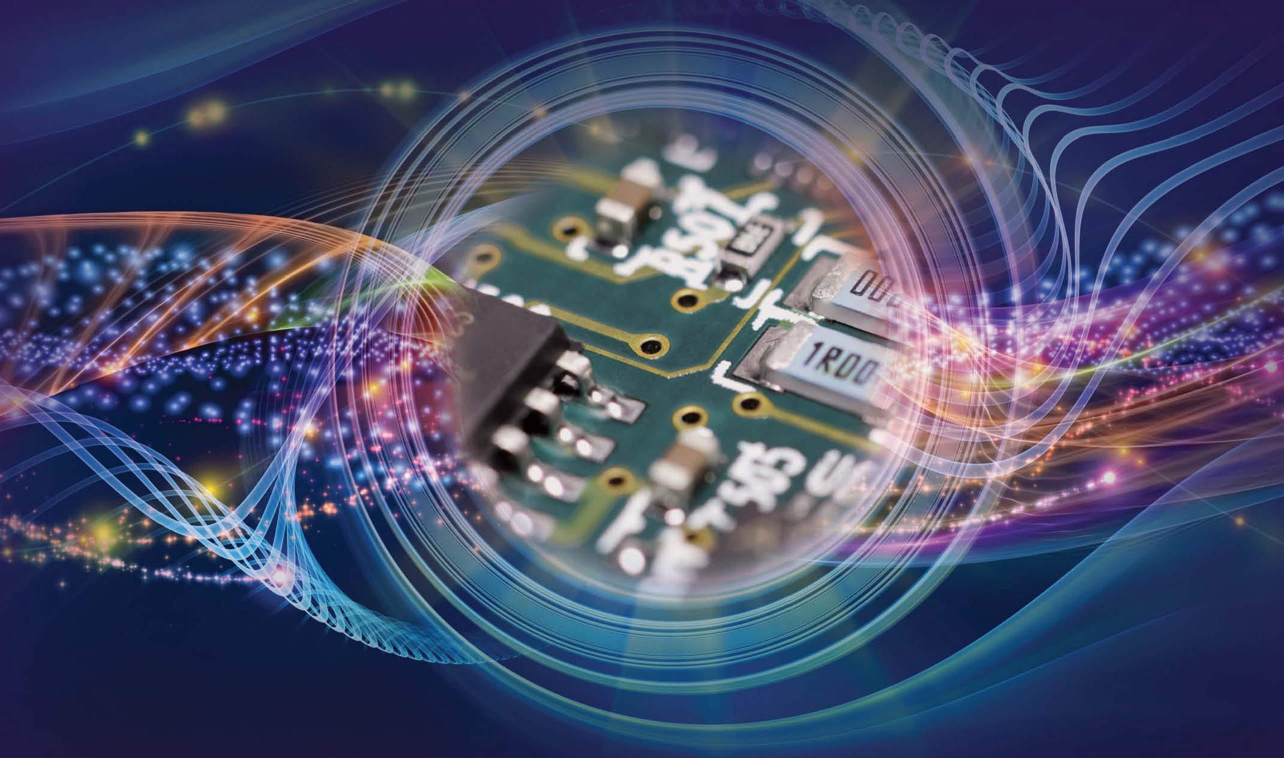
RADIO RECEIVER TECHNOLOGY

Principles, Architectures and Applications



RALF RUDERSDORFER

WILEY

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PRINCIPLES, ARCHITECTURES AND APPLICATIONS

Ralf Rudersdorfer

In cooperation with

Ulrich Graf
(in I.1, I.2, II.8.1, III.9, IV.5, V.2.3, V.3)

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(in I.2.3, I.3, III.6.1, III.9.5)

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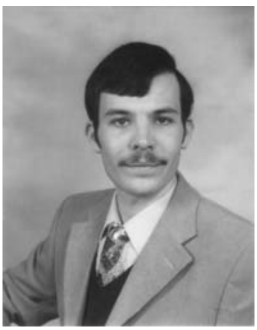
About the Author



Ralf Rudersdorfer, born in 1979, began his career at the Institute for Applied Physics. He then changed to the Institute for Communications Engineering and RF-Systems (formerly Institute for Communications and Information Engineering) of the Johannes Kepler University Linz, Austria, where he is head of Domain Labs and Technics. His activities included the setting up of a measuring station with attenuated reflection properties/antenna measuring lab and furnishing the electronic labs of the Mechatronics Department with new basic equipment.

He began publishing technical papers at the age of 21. In August 2002 he became a Guest Consultant for laboratory equipment and RF hardware and conducted practical training courses in 'Electronic Circuit Engineering' at the reactivated Institute for Electronics Engineering at the Friedrich Alexander University Erlangen-Nuremberg, Germany. In 2006 he applied for a patent covering the utilization of a specific antenna design for two widely deviating ranges of operating frequencies, which was granted within only 14 months without any prior objections. In the winter semesters 2008 to 2011 the Johannes Kepler University Linz, Austria, commissioned him with the execution of the practical training course on 'Applied Electrical Engineering'.

Rudersdorfer is the author of numerous practice-oriented publications in the fields of radio transmitters and radio receivers, high-frequency technology, and general electronics. Furthermore, he was responsible for the preparation of more than 55 measuring protocols regarding the comprehensive testing of transmitting and receiving equipment of various designs and radio standards issued and published by a trade magazine. During this project alone he defined more than 550 intercept points at receivers. He has repeatedly been invited to present papers at conferences and specialized trade fairs. At the same time he is active in counseling various organizations like external cooperation partners of the university institute, public authorities, companies, associations, and editorial offices on wireless telecommunication, radio technology, antenna technology, and electronic measuring systems.

In the do-it-yourself competition at the VHF Convention Weinheim, Germany, in 2003 he received the Young Talent Special Award in the radio technology section. At the short-wave/VHF/UHF conference conducted in 2006 at the Munich University of Applied Sciences, Germany, he took first place in the measuring technology section. The argumentation for the present work in its original version received the EEEfCOM Innovation Award 2011 as a special recognition of achievements in Electrical and Electronic Engineering for Communication. Already at the age of 17 Ralf Rudersdorfer was active as a licensed radio amateur, which may be regarded as the cornerstone of his present interests.

Owing to his collaboration with industry and typical users of high-end radio receivers and to his work with students, the author is well acquainted with today's technical problems. His clear and illustrative presentation of the subject of radio receivers reflects his vast hands-on experience.

Preface

The wish to receive electromagnetic waves and recover the inherent message content is as old as radio engineering itself. The progress made in technical developments and circuit integration with regard to receiver systems enables us today to solve receiver technology problems with a high degree of flexibility. The increasing digitization, which shifts the analog/digital conversion interface ever closer to the receiving antenna, further enhances the innovative character. Therefore, the time has come to present a survey of professional and semi-professional receiver technologies.

The purpose of this book is to provide the users of radio receivers with the required knowledge of the basic mechanisms and principles of present-day receiver technology. Part I presents realization concepts on the system level (block diagrams) tailored to the needs of the different users. Circuit details are outlined only when required for comprehension. An exception is made for the latest state-of-the-art design, the (fully) digitized radio receiver. It is described in more detail, since today's literature contains little information about its practical realization in a compact form.

The subsequent sections of the book deal with radio receivers as basically two-port devices, showing the fields of application with their typical requirements. Also covered in detail are the areas of radio receiver usage which are continuously developed and perfected with great effort but rarely presented in publications. These are (besides modern radio direction finding and the classical radio services) predominantly sovereign radio surveillance and radio intelligence. At the same time, they represent areas where particularly *sophisticated radio receivers* are used. This is demonstrated by the many examples of terrestrial applications shown in Part II.

A particular challenge in the preparation of the book was the *systematic presentation* of all characteristic details in order to comprehend, understand and evaluate the respective equipment properties and behaviour. Parts III and IV, devoted to this task, for the first time list all receiver parameters in a comprehensive, but easy to grasp form. The description consistently follows the same sequence: Physical effect or explanation of the respective parameter, its acquisition by measuring techniques, and the problems that may occur during measurement. This is followed by comments about its actual practical importance. The measuring techniques described result from experience gained in extensive laboratory work and in practical tests. Entirely new territory in the professional literature is entered in Part IV with the model for an evaluation of practical operation and the related narrow margin of interpretation.

The Appendix contains valuable information on the dimensioning of receiving systems and the mathematical derivation of non-linear effects, as well as on signal mixing and secondary reception. Furthermore, the Concluding Information provides a useful method for converting different level specifications as often encountered in the field of radio receivers.

Easy comprehension and reproducibility in practice were the main objectives in the preparation of the book. Many pictorial presentations were newly conceived, and the equations introduced were supplemented with practical calculations.

In this way the present book was compiled over many years and introduces the reader with a basic knowledge of telecommunication to the complex matter. All technical terms used in the book are thoroughly explained and synonyms given that may be found in the relevant literature. Where specific terms reappear in different sections, a reference is made to the section containing the explanation. Due to the many details outlined in the text the book is well suited as a reference work, even for the specialist. This is reinforced by the *index*, with more than *1,200 entries, freely after the motto*:

When the expert (developer) finds the answer to his story,
spirits rise in the laboratory,
and so one works right through the night
instead of only sleeping tight!

Acknowledgements

The professional and technically sound compilation of a specialized text always requires a broad basis of experience and knowledge and must be approached from various viewpoints. Comments from specialists with many years of practical work in the relevant field were therefore particularly helpful.

My special thanks go to the electrical engineers Harald Wickenhäuser of Rohde&Schwarz Munich, Germany, Hans Zahnd, of the Hans Zahnd engineering consultants in Emmenmatt, Switzerland, and Ulrich Graf, formerly with Thales Electron Devices, Ulm, Germany, for their many contributions, long hours of constructive discussions and readiness to review those parts of the manuscript that deal with their field of expertise. Furthermore, I wish to thank Dr. Markus Pichler, LCM Linz an der Donau, Austria, for his suggestions regarding mathematical expressions and notations which were characterized by his remarkable accuracy and willingness to share his knowledge. Thanks also go to Erwin Schimbäck, LCM Linz an der Donau, Austria, for unraveling the mysteries of sophisticated electronic data processing, and to former Court Counsellor Hans-Otto Modler, previously a member of the Austrian Federal Police Directorate in Vienna, Austria, for proofreading the entire initial German manuscript.

I want to thank the electrical engineer Gerhard K. Büsching, MEDI-translat, Neunkirchen, Germany, for his readiness to agree to many changes and his patience in incorporating these, his acceptance of the transfer of numerous contextual specifics, enabling an efficient collaboration in a cooperative translation on the way to the international edition of this book. My thanks are also due to Dr. John McMinn, TSCTRANS, Bamberg, Germany, for the critical review of the English manuscript from a linguistic point of view.

My particular gratitude shall be expressed to the mentors of my early beginnings: Official Councellor Eng. Alfred Nimmervoll and Professor Dr. Dr. h.c. Dieter Bäuerle, both of the Johannes Kepler University Linz, Austria, as well as to Professor Dr. Eng. Dr. Eng. habil. Robert Weigel of the Friedrich Alexander University Erlangen-Nuremberg, Germany, for their continued support and confidence and their guidance, which helped inspire my motivation and love for (radio) technology.

I wish to especially recognize all those persons in my environment, for whom I could not always find (enough) time during the compilation of the book.

Finally, not forgotten are the various companies, institutes and individuals who provided photographs to further illustrate the book.

May the users of the book derive the expected benefits and successes in their dedicated work. I hope they will make new discoveries and have many ‘aha’ moments while reading or consulting the book. I want to thank them in advance for possible suggestions, constructive notes and feedback.

Ralf Rudersdorfer
Ennsdorf, autumn 2013

I

Functional Principle of Radio Receivers

I.1 Some History to Start

Around 1888 the physicist Heinrich Hertz experimentally verified the existence of electromagnetic waves and Maxwell's theory. At the time his transmitting system consisted of a spark oscillator serving as a high frequency generator to feed a dipole of metal plates. Hertz could recognize the energy emitted by the dipole in the form of sparks across a short spark gap connected to a circular receiving resonator that was located at some distance. However, this rather simple receiver system could not be used commercially.

I.1.1 Resonance Receivers, Fritters, Coherers, and Square-Law Detectors (Detector Receivers)

The road to commercial applications opened only after the Frenchman Branly was able to detect the received high-frequency signal by means of a coherer, also known as a *fritter*. His *coherer* consisted of a tube filled with iron filings and connected to two electrodes. The transfer resistance of this setup decreased with incoming high-frequency pulses, producing a crackling sound in the earphones. When this occurred the iron filings were rearranged in a low-resistance pattern and thus insensitive to further stimulation. To keep them active and maintain high resistance they needed to be subjected to a shaking movement. This mechanical shaking could be produced by a device called a Wagner hammer or knocker. A receiving system comprising of a dipole antenna, a coherer as a detector, a Wagner hammer with direct voltage source and a telephone handset formed the basis for Marconi to make radio technology successful world-wide in the 1890s.

The components of this receiver system had to be modified to meet the demands of wider transmission ranges and higher reliability. An increase in the range was achieved by replacing the simple resonator or dipole by the Marconi antenna. This featured a high vertical radiator as an isolated structure or an expanded fan- or basket-shaped antenna

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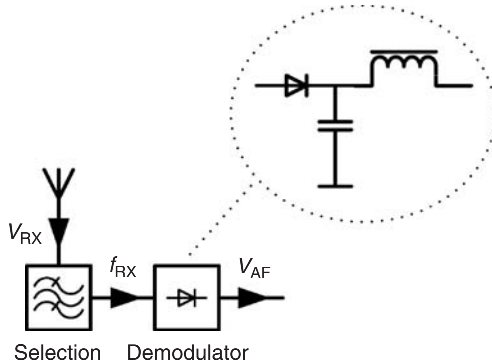

Figure I.1 Functional blocks of the detector receiver. The demodulator circuit shown separately represents the actual detector. With the usually weak signals received the kink in the characteristic curve of the demodulator diode is not very pronounced compared to the signal amplitude. The detector therefore has a nonlinear characteristic. It is also known as a square-law detector. (The choke blocks the remaining RF voltage. In the simplest versions it is omitted entirely.)

of individual wires with a ground connection. The connection to ground as a ‘return conductor’ had already been used in times of wire-based telegraphy.

The selectivity which, until then, was determined by the resonant length of the antenna, was optimized by oscillating circuits tuned by means of either variable coils or variable capacitors. At the beginning of the last century a discovery was made regarding the rectifying effect that occurs when scanning the surface of certain elements with a metal pin. This kind of detector often used a galena crystal and eventually replaced the coherer. For a long while it became an inherent part of the *detector* receiver used by our great-grandparents (Fig. I.1).

The rapid growth of wireless data transmission resulted in further development of receiving systems. Especially, the increase in number and in density of transmitting stations demanded efficient discriminatory power. This resulted in more sophisticated designs which determined the selectivity not only by low-attenuation matching of the circuitry to the antenna but also by including multi-circuit bandpass filters in the circuits which select the frequency. High circuit quality was achieved by the use of silk-braided wires wound on honeycomb-shaped bodies of suitable size or of rotary capacitors of suitable shape and adequate dielectric strength. This increased not only the selectivity but also the accuracy in frequency tuning for station selection.

I.1.2 Development of the Audion

Particularly in military use and in air and sea traffic, wireless telegraphy spread rapidly. With the invention of the electron tube and its first applications as a rectifier and RF amplifier came the discovery, in 1913, of the feedback principle, another milestone in the development of receiver technology. The use of a triode or multi-grid tube, known as the *audion*, allowed circuit designs that met all major demands for receiver characteristics.

For the first time it was possible to amplify the high-frequency voltage picked up by the antenna several hundred times and to rectify the RF signal simultaneously. The unique feature, however, was the additional use of the feedback principle, which allowed part of the amplified high frequency signal from the anode to be returned in the proper phase to the grid of the same tube. The feedback was made variable and, when adjusted correctly, resulted in a pronounced undamping of the frequency-determining grid circuit. This brought a substantial reduction of the receive bandwidth (Section III.6.1) and with it a considerable improvement of the selectivity. Increasing the feedback until the onset of oscillation offered the possibility of making the keyed RF voltage audible as a beat note. In 1926, when there were approximately one million receivers Germany, the majority of designs featured the audion principle, while others used simple detector circuits.

The nomenclature for audion circuits used ‘v’, derived from the term ‘valve’ for an electron tube. Thus, for example, 0-v-0 designates a receiver without RF amplifier and without AF amplifier; 1-v-2 is an audion with one RF amplifier and two AF amplifier stages. Improvements in the selective power and in frequency tuning as well as the introduction of direct-voltage supply or AC power adapters resulted in a vast number of circuit variations for industrially produced receiver models. The general interest in this new technology grew continuously and so did the number of amateur radio enthusiasts who built their devices themselves. All these various receivers had one characteristic in common: They always amplified, selected and demodulated the desired signal at the same frequency. For this reason they were called *tuned radio frequency* (TRF) *receivers* (Fig. I.2).

Due to its simplicity the TRF receiver enabled commercial production at a low price, which resulted in the wide distribution of radio broadcasting as a new medium (probably the best-known German implementation was the ‘Volksempfänger’ (public radio receiver)). Even self-built receivers were made simple, since the required components were readily available at low cost. However, the tuned radio frequency receiver had inherent technical deficiencies. High input voltages cause distortions with the audion, and circuits with several cascading RF stages of high amplification tend to self-excitation. For reasons of electrical synchronization, multiple-circuit tuning is very demanding with respect to mechanical precision and tuning accuracy, and the selectivity achievable with these circuits depends on the frequency (Fig. I.3). Especially the selectivity issue gave rise to the principle of superheterodyne receivers (superhet in short) from 1920 in the US

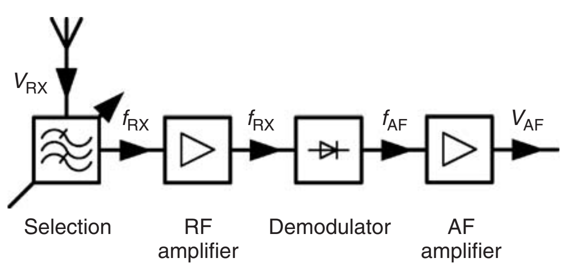

Figure I.2 Design of the tuned radio frequency receiver. Preamplification of the RF signal received has resulted in a linearization of the demodulation process. The amplified signal appears to be rather strong compared to the voltage threshold of the demodulator diode (compare with Figure I.1).

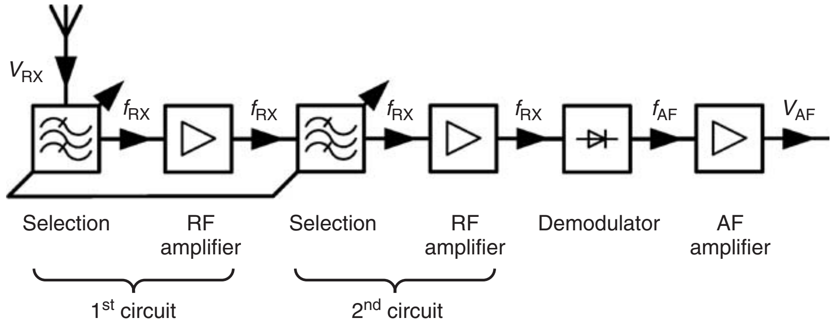

Figure I.3 Multi-tuned radio frequency receiver with synchronized tuning of the RF selectivity circuits. In the literature this circuit design may also be found under the name dual-circuit tuned radio frequency receiver.

and 10 years later in Europe. The superhet receiver solved the problem in the following way. The received signal was preselected, amplified and fed to a mixer, where it was combined with a variable, internally generated oscillator signal (the heterodyne signal). This signal originating from the local oscillator is also known as the LO injection signal. Mixing the two signals (Section V.4.1) produces (by subtraction) the so-called IF signal (intermediate frequency signal). It is a defined constant RF frequency which, at least in the beginning, for practical and RF-technological reasons was distinctly lower than the receiving frequency. By using this low frequency it was possible not only to amplify the converted signal nearly without self-excitation, but also to achieve a narrow bandwidth by using several high quality bandpass filters. After sufficient amplification the intermediate frequency (IF) signal was demodulated. Because of the advantages of the heterodyne principle the problem of synchronizing the tuning oscillator and RF circuits was willingly accepted. The already vast number of transmitter stations brought about increasing awareness of the problem of widely varying receive field strengths (Section III.18). The TRF receiver could cope with the differing signal levels only by using a variable antenna coupling or stage coupling, which made its operation more complicated. By contrast, the utilization of automatic gain control (Section III.14) in the superhet design made it comparatively easy to use.

I.2 Present-Day Concepts

I.2.1 Single-Conversion Superhet

The *superheterodyne receiver* essentially consists of RF amplifier, mixer stage, intermediate frequency amplifier (IF amp), demodulator with AF amplification, and tunable oscillator (Fig. I.4). The high-frequency signal obtained from the receiving antenna is increased in the preamplifier stage in order to ensure that the achieved signal-to-noise ratio does not deteriorate in the subsequent circuitry. In order to process a wide range from weak to strong received signals it is necessary to find a reasonable compromise between the maximum gain and the optimum signal-to-noise ratio (Section III.4.8). Most modern systems can do *without* an RF preamplifier, since they make use of low-loss selection and

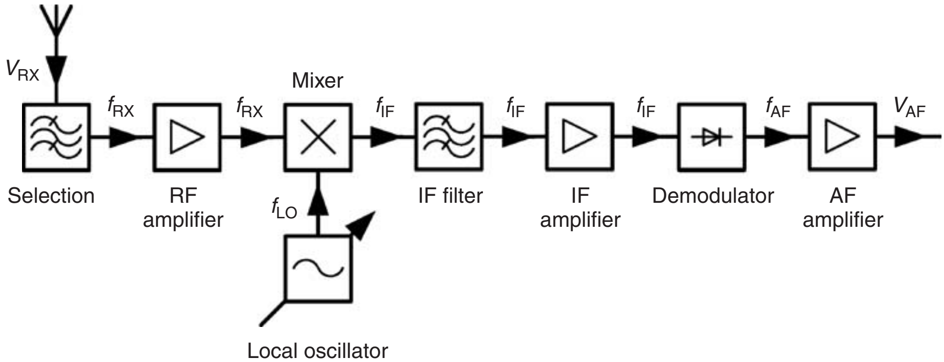

Figure I.4 Functional blocks of the simple superhet. Tuning the receiving frequency is done by varying the frequency of the LO injection signal. Only the part of the converted signal spectrum that passes the passband characteristic (Fig. III.42) of the (high-quality) IF filter is available for further processing.

mixer stages with low conversion loss. The required preselection is achieved by means of a tunable preselector or by using switchable bandpass filters. These are designs with either only a few coils or with a combination of high-pass and low-pass filters.

Previously, the mixer stage (Section V.4) was designed as an additive mixer using a triode tube. This was later replaced by a multiplicative mixer using a multi-grid tube like a hexode (in order to increase the signal stability some circuit designs made use of beam-reflection tubes as mixers). With the continued progress in the development of semiconductors, field-effect transistors were used as additive mixers. These feature a distinct square characteristic and are clearly superior to the earlier semiconductor mixers using bipolar transistors. Later developments led to the use of mixers with metal oxide field-effect transistors (FETs). The electric properties of such FETs with two control electrodes correspond to those of cascade systems and enable improved multiplicative mixing. High oscillator levels result in acceptable large-signal properties (Section III.12). Symmetrical circuit layouts suppressing the interfering signal at the RF or IF gate are still used today in both simple- and dual-balanced circuit designs with junction FETs. Only with the introduction of Schottky diodes for switches did it become possible to produce simple low-noise mixers with little conversion damping in large quantities as modules with defined interface impedances. Measures such as increasing the local oscillator power by a series arrangement of diodes in the respective branch circuit resulted in high-performance mixers with a very wide dynamic range, which are comparatively easy to produce. Today, they are surpassed only by switching mixers using MOSFETs as polarity switches and are controlled either by LO injection signals of very high amplitudes or by signals with extremely steep edges from fast switching drivers [1]. With modern switching mixers it becomes particularly important to terminate all gates with the correct impedance and to process the IF signal at high levels and with low distortion.

The first IF amplifiers used a frequency range between about 300 kHz and 2 MHz. This allowed cascading several amplifier stages without a significant risk of self-excitation, so that the signal voltage suitable for demodulation could be derived even from signals close to the sensitivity limit (Section III.4) of the receiver. Initially, the necessary selection was achieved by means of multi-circuit inductive filters. Later on the application of highly selective quartz resonators was discovered, which soon replaced the LC filters. The use of several quartz bridges in series allowed a bandwidth adapted to the restrictions of the band allocation and the type of modulation used. Since quartz crystals were costly, several bridge components with switchable or variable coupling were used instead. This enabled manual matching of the bandwidth according to the signal density, telegraphy utilization or radiotelephony. Sometime later, optimum operating comfort was obtained by the use of several quartz filters with bandwidths matched to the type of modulation used. Replacing the quartz crystals by ceramic resonators provided an inexpensive alternative. The characteristics of mechanical resonators were also optimized to suit high performance IF filters. Electro-mechanical transducers, multiple mechanical resonators and so-called reverse conversion coils could be integrated into smaller housings, making them fit for use in radio receivers. The high number of filter poles produced with utmost precision were expensive, but their filter properties were unsurpassed by any other analog electro-mechanical system.

Continued progress in the development of small-band quartz filters for near selection (Section III.6) allowed extending the range of intermediate frequencies up to about 45 MHz. Owing to the crystal characteristics, filters with the steepest edges operated at around 5 MHz. Lower frequencies required very large quartz wafers, while higher frequencies affected the slew rate of filters having the same number of poles. Modern receivers already digitize the RF signal at an intermediate frequency, so that it can be processed by means of a high-performance digital signal processor (DSP). The functionality of the processor depends only on the operating software. It not only performs the 'calculation' of the selection, but also the demodulation and other helpful tasks like that of notch-filtering or noise suppression.

The maximum gain, especially of the intermediate frequency amplifier, was adapted to the level of the weakest detectable signal. With strong incoming signals, however, the gain was too high by several orders of magnitude and, without counter measures, resulted in overloading the system. In order to match the amplifier to the level of the useful signal and to compensate for fading fluctuations, the automatic gain control (AGC) was introduced (Section III.14). By rectifying and filtering the IF signal before its demodulation, a direct voltage proportional to the incoming signal level is generated. This voltage was fed to amplifier stages in order to generate a still undistorted signal at the demodulator even from the highest input voltages, causing the lowest overall gain. When the input level decreased the AGC voltage also decreased, causing an increase in the gain until the control function is balanced again. However, the amplifier stages had to be dimensioned so that their gain is controlled by a direct voltage. Very low input signals produce no control voltage, so that the maximum IF gain is achieved. The first superhets for short-wave reception were designed with electron tubes having a noise figure (Section III.4.2) high enough that suitable receiver sensitivities could not be achieved without an RF preamplifier. In order to protect critical mixer stages from overloading, the RF preamplifier was usually integrated into the AGC circuit.

To ensure that signals of low receive field strength and noise were not audible at full intensity, some high-end receivers featured a combination of manual gain control (MGC) and automatic gain control (AGC), the so-called delayed control or delayed AGC (Fig. I.5).

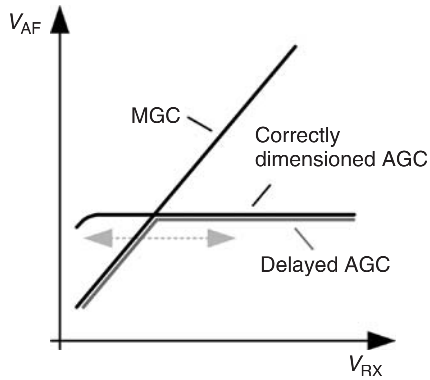

Figure I.5 Functional principle of different RX control methods. In the case of *manual control* the preset gain is kept constant, that is, the AF output voltage follows the RF input voltage proportionally. The characteristic curve can be shifted in parallel by changing the MGC voltage (the required control voltage is supplied from an adjustable constant voltage source). If dimensioned correctly, the automatic gain control (AGC) maintains a constant AF output voltage over a wide range of input voltages. The *delayed AGC* is not effective with weak input signals, but becomes active when the signal exceeds a certain preadjusted threshold and automatically maintains a constant AF output voltage – it is therefore called the 'delayed' gain control.

The automatic control of the gain cuts in only at a certain level, while with lower RF input signals the gain was kept constant. This means that up to an adjustable threshold both the input signal and the output signal increased proportionally. Thus, the audibility of both weak input signals and noise is attenuated to the same degree [2]. This makes the receiver sound clearer. In addition, the sometimes annoying response of the AGC to interfering signals of frequencies close to the receiving frequency (Section III.8.2) that may occur with weak useful signals, can be limited.

During the time when radio signals were transmitted in the form of audible telegraphy or amplitude-modulation signals a simple diode detector was entirely suitable as a demodulator. This was followed by a variable multi-stage AF amplifier for sound reproduction in headphones or loudspeakers. In order to make simple telegraphy signals audible an oscillator signal was fed to the last IF stage in such a way that a beat was generated in the demodulator as a result of this signal and the received signal. When the received signal frequency was in the centre of the IF passband (see Figure III.42) and the frequency of the beat-frequency oscillator deviated by, for example, 1 kHz, a keyed carrier became audible as a pulsating 1 kHz tone. This beat frequency oscillator (BFO) is therefore known as heterodyne oscillator (LO).

With strong input signals the generation of the beat no longer produces satisfactory results. The loose coupling was therefore soon replaced by a separate mixing stage, called the product detector since its output signal is generated by multiplicative mixing. With product detectors it then became possible to demodulate single-side-band (SSB) modulation that could not be processed with an AM detector.

Besides the task of developing a large-signal mixer, a symmetrical quartz filter with steep edges or a satisfactorily functioning AGC (that is well adapted to the modulation type used), especially the design of a variable local oscillator for the superhet presented an enormous challenge for the receiver developer.

The first heterodyning oscillators oscillated freely. Tuning was either capacitive by a rotatable capacitor or inductive after ferrites became available. The first generation of professional equipment used an oscillator resonance circuit that varied synchronously with the input circuits of the RF amplifier stages. For this the variable capacitors had the same number of plate packages as the number of circuits that needed tuning. In most amateur radio equipment, however, the input circuits were tuned separately from the oscillator for practical reasons. Any major detuning of the oscillator therefore required readjusting of the preselector. The frequency of the freely oscillating oscillators was lower than the received frequency. The higher the tuning frequency the lower was the stability with varying supply voltages and temperatures. Frequency stability could be achieved only by utmost mechanical precision in oscillator construction, the integration of cold thermostats, and the use of components having defined temperature coefficients. By combining these measures an optimum compensation was obtained over a wide temperature range. Manufacturing a frequency-stabilized tuning oscillator was difficult, even with industrial production methods, and required extra efforts of testing and measuring.

In order to prevent frequency fluctuations due to changing supply voltages and/or loads, oscillators are usually supplied with voltages from electronically regulated sources. Load variations originating from the mixing stage or subsequent amplifier or keying stages during data transmission are counteracted by incorporating at least one additional buffer stage. Its only task is the electrical isolation of the oscillator from the following circuits.

In the beginning, the receive frequency was indicated as an analog value by means of a dial mounted on the axis of the oscillator tuning element. The dial markings directly indicated the receive frequencies or wavelengths and, in the case of broadcast receivers, showed the stations that could be received. (A few units had a mechanical digital display of the frequency. Among them were the NCX-5 transceiver from National and the 51S-1 professional receiver from Collins. They allowed a tuning accuracy of 1 kHz.)

An accurate reproduction of the tuned-in frequency was possible only with a digital frequency counter used for determining and displaying the operating frequency. The display elements used were Nixie tubes, later the LED dot-matrix or seven-element displays, and recently mostly LC displays. To indicate the receive frequency, the frequency counted at the oscillator must be corrected when resetting the counter either by direct comparison of the BFO frequency counted in a similar manner or by preprogramming the complements.

I.2.2 Multiple-Conversion Superhet

The mixer stage of a superheterodyne receiver satisfies the mathematical condition for generating an intermediate frequency from the heterodyne signal with two different receive frequencies (III.5.3). Both the difference between the receive frequency (f_{RX}) and the LO frequency (f_{LO}) and the difference between the LO frequency and a second receive frequency generate the same intermediate frequency (f_{IF}). The two receive frequencies form a mirror image relative to the frequency of the oscillator, both separated by the IF. The unwanted receive frequency is therefore called the image frequency. The frequency of any such signal is equal to the IF and directly affects the wanted signal or, in extreme cases, covers it altogether. To avoid this, the image frequency must be suppressed. This is usually done by preselection, i.e. by means of the resonance circuits of the RF preamplifier or the preselector. At the beginning of the superhet era the near selection (Section III.6), responsible for the selectivity by filtering the useful signal from the adjacent signals, was possible only with high-quality multi-circuit bandpass filters having a low frequency. From the actual image frequency it is obvious that, for a low IF, it can be suppressed only with a considerable amount of filtering. Especially with receivers designed for several frequency ranges, the reception of high-frequency signals was strongly affected by an insufficiently suppressed image frequency (Section III.5.3). It was therefore necessary to find a compromise between image frequency suppression and selectivity, based on the intermediate frequency.

This problem was solved by twofold heterodyning. To reject the image frequency the first IF was made as high as possible; the higher the IF the lower the effort to suppress the image frequency (see Fig. III.36). A second mixer converted to a second IF so low that good near selection was possible at an acceptable cost (Fig. I.6). But the second mixer again produces both a useful frequency and an image frequency. The second image frequency must also be suppressed as far as possible by means of a filter operating on the first IF. In the era of coil filters this required very careful selection of the frequency.

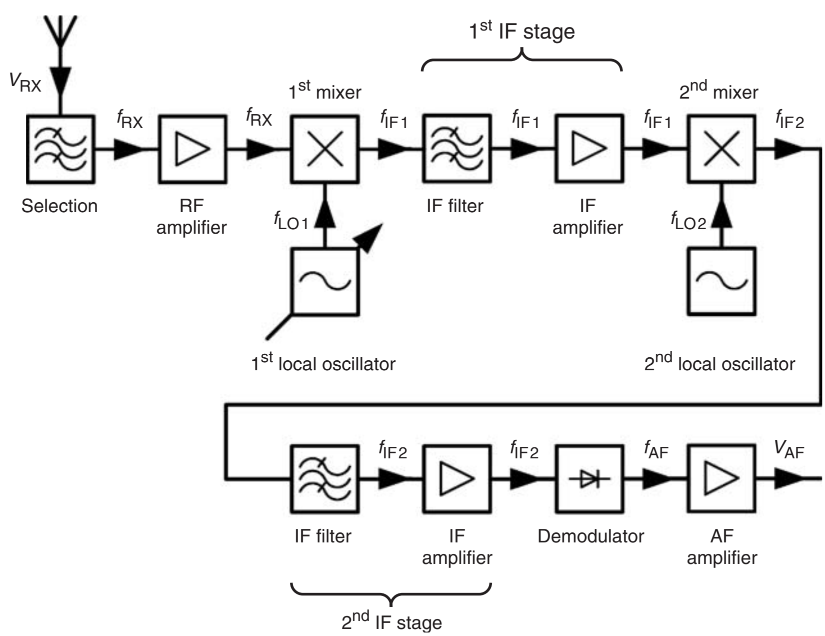

Figure I.6 Operating principle of multiple-conversion superheterodyne receivers. The design shown here is called a dual-conversion superhet. The first IF is a high frequency and serves mainly to prevent receiving image frequencies. The second mixer changes to a lower IF in order to perform the main selection.

The higher the first IF was chosen in the *dual-conversion superhet*, the more difficult it became to manufacture a variable freely-oscillating first local oscillator with a frequency low enough to cause sufficient frequency drifts (Section III.15), for example, for stable telegraphy reception at narrow bandwidths. If the LO frequency was above the receive frequency in one frequency range and below it in the other, the analog frequency scales had to be marked in opposing directions, making operating the equipment cumbersome. Attempts were therefore made to stabilize the first oscillator as well as possible. Initially, this utilized the converter method – the first oscillator remained untuned and was stabilized by a quartz element, while tuning was achieved with the second local oscillator. However, this required that the filter of the first IF be as wide as the entire tuning range. This design was used in almost all early equipment generations for semi-professional use (including amateur radio service) like those produced by Heathkit or Collins. In order to minimize overloading due to the high number of receiving stations within one band, the tuning range was limited to only a few hundred kHz. In the Collins unit, featuring electron tubes, the first IF was merely 200 kHz wide. With a tunable second local oscillator at a lower frequency the conversion to a lower, narrower second IF was simple and stable.

Nevertheless, the problem of large-signal immunity (Section III.12) remained. By using a first tunable local oscillator at a high frequency it was attempted to again reduce the bandwidth of the first IF to the strictly necessary maximum bandwidth, depending on the widest modulation type to be demodulated. At first, the premix system was used. This consisted of a low-frequency tuned oscillator of sufficient frequency stability and a mixer for converting the signal to the required frequency by means of switchable signals from the quartz oscillators. Since the mixing process produced spurious emissions, subsequent filtering with switchable bandwidths was necessary. This is a complex method, but free of the deficiencies described above. It established itself with Drake and TenTec in the semi-professional sector (Fig. I.7). With a tunable first local oscillator it is sufficient for the second LO to use a simple quartz oscillator with a fixed frequency.

As long as the required frequency bands were restricted to a reasonable number (like the short-wave broadcasting bands or the classical five bands of amateur radio services) this principle left nothing to be desired. However, the need for receivers covering all frequency ranges from <1 MHz to 30 MHz inevitably increased the number of expensive quartz elements and increased the demands on near selection of the premixer. This changed only with the availability of low-cost digital integrated semiconductor circuits, which simplified frequency dividing. When dividing the output frequency of an oscillator to a low frequency and comparing it with the divided frequency of a reference signal stabilized by quartz elements, the oscillator can be synchronized by means of a voltage-dependent component (like a varactor diode) using a direct voltage derived from the phase difference between the two signals for retuning the oscillator. This was the beginning of phase-locked loops (PLL) and voltage-controlled oscillators (VCO) (Fig. I.8). Particularly the PLL circuits gave an enormous boost to the advancement of frequency tuning in receivers. Today, highly integrated circuits enable the design of complex and powerful tuned oscillator systems for all frequency ranges. Using several control loops they achieve very high resolution with very small frequency tuning increments [3], short settling times (Section III.15) even with wide frequency variations, and little sideband noise (Section III.7.1). Those circuits used for generating heterodyne signals are called synthesizers.

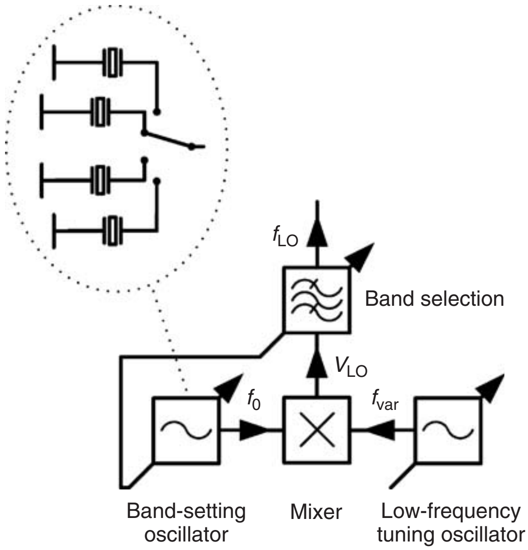

Figure I.7 Architecture of a premixer assembly which feeds an LO injection signal of a stable frequency to the first mixer of a multiple-conversion superhet receiver. The separately depicted circuit design of switchable quartz elements is of course part of an oscillator in actual equipment.

But it is necessary to use processors to make such circuits more ergonomic and the many functions easier to use. With processors the operating frequency can be tuned almost continuously by means of an optical encoder or be activated directly by a number entered via the keyboard. It is possible to store many frequencies in a memory. In the latest developments the loop for fine-tuning is replaced by direct digital synthesis (DDS) (Fig. I.9). This generates an artificial sinusoidal from the digital input information and the signal is tunable in increments of $\ll$1 Hz. It is controlled by the operating processor,

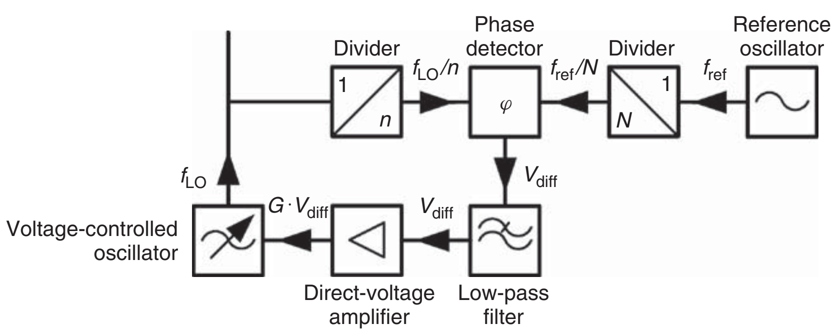

Figure I.8 VCO with phase-locked loop. The direct voltage V_{diff} for automatic frequency tracking is smoothed in the so-called loop filter to prevent spurious signals and sideband noise. V_{diff} is adapted to the required voltage range of the voltage-controlled oscillator via subsequent amplification by the factor G. This results in the constant output frequency $f_{LO} = n \cdot f_{ref}/N$.

Figure I.9 Complete DDS capable of producing output signals up to 400 MHz with a resolution of 14 bits. Only a reference clock and a low-pass filter must be provided externally. (Company photograph of Analog Devices.)

which is required in any case. Depending on the resolution of the D/A converter in the DDS module the output signal generated has very little phase noise (Fig. III.50) and unwanted spurious components (Fig. III.51). Owing to the rapid progress made in this technology DDS generators are currently used in almost every radio receiver. Fully integrated circuits that can generate output signals up to 500 MHz are available. (An example of this technology is AD9912 from Analog Devices, featuring a phase noise as low as −131 dBc/Hz at 10 kHz separation distance with an output frequency of 150 MHz. The output frequency can be varied by increments as small as 3.6 μHz [4]. The spurious emissions actually occurring depend to a large extent on the type of programming.)

It was quickly realized that large-signal problems can be eliminated only if the first narrow-band selection takes place in an early stage of the receive path. In multiple-conversion systems quartz filters with a frequency in the range of about 5 MHz to 130 MHz were therefore included already in the first IF. The first IF is amplified just enough so that the subsequent stages do not noticeably affect the overall noise factor (Section V.1). In high-linearity RF frontends there is no amplification at all upstream of the first mixer. The narrower the bandwidth in the first IF the higher is its relieving effect for the second mixer. Usually the second mixer stage is much simpler than the first mixer. Nowadays, the latest high-end radio receivers match the selected bandwidth already in the first IF stage to the respective transmission method by switching roofing filters (Fig. I.10). (Quartz filters are used in most cases. The commonly used term ‘roofing’ filter indicates its protective effect on all subsequent stages, just as the roof of a house protects all rooms underneath from the weather.) This satisfies the need for matching the selection to the modulation in order to achieve optimum large-signal immunity or for processing the useful signal with low frequency spacing to strong interferences.

For the second IF, almost all professional receivers used a frequency for which selection filters were readily available on the market, usually the frequency of 455 kHz. Telefunken developed their own mechanical filters of 200 kHz and 500 kHz, while Japanese developers chose to use their own frequencies, probably for competitive reasons. In professional systems amplification was made so high that the AGC cut in even with the weakest signals. This made such signals strong enough to be displayed (Section III.14) and to