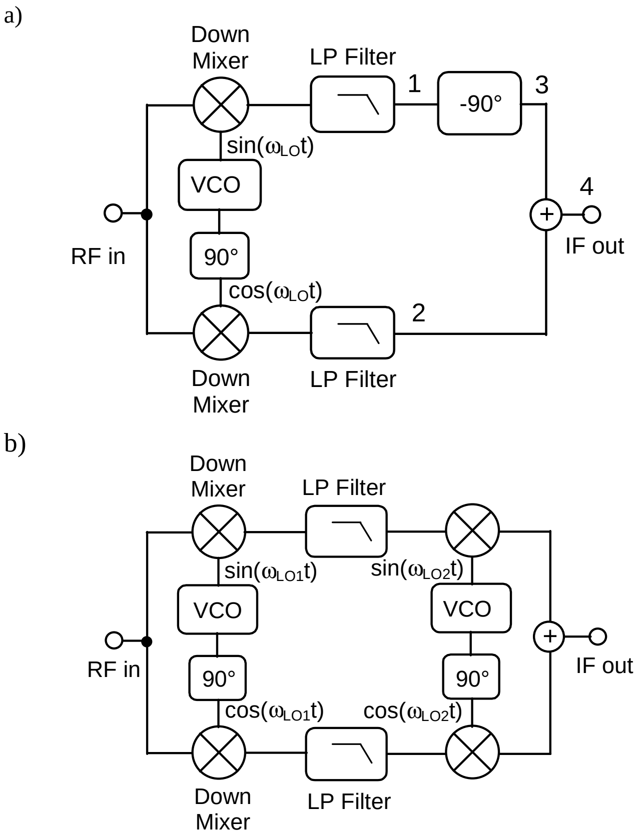

Fig. 2.5a,b. Image reject techniques, LP: Lowpass: **a** Hartley; **b** Weaver

In Fig. 2.5a, the Hartley architecture is illustrated. Let us assume an input signal of $v_{in}(t) = V_{RF}\cos\omega_{RF}t + V_{RFi}\cos\omega_{RFi}t$ with V_{RFi} and ω_{RFi} denoting the voltage amplitude and frequency of the image component. We assume that $\omega_{RF}>\omega_{LO}$.

After multiplication with $\sin\omega_{LO}t$ and $\cos\omega_{LO}t$ in the upper and lower path, respectively, and low pass filtering of harmonics and undesired intermodulation products, we get the following intermediate results at points 1 and 2:

$$v_1(t) = -\frac{V_{RF}}{2}\cdot\sin\left(\omega_{RF}-\omega_{LO}\right)t + \frac{V_{RFi}}{2}\cdot\sin\left(\omega_{LO}-\omega_{RFi}\right)t \qquad (2.4)$$

$$v_2(t) = \frac{V_{RF}}{2}\cdot\cos\left(\omega_{RF}-\omega_{LO}\right)t + \frac{V_{RFi}}{2}\cdot\cos\left(\omega_{LO}-\omega_{RFi}\right)t\,. \qquad (2.5)$$

The 90° phase shift in the VCO can be generated by a quadrature VCO as presented in Sect. 11.6.2. Of course, optionally, a common VCO can be used together with a 90° phase shifter. Considering a further phase-shift of –90° in $v_1(t)$ we obtain

$$v_3(t) = \frac{V_{RF}}{2}\cdot\cos\left(\omega_{RF}-\omega_{LO}\right)t - \frac{V_{RFi}}{2}\cdot\cos\left(\omega_{LO}-\omega_{RFi}\right)t\,. \qquad (2.6)$$

Adding $v_2(t)$ and $v_3(t)$ yields $v_4(t) = V_{RF}\cdot\cos\left(\omega_{RF}-\omega_{LO}\right)t$, verifying that the desired signal is recovered and the image is rejected. However, full image rejection mandates ideal matching of the phases and amplitudes in the paths. A gain mismatch would be caused by the 90° phase shifter. To reduce corresponding amplitude mismatches it is advantageous to split the total phase shift of 90° into 45° in the upper path and –45° in the lower path. For these phase shifters, RC or LC filters can be used. RC filters exhibit wider bandwidths, whereas the LC counterparts yield lower losses.

An optional approach is offered by the Weaver architecture depicted in Fig. 2.5b. The bandwidth limiting and process variation dependent phase shifters are replaced by a second pair of quadrature mixers fed by an additional VCO typically having lower frequency than the preceding one. Larger bandwidth and better image rejection can be achieved at the expense of higher power consumption and circuit complexity. Optionally, the second IF can be mixed down to DC leading to the direct conversion approach, which is subject to discussions in the next section.

As for other I/Q based architectures, phase and amplitude mismatches in the quadrature mixers can significantly degrade the performance. Given fully symmetrical designs, the mismatches are mainly determined by process variations. Those process variations are relatively small for fully integrated solutions. Practical implementations typically exhibit image rejection of more than 30 dB, which is sufficient for many applications.

2.1.4 Direct Conversion Receiver

The motivation of increased integration has led to the direct conversion receiver, which is also referred to as homodyne or zero-IF approach [Raz97, Zha03]. The idea is to translate the RF signal directly to zero-IF frequency thereby exhibiting the following advantages. First, the channel filtering can be performed by a lowpass filter. Recall that a more complex bandpass filter is necessary for the superheterodyne receiver. Second, the IF frequency of zero eliminates the image problem. Hence, no external high-Q image reject filter is required making fully integrated solutions feasible.

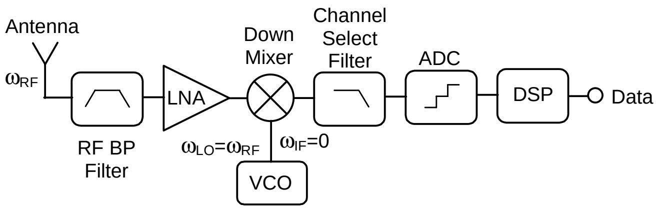

Fig. 2.6. Illustration of zero-IF approach

In Fig. 2.6, a simple direct conversion architecture is illustrated, which can be used for processing of amplitude modulated signals featuring the same information at the two sidebands allocated around the carrier frequency. For more sophisticated frequency and phase modulations schemes, the information within the two sidebands can be different. However, after conversion around DC, these sidebands can't be separated leading to a loss of information. This can be prevented by using quadrature mixing with in-phase (I) and quadrature (Q) signals as illustrated in Fig. 2.7. Consequently, the information of both sidebands can be preserved allowing efficient modulation schemes.

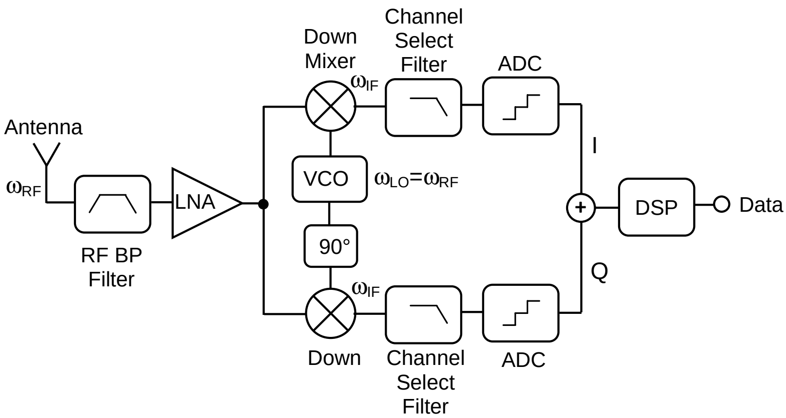

Fig. 2.7. Illustration of the zero IF approach with I/Q quadrature mixing

The zero-IF approach seems to be superior compared with other architectures. However, the following issues impede its widespread use in today's radios. The RF carrier and the local oscillator are at the same frequency. Thus, LO leakage to the mixer input can lead to self mixing resulting in a time-varying DC offset at the output of the mixer. This DC offset may corrupt the signal and can lead to a saturation of the following stages thereby significantly degrading the upper boundary of the dynamic range. Consequently, sophisticated offset cancellation techniques are required in practical implementations. We will learn in Sect. 4.3.3 that the flicker noise of the active devices becomes significant at low frequencies. Thus, low noise amplification and active filtering is difficult for zero-IF topologies degrading the lower limit of the dynamic range.

2.1.5 Low-IF Receiver

One integrated receiver solution, which mitigates some problems associated with the direct conversion receiver is the low-IF receiver [Cro98]. Similar to the direct conversion receiver, a quadrature mixer is used to translate the desired channels to a low IF frequency. Typically, an IF frequency in the order of one up to two channel bandwidths corresponding to 50 kHz to 10 MHz are used as IF frequency. The image rejection can be performed by mixer topologies similar to the Hartley or Weaver architecture. Due to the low IF frequency, channel filtering is relatively simple. Common switched capacitor filters can be applied. Consequently, all relevant filters can be implemented on-chip.

Unlike the zero-IF architecture, the low-IF receiver is not sensitive to the parasitic DC offset, LO leakage and flicker noise. We can conclude that the low IF topology is an excellent compromise between the zero-IF and the super-heterodyne architecture. Thus, the low-IF approach is quite popular in today's receivers. However, as for the zero-IF topology, process variations can introduce I/Q imbalances, which degrade the performance. Corresponding compensation techniques can be applied [Win04].

2.1.6 Digital-IF Receiver

To make systems more flexible, as much signal processing as possible is transferred into the digital domain. Figure 2.8 depicts a realisation of a digital-IF receiver. The idea is to perform the demanding channel filtering completely in the digital domain. Thus, the requirements for the RF filters are relaxed. Simple RF filters may be employed for coarse band selection. The major advantage is the flexibility of the architecture. The receiver can be reconfigured for a variety of systems with different modulation types, channel frequencies and bandwidths meeting the demands of different standards. Moreover, the digital approach avoids the phase and amplitude mismatch problems of analogue I/Q signals. Generally, the impact of process tolerances is less significant.

However, digital-IF receivers are still in their infancy. One of the main critical issues is the extremely high dynamic range required for the ADC, or the AGC (Automatic Gain Control) circuit located in front of the ADC. A wanted channel, which may be significantly attenuated during air propagation, mandates a very high sensitivity with respect to the inherent noise properties, whereas an unfiltered non-desired channel with high power can saturate the ADC.

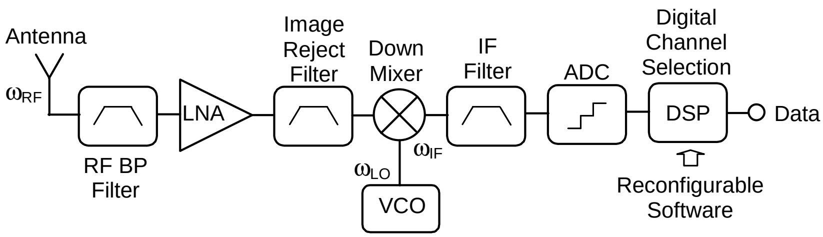

Fig. 2.8. Simplified digital-IF receiver

Typical IF values are around 100 MHz, demanding sampling rates of 200 MHz, which are easily achievable with plain vanilla technologies. Speed and resolution of an ADC have to be traded off. Considering typical dynamic range requirements, resolutions in the range of 12–16 bits are necessary, which is very difficult to obtain together with the high speed. The subsequent baseband filtering requires enormous processing power. With present technology, the excessive power consumption limits the use of digital IF receivers for mobile applications.

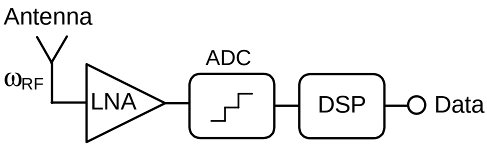

Fig. 2.9. Vision of digitalised receiver with RF analogue to digital conversion

A further architecture to be envisioned is illustrated in Fig. 2.9 [Hen99]. Given that the challenges associated with the figure of merit described by

$$\mathrm{FOM} = \frac{\text{dynamic range} \cdot \text{resolution}}{\text{power consumption}} \tag{2.7}$$

can be solved, the analogue to digital conversion may be accomplished at RF without requiring any frequency conversion in the analogue domain. Considering the current state-of-the-art this seems to be impossible. However, in the area of microelectronics, we have witnessed that the impossible has been made possible for many times by employing enhanced technologies and techniques. Let us meet the challenge.

2.1.7 Impulse Radio Receiver

In recent years, impulse based radios receive a revival due to its promising properties for short range, low power and high speed applications [Por03, Uwb06, Weis04, Paq04, Opp04, Zas03, Sto04, Bar06, Ba206]. In the USA, corresponding UWB (Ultra-Wideband) standards have already been published by the FCC (Federal Communications Commission) [Fcc02], whereas in Europe the community is still waiting for adequate standards. A complete UWB chip set is already available [Fre06].

Let us recall that the first efficient radio transmissions have been performed on the basis of impulse transmission. Today, the UWB standard employs impulse transmission within a frequency band between 3.1 GHz and 10.6 GHz. Pulse position modulation (PPM) can be employed for data transmission. The major benefit of the impulse radio is the low complexity. Compared to conventional receivers, no power consuming PLL synthesisers are required. Due to the large bandwidth available, the demands for the frequency accuracy are much more relaxed. Frequency down-conversion is not necessary. However, mixers may be applied for correlation purposes.

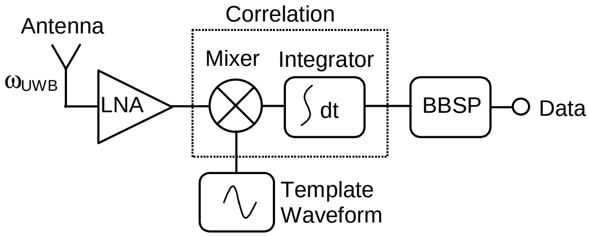

Fig. 2.10. Example of top-level schematics of impulse radio receiver, BBSP: Baseband Signal Processing

An example of an architecture is outlined in Fig. 2.10 [Opp05]. It consists of an antenna, an LNA, a correlation circuitry and the baseband processing. After amplification, the received signal is correlated with a template waveform. A mixer and a template waveform generator can be applied for this task. The output signal of the mixer is integrated to maximise the received signal level with respect to the inherent noise power. To encode the data, the output of the correlation circuit is processed in the baseband. Challenges in terms of circuit design are the speed and the bandwidth of the RF components. Due to the large bandwidth, wideband receivers may be susceptible to interferers.

2.1.8 Receiver Comparison

In Table 2.1, the advantages and disadvantages of the different receiver architectures are summarised. The final choice strongly depends on the individual specifications and the available technology.

Table 2.1. Comparison of receiver architectures

<table>
<tr><th>Architecture</th><th>Complexity</th><th>Full integration</th><th>Power cons.</th><th colspan="2">Comments</th></tr>
<tr><td>Super-regenerative</td><td rowspan="2">Low</td><td rowspan="2">Possible</td><td rowspan="2">Very low</td><td rowspan="2">No carrier, impulse with wide bandwidth can cause interferences with other systems if emitted power not limited</td><td>High sensitivity because of resonant feedback</td></tr>
<tr><td>Impulse radio</td><td>High bandwidth of 3.11–10.6 GHz allows high data rates</td></tr>
<tr><td>Super-heterodyne</td><td>Moderate</td><td rowspan="2">Off-chip image reject and channel select filter required</td><td>Moderate</td><td colspan="2">IF has to be traded off for image rejection and channel selection</td></tr>
<tr><td>Dual super-heterodyne</td><td>High</td><td>High</td><td colspan="2">Good image rejection and channel selection possible</td></tr>
<tr><td>Direct conversion</td><td>Low</td><td>Possible</td><td>Low</td><td colspan="2">DC offsets can significantly degrade the performance, sensitive to flicker noise</td></tr>
<tr><td>Low-IF</td><td>Low/moderate</td><td>Possible</td><td>Low/moderate</td><td colspan="2">Good overall performance</td></tr>
<tr><td>Digital-IF</td><td>RF: very low
Baseband: very high</td><td>Possible</td><td>Very high</td><td colspan="2">Very flexible architecture, can handle different standards, modulation and frequencies, ADC limits dynamic range which is a major drawback</td></tr>
</table>

2.2 Transmitter

The three primary functions of common transmitters are modulation, frequency conversion and power amplification. Consequently, the key performance parameters are modulation accuracy, spectral purity and RF output power. Since a strong signal is locally available, band selection and noise are not as critical as in receivers. Moreover, the variation of the signal level is small relaxing the requirements in terms of the dynamic range. Thus, transmitters are less complex and are found in a smaller variety of approaches than receivers. The generation of high output power leads to a high DC power consumption. Thus, in active operation, the power consumption of transceivers is determined by the transmitter rather than by the receiver. However, a transmitter can be completely shut down after signal transmission to save power.

To transmit data, modulation modes with both constant and variable signal amplitude can be employed. The first scheme is more power efficient, whereas the latter one is more spectral efficient at the expense of challenging requirements in terms of linearity.

2.2.1 Direct Conversion Transmitter

Figure 2.11 illustrates the principle of a direct conversion architecture. The baseband signal is up-converted to RF, bandpass filtered, amplified and lowpass filtered before the signal is emitted by the antenna. The direct up-conversion architecture suffers from the so called injection pulling, where a part of the strong power amplifier signal is coupled back to the oscillator operating at the same RF frequency. Thus, undesired DC components are generated. Reasons for the coupling are the non-ideal substrate isolation and reflections at the component interfaces.

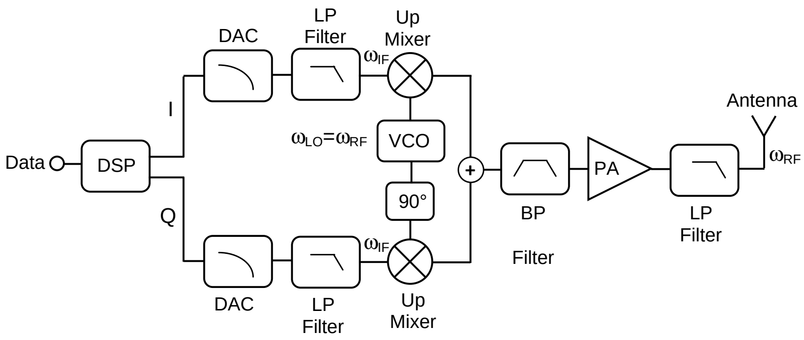

Fig. 2.11. Architecture of direct conversion transmitter, PA: Power Amplifier, DAC: Digital Analogue Converter

Injection pulling may lead to spectral interferences, additional noise and frequency drifts. Sophisticated shielding methods may be used to alleviate this problem. One solution is the separation of the VCO and the PA on different chips. However, the aim for single chip solutions makes this idea unattractive.

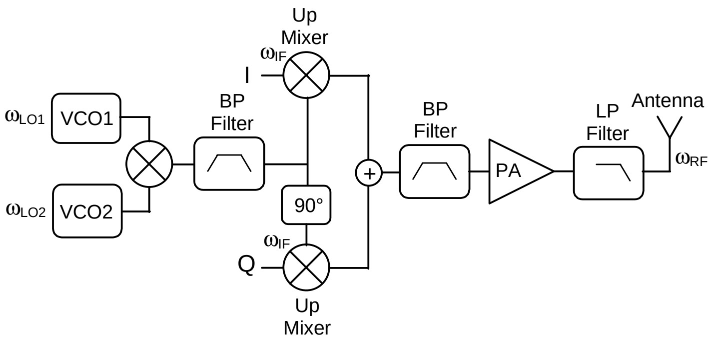

Fig. 2.12. Illustration of offset direct conversion transmitter

The injection pulling can be avoided if the frequencies of the power amplifier and the oscillator are different. To this end, the up-conversion can be performed in two steps, where the two VCOs run at the different frequencies. Alternatively, as illustrated in Fig. 2.12, the frequencies $\omega_{LO1} \neq \omega_{LO2}$ of two VCOs can be added or subtracted to obtain the desired oscillation frequency.

2.2.2 Direct Modulation Transmitter

A typical architecture of a direct modulation transmitter is illustrated in Fig. 2.13. The baseband signal is modulated and up-converted in one single step. By means of the frequency control voltage, the VCO is modulated by the applied data. Subsequently, the signal is amplified, low pass filtered and emitted via antenna. Amplitude modulated signals can't be transmitted since the VCO is always in saturation. The architecture is well suited for frequency and phase modulations. Among the advantages of this approach are the low complexity, the increased ability for integration and the low power consumption.

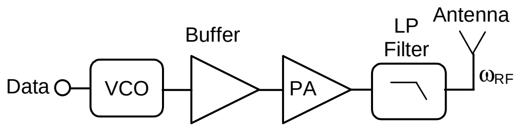

Fig. 2.13. Architecture of direct modulation transmitter

One critical issue associated with the direct modulation is the frequency stability of the VCO during the transmission. The following disturbances may change the VCO frequency and corrupt the modulation: injection pulling, supply voltage variations, and impedance variations between the VCO and the PA. The latter effect can be mitigated by implementation of a buffer with high isolation. A PLL (Phase Locked Loop) is often added to improve the frequency stability and to reduce the content of harmonics and noise.

2.2.3 Impulse Radio Transmitter

In Fig. 2.14, the simple architecture of an impulse radio transmitter is illustrated consisting of a pulse generator, a timing circuit and a clock oscillator [Opp05]. PPM is used for data modulation. A programmable delay circuit can be employed to determine the timing. The desired waveform is produced by the pulse generator, while the clock oscillator defines the pulse repetition frequency. Step, Gaussian or monocycle pulses are suited for UWB communication since they have a broadband frequency spectrum.

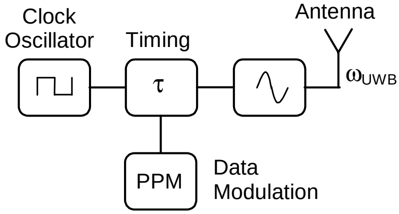

Fig. 2.14. Example of top-level schematics of impulse radio transmitter

2.2.4 Transmitter Comparison

In Table 2.2, the advantages and disadvantages of the different transmitter approaches are summarised. As for the receiver, the final choice strongly depends on the individual specifications, applications and the employed technology.

Table 2.2. Comparison of transmitter architectures

Architecture	Complexity	Full integration	Power consumption	Comments
Direct conversion	Low	Possible since no sophisticated filters are required. However technology must be capable of providing enough output power	Similar since major power drawn by PA, offset approaches slightly higher	Sensitive to injection pulling
Offset direct conversion	Moderate			Injection pulling alleviated
Direct modulation	Very low			Modulation can be corrupted by frequency variations
Impulse radio	Very low		Very low since output power restricted due to potential for interferences with other standards	High bandwidth allows high data range at low coverage range

2.3 Transceiver Example

Obviously, transceivers consist of both a receiver and a transmitter. Figure 2.15 depicts a simple super-heterodyne transceiver. In many cases, a transceiver needs only one multifunctional VCO since it may be used for both the receiver and transmitter. This holds also for the antenna. SPDT (Single Pole Double Throw) switches can be employed to change between the receive- and transmit- modes. Drawback of these switches is the additional losses of around 0.5–2 dB, which directly add to the overall noise figure in the receiver and reduce the effective PA power. However, the benefit regarding the saved space and costs with respect to a second antenna may be considerable. For detailed information concerning switches, the reader is referred to Sect. 13.1.

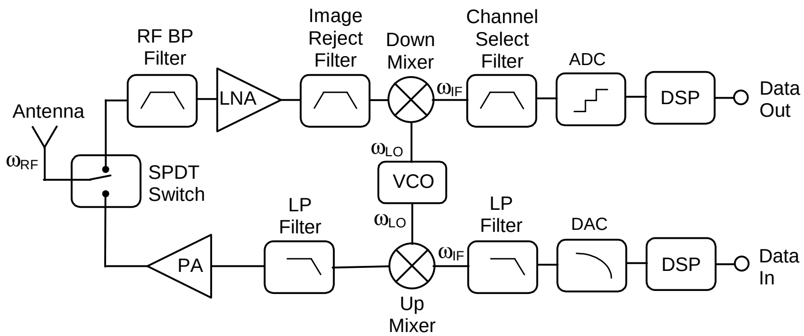

Fig. 2.15. Transceiver architecture of super-heterodyne transceiver, SPDT: Single Pole Double Throw

2.4 Smart Antenna Transceivers

Recall that maximum antenna gain can be achieved with antennas providing a high directivity. On the other hand, the probability of spatially dependent fading increases with raised directivity. The probability of fading can be decreased by employing multiple antennas, which are properly spaced apart from each other. To make sure that one antenna receives a non-faded signal in case that one antenna is in a fading whole, antenna distances in the order of fractions of a wavelength are reasonable. Based on the signal detected by a RSSI (Received Strengths Indicator), the system may choose the optimum antenna. Passive or active switches can be applied for this task. The drawback of this switched antenna approach is the increased system size. We have to keep in mind that antennas consume significant space. An advantage of this approach is the low control complexity. However, only one antenna is active at the same time. Thus, the potential of the other antennas is not exploited.

To achieve diversity gain and to combine the signals available at all antennas in the most efficient way, the complex weighting vector w_i of the signal path must be adjusted [Lib99, Witt00]. The weighting vector w_i of each active antenna path is a function of phase and amplitude. All vectors are optimised to maximise the quality of the available signal, which can be specified by the received power or more meaningful by the bit error rate available in the baseband. This approach is widely known as adaptive antenna combining or MIMO (Multiple In Multiple Out) approach and is a promising technique to reach wireless data rates of beyond 50 Mb/s in realistic environments. Since the impact of inter-symbol interferences can be mitigated, the coverage range and indoor penetration is enhanced. Through range extension, initial costs for system installations can be reduced. Moreover, the number of simultaneous subscribers supported in each cell can also be increased.

The weighting factor can be adjusted in both the transmitter and the receiver. Typically, in active operation, receiver paths consume less power than transmitter branches. Thus, for mobile applications, it can be advantageous to perform the weighting in the receiver only, a concept referred to as MISO (Multiple In Single Out). As illustrated in Fig. 2.16 for a receiver, w_i can either be set and combined in the analogue RF, LO, IF, or digital BB (Baseband) section. Due to the flexibility, this task is frequently performed in the BB. However, it is obvious that the latter solution requires the highest power consumption since all components from RF to BB have to be operated in parallel. Alternatively, to minimise the power consumption for mobile applications, the weighting can be accomplished in the RF part [Ell21, Ell29]. Promising enhancements of the bit error rates in environments with strong multipath propagation has been demonstrated [Ell2]. The design of high performance phase shifter ICs is challenging. Referring to Sect. 14, they introduce amplitude variations vs the phase control making precise vector adjustments difficult. Moreover, low loss phase shifter ICs tend to have a small bandwidth.

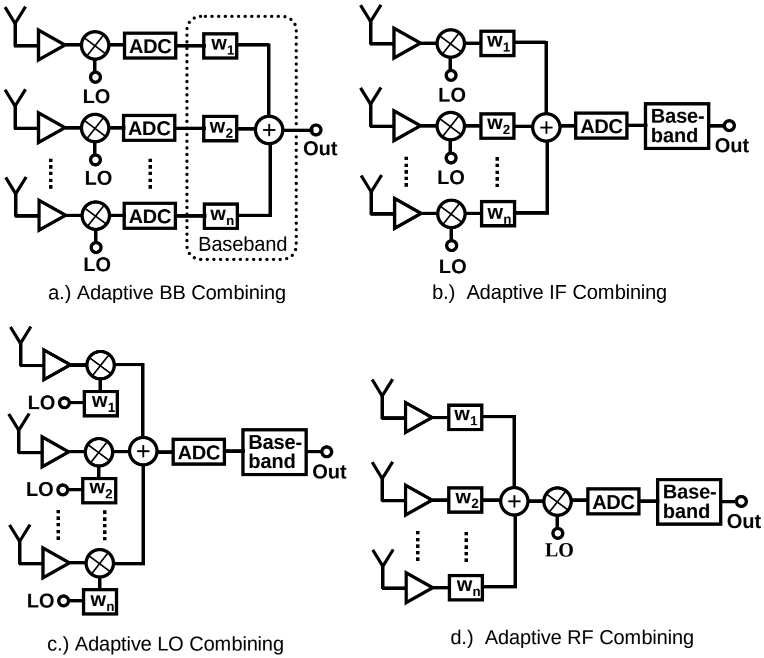

Fig. 2.16a–d. Adaptive antenna receivers, weighting factor w_i is a function of amplitude and phase with i {1..n} as number of antenna paths, combining can be performed in: **a** BB; **b** IF; **c** LO; **d** RF section

2.5 Tutorials

1. What are the general tasks of wireless transceivers? Why do we need transceivers at high and allocated frequencies? What are the main performance parameters?
2. Explain the single super-heterodyne receiver architecture.
3. What is the problem if an interferer is located close to the desired RF frequency? Consider the filtering. How can we mitigate this problem? How do we have to choose the IF frequency?
4. How is the image signal at IF generated? What is the problem of this image signal? How do we have to choose the IF frequency to simplify the suppression of the image frequency?
5. Explain further concepts allowing image rejection.
6. For the single heterodyne receiver, what are the design tradeoffs in terms of the IF frequency?
7. Explain the double heterodyne receiver. What is the advantage in terms of channel selectivity and image rejection? What is the economic disadvantage?

8. Explain the direct conversion receiver. What are the pros and cons? Suggest solutions to mitigate the disadvantages of the concept. Compare the direct conversion receiver with the low-IF architecture.
9. Outline the functionality of the impulse based receiver.
10. Which receiver architecture would you use for a system demanding for highest data rate and coverage range and where power consumption and costs do not matter? Which one would you choose for a low cost system with high data rate and very small coverage range?
11. What are the main performance parameters of transmitters?
12. Discuss the architecture, and the pros and cons of the key transmitter approaches.
13. Illustrate the architecture of a complete zero-IF transceiver with IQ mixers. What is the advantage of the IQ modulation?
14. Envision future transceiver concepts.
15. What are the advantages and disadvantages of multi-antenna systems? What does MIMO, SIMO and MISO mean? Which one provides a good tradeoff regarding the performance to power consumption and complexity figure of merit? How can we adjust the vector for smart antenna combining? Illustrate the signal combining in the RF, LO, IF and BB. What are the pros and cons? Suggest circuits for variable gain amplifiers and phase shifters operating in the RF path.

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