CHAPTER

7 Radio receivers

In this chapter we will be mostly concerned with the sections of the receiver that come before the detector, sections that are common to nearly all receivers: AM, FM, television, cell phones, etc. Basic specifications for any kind of radio receiver are *gain, dynamic range, sensitivity* and *selectivity*, i.e., does a weak signal at the selected frequency produce a sufficiently strong and uncorrupted output (audio, video, or data) and does this output remain satisfactory in the presence of strong signals at nearby frequencies?

Sensitivity is determined by the noise power contributed by the receiver itself. Usually this is specified as an equivalent noise power at the antenna terminals. Selectivity is determined by a bandpass-limiting filter and might be specified as "3 dB down at 2 kHz from center frequency and 20 dB down at 10 kHz from center frequency." (Receiver manufacturers usually do not specify the exact bandpass shape.)

7.1 Amplification

Let us consider how much amplification is needed in ordinary AM receivers. One milliwatt of audio power into a typical earphone produces a sound level some 100 dB above the threshold of hearing. A barely discernable audio signal can therefore be produced by −100 dBm (100 dB below 1 mW or 10^{-13} watts). Let us specify that a receiver, for comfortable earphone listening, must provide 50 dB more than this threshold of hearing, or 10^{-8} watts. You can see that, with efficient circuitry, the batteries in a portable receiver could last a very long time! (Sound power levels are surprisingly small; you radiate only about 1 mW of acoustic power when shouting and about 1 nW when whispering.) How much signal power arrives at a receiver? A simple wire antenna could intercept 10^{-8} watts of RF power at a distance of about 20 000 km from a 10 kW radio station at 1 MHz having an omnidirectional transmitting antenna, so let us first consider "self-powered" receivers.

7.2 Crystal sets

The earliest radios, crystal sets, were self-powered. A crystal diode rectifier recovered the modulation envelope, converting enough of the incoming RF power into audio power to drive the earphone. A simple *LC* tuned circuit served as a bandpass filter to select the desired station and could also serve as an antenna matching network. The basic crystal set receiver is shown in Figure 7.1.

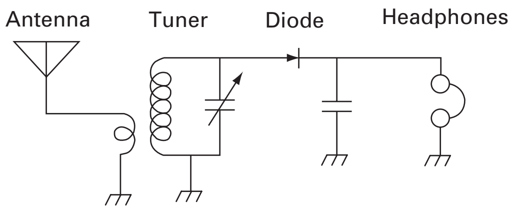

Figure 7.1. Self-powered crystal set receiver.

The considerations given above show that a self-powered receiver can have considerable range. But when the long-wire antenna is replaced by a compact but very inefficient loop antenna and the earphone is replaced by a loud-speaker, amplification is needed. In addition, we will see later that the diode detector, when operated at low signal levels, has a square-law characteristic, which causes the audio to be distorted. For proper envelope detection of an AM signal, the signal applied to a diode detector must have a high level, several milliwatts. The invention of the vacuum tube, followed by the transistor, provided the needed amplification. Receivers normally contain both RF and audio amplifiers. RF amplification provides enough power for proper detector operation, while subsequent audio amplification provides the power to operate loudspeakers.

7.3 TRF receivers

The first vacuum tube radios used a vacuum tube detector instead of a crystal, and added RF preamplification and audio post-amplification, as described above. These *TRF* (Tuned Radio Frequency) sets[1] had individual tuning adjustments for each of several cascaded RF amplifier stages. Changing stations

[1] Early radios were called “radio sets” because they were literally a set of parts including one or more tubes and batteries (or maybe just a crystal detector), inductors, “condensers,” resistors, and headphones. Many of these parts were individually mounted on wooden bases, and, together with “hook-up” wires, would spread out over a table top.

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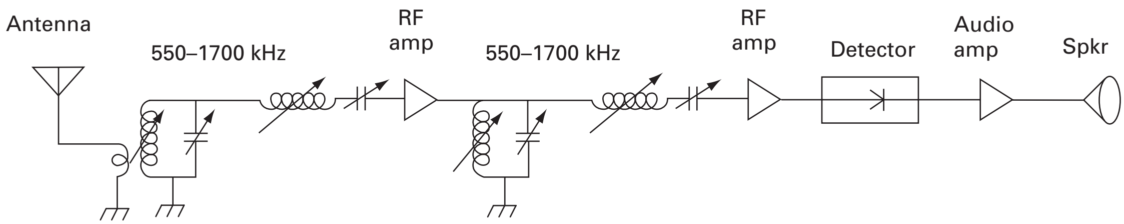

Figure 7.2. TRF receiver.

required the user to adjust several dials (often with the aid of a tuning chart or graph).

Figure 7.2 shows a hypothetical TRF receiver with cascaded amplifiers and bandpass filters.

Note that all the inductors and capacitors should be variable in order to tune the center frequency of the bandpass filters and also maintain the proper bandwidth, which is about 10 kHz for AM. (In a practical circuit, the bandpass filters would use a coupled-resonator design rather than the straightforward lowpass-to-bandpass conversion design shown here.)

7.4 The superheterodyne receiver

The disadvantages of TRF sets were the cost and inconvenience of having many tuning adjustments. Most of these adjustments were eliminated with the invention of the superheterodyne circuit by Edwin H. Armstrong in 1917. Armstrong's circuit consists of a fixed-tuned, i.e., single-frequency, TRF back-end receiver, preceded by a frequency converter front-end (mixer and local oscillator) so that the signal from any desired station can be shifted to the frequency of the TRF back-end. This frequency is known as the intermediate frequency or IF. The superheterodyne is still the circuit used in nearly every radio, television, and radar receiver. Among the few exceptions are some toy walkie-talkies, garage-door openers, microwave receivers used in radar-controlled business place door openers, and highway speed trap radar detectors. Figure 7.3 shows the classic broadcast band "superhet."

Selectivity is provided by fix-tuned bandpass filters in the IF amplifier section. The AM detector here is still a diode, i.e., the basic envelope detector. (In Chapter 18 we will analyze this detector, among others.) All the RF gain can be contained in the fixed-tuned IF amplifier, although we will see later that there are sometimes reasons for having some amplification ahead of the mixer as well. Figure 7.3 also serves as the block diagram for FM broadcast receivers, where the IF frequency is usually 10.7 MHZ, and for television receivers, where the IF center frequency is commonly around 45 MHZ.

Note: There was indeed a *heterodyne* receiver that preceded the superheterodyne. Invented by radio pioneer Reginald Fessenden, the heterodnye receiver

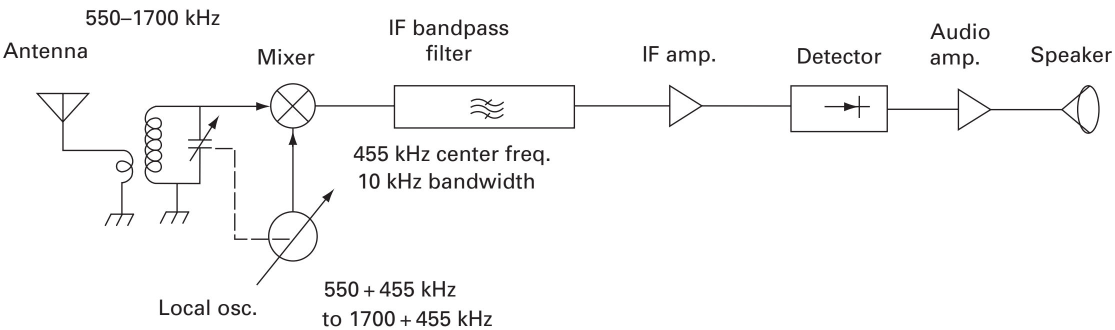

Figure 7.3. Standard superheterodyne receiver for the AM broadcast band.

converted the incoming RF signal directly to audio. This design, known as a "direct-conversion receiver," is disucussed below.

7.4.1 Image rejection

The superhet has some disadvantages of its own. With respect to signals at the input to the mixer, the receiver will simultaneously detect signals at the desired frequency and also any signals present at an undesired frequency known as the *image frequency*. Suppose we have a conventional AM receiver with an IF frequency of 455 kHz and suppose the local oscillator is set at 1015 kHz in order to receive a station broadcasting at 1015 − 455 = 560 kHz (560 kHz is near the lower edge of the AM broadcast band). All the mixers we have considered will also produce a 455-kHz IF signal from any input signal present at 1470 kHz, i.e., 455 kHz above the local oscillator. If the receiver has no RF filtering before the mixer and if there happens to be a signal at 1470 kHz, it will be detected along with the desired 560 kHz signal. A bandpass filter ahead of the mixer is needed to pass the desired frequency and greatly suppress signals at the image frequency. Note that in this example (the most common AM receiver design), this anti-image bandpass filter must be tunable and, for the receiver to have single-dial tuning, the tuned filter must always "track" 455 kHz below the L.O. frequency. In this example, the tracking requirement is not difficult to satisfy; since the image frequency is more than an octave above the desired frequency, the simple one-section filter shown in Figure 7.2 can be fairly broad and still provide adequate image rejection, maybe 20 dB. (Note, though, that 20 dB is not adequate if a signal at the image frequency is 20 dB stronger than the signal at the desired frequency.)

What if a receiver with the same 455 kHz IF frequency is also to cover the short-wave bands? The worst image situation occurs at the highest frequency, 30 MHz, where the image is only about 3% higher in frequency than the desired frequency. A filter 20 dB down at only 3% from its center frequency will need to have many sections, all of which must be tuned simultaneously with a mechanical multisection variable capacitor or voltage-controlled varicaps. As explained above, the center frequency of the filter must be track with a 455 kHz offset from the L.O. frequency in order that the desired signal fall within the narrow IF passband. Image rejection is not simple when the IF frequency is much lower than the input frequency.

Solving the image problem

A much higher IF frequency can solve the image problem. If the AM broadcast band receiver discussed above were to have an IF of 10 MHz rather than 455 kHz, the L.O. could be tuned to 10.560 MHz to tune in a station at 560 kHz. The image frequency would be 20.560 MHz. As the radio is tuned up to the top end of the AM broadcast band, 1700 kHz, the image frequency increases to 21.700 MHz. In this case, a fixed-tuned bandpass filter, wide enough to cover the entire broadcast band, can be placed ahead of the receiver to render the receiver insensitive to images. This system is shown in Figure 7.4. Only the local oscillator needs to be changed to tune this receiver. Of course, the 10 MHz IF filter must still have a narrow 10 kHz passband to establish the receiver's basic selectivity.

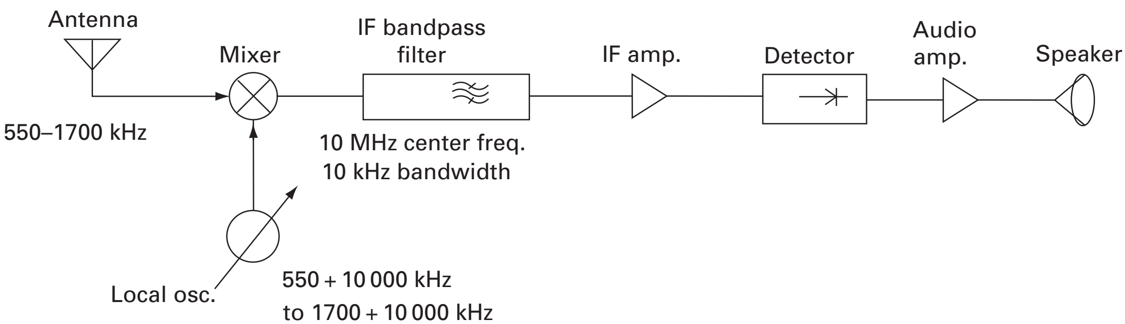

Figure 7.4. Image-free broadcast receiver using a 10 MHz IF.

The circuit of Figure 7.4 is entirely practical although it is more expensive to make the necessary narrowband filters at higher frequencies; quartz crystal resonator elements must be used in place of lumped *LC* elements. If the input band is wider, e.g., 3–30 MHz for a short-wave receiver, the IF frequency would have to be much higher, and narrowband filters become impractical. (Even at 10 MHz, a bandwidth of 10 kHz implies a very narrow fractional bandwidth, 0.1%.) A solution to both the image problem and the narrow fractional bandwidth problem is provided by the *double-conversion superhet*.

Double conversion superhet

Figure 7.5 shows how a second frequency converter takes the first IF signal at 10 MHz and converts it down to 455 kHz, where it can be processed by the standard IF section of the receiver of Figure 7.3. The 10-MHz first IF filter can be wider than the ultimate passband.

Suppose, for example, that the first IF section has a bandwidth of 500 kHz. The second L.O. frequency is at 10.455 MHz, so the second mixer would

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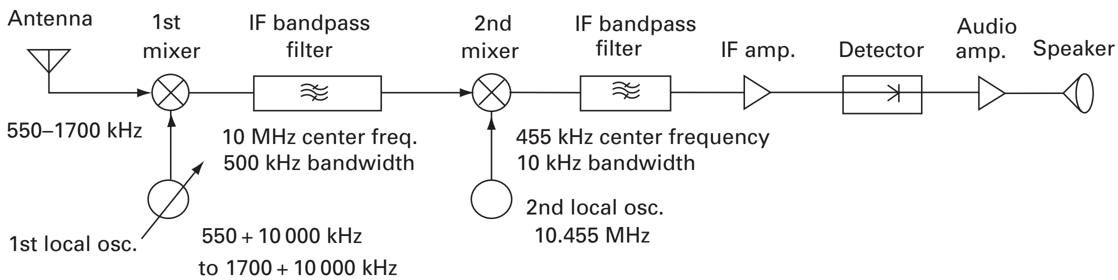

Figure 7.5. Double conversion superhet.

produce an image from a signal at 10.910 MHz. But note that our first IF filter cuts off at 10 MHz + 0.500 MHz /2 = 10.25 MHz, so there will be no signals at 10.910. This system has its own special disadvantages: the receiver usually cannot be used to receive signals in the vicinity of its first IF, since it is difficult to avoid direct feedthrough into the IF amplifier. Multiple conversions require multiple local oscillators and various sum and difference frequency combinations inevitably are produced by nonlinearities and show up as spurious signals known as "birdies."

Present practice for communications receivers is to use double or triple conversion with a first IF frequency at, say, 40 MHz. The front-end image filter is usually a 30 MHz lowpass filter. In as much as modern crystal filters can have a fairly small bandwidth even at 40 MHz, the output of the first IF section can be mixed down to a second IF with a much lower frequency. Sometimes triple conversion is necessary when the final IF frequency is very low, e.g., 50 kHz. The use of first IF frequencies in the VHF region requires very stable local oscillators but crystal oscillators and frequency synthesizers provide the necessary stability. (Oscillator phase noise was a problem in the first generation of receivers with synthesized local oscillators; the oscillator sideband noise was shifted into the passband by strong signals near the desired signal but outside the nominal passband.)

Image rejection mixer

Another method of solving the image problem is to use an image rejection mixer, such as the circuit shown in Figure 7.6.

This circuit uses two ordinary mixers (multipliers). The lower multiplier forms the product of $\cos(\omega_{L.O.}t)$ and an input signal, $\cos[(\omega_{L.O.}\pm\omega_{IF})\,t]$, depending on whether the input signal is above or below the L.O. frequency. The upper multiplier has a 90° delay in its connection to the L.O., so it forms the product of $\sin(\omega_{L.O.}t)$ and $\cos[(\omega_{L.O.}\pm\omega_{IF})t]$. Neglecting the sum frequency terms, the outputs of the upper and lower multipliers are, respectively, $\mp\sin(\omega_{IF}t)$ and $\cos(\omega_{IF}t)$. The output from the lower multiplier is delayed by 90°, so the upper and lower signals at the input to the adder are $\mp\sin(\omega_{IF}t)$ and $\sin(\omega_{IF}t)$. Thus, for an input frequency of $\omega_{L.O.} - \omega_{IF}$, the output of the adder is $2\sin(\omega_{IF}t)$, but when the input frequency is $\omega_{L.O.} + \omega_{IF}$, the output of the adder is

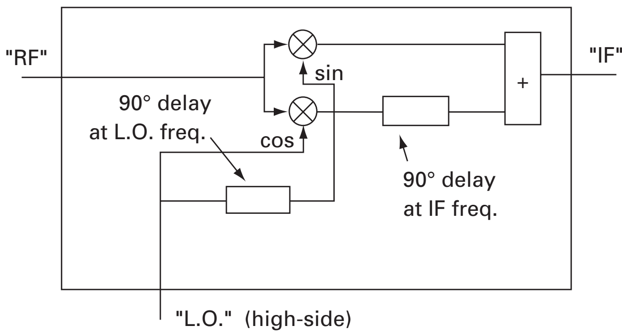

Figure 7.6. Image rejection mixer.

zero. Thus, this mixer rejects signals above the L.O. frequency. The same circuit crops up in Chapter 8, as a *single-sideband generator*. In practice this circuit might provide 20–40 dB of image rejection. It can be used together with the standard filtering techniques to get further rejection.

Zero IF frequency – direct conversion receivers

The evolution of the superhet, which was always toward higher IF frequencies and multiple conversions, has taken a new twist with the advent of the nearly limitless signal processing power available from DSP chips. Direct conversion receivers, in a reversion to the heterodyne architecture, shift the center frequency of the desired signal, ω_C, all the way to zero Hz ("baseband"). Generally this requires that the signal be mixed separately with local oscillator signals $\cos(\omega_C t)$ and $\sin(\omega_C t)$ to preserve all the signal information. To see this, note that the input signal, which is sinusoidal, will, in general, be out of phase at times with $\cos(\omega_C t)$ and at other times with $\sin(\omega_C t)$. Thus, the outputs of the "cosine mixer" or "sine mixer" can go to zero but, together, these "I" (in-phase) and "Q" (quadrature) signals contain all the signal information. To see this, note that the original signal could be easily reconstructed from the I and Q signals. Lowpass filtering of the I and Q signals determines the passband of the receiver, e.g., 5-kHz rectangular lowpass filters on the I and Q signals would give the receiver a flat passband extending 5 kHz above and 5 kHz below the L.O. frequency. The classic image problem, severe at low IF frequencies, disappears when the IF frequency is zero. The low-frequency I and Q signals can be digitized directly for subsequent digital processing and demodulation (see Problem 7.8). No bulky IF bandpass filters are required. Even tiny surface acoustic wave (SAW) bandpass filters are huge, compared to the real estate on DSP chips. With this architecture, nearly 100% of a receiver can be incorporated on a chip, including a tunable frequency synthesizer to produce the L.O. signals. Figure 7.7 shows a block diagram of a direct-conversion receiver. Everything on this diagram plus an L.O. synthesizer is available on a single chip intended for use in HD television receivers.

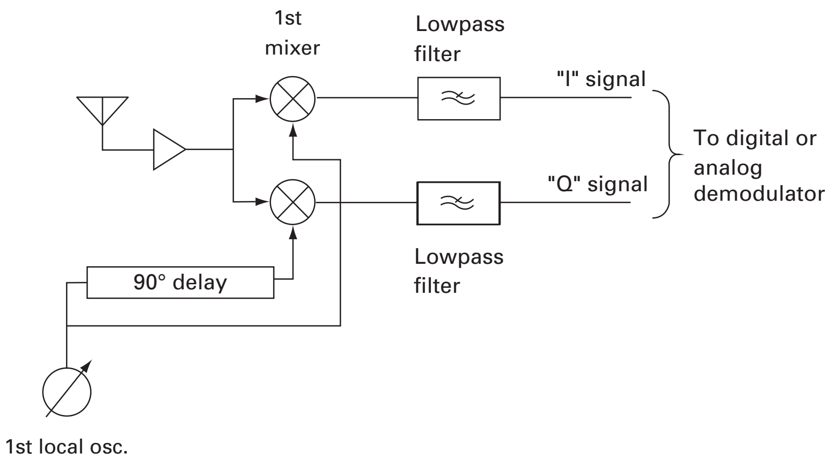

Figure 7.7. Direct conversion receiver.

7.4.2 Automatic gain control

Nearly every receiver has some kind of automatic gain control (AGC) to adjust the gain of the RF and/or IF amplifiers according to the strength of the input signal. Without this feature the receiver will overload; overdriven amplifiers go nonlinear ("clip") and the output will be distorted as well as too loud. The output sound level of an FM receiver, depending on the design of the demodulator, may not vary with signal level but overloading the IF amplifier stages will still produce distortion, so FM receivers also need AGC. Television receivers need accurate AGC to maintain the correct contrast level (analog TV) or threshold levels (digital TV). Any AGC circuit is a feedback control system. In simple AM receivers the diode detector provides a convenient dc output voltage that can control the bias current (and hence gain) of the RF amplifiers. The controlled bias current can also be used to drive a signal strength indicator.

7.5 Noise blankers

Many receivers, including most television receivers, have a noise blanker circuit to reduce the effects of impulse noise such as the spiky noise produced by automobile ignition systems. Here the interfering pulses are of such short duration that the IF stages can be gated off briefly while the interference is present. The duty cycle of the receiver remains high and the glitch is all but inaudible (or invisible). An important consideration is that the gating must be done before the bandwidth is made very narrow since narrow filters elongate pulses.

7.6 Digital signal processing in receivers

Advances in digital electronics, notably fast A-to-D conversion and processors, make it possible to do all-digital filtering and detection in a receiver. Any desired filter amplitude and phase response can be realized.

Besides direct-conversion receivers on a chip, there are many single-chip superhet chips, usually using image cancelling mixers followed by digital bandpass filters operating at low IF frequencies. Adaptive digital filters can correct for propagation problems such as multipath signals. Digital demodulators allow the use of elaborate signal encoding which provides high spectral efficiency (bits/sec/Hz) as well as error correction through the use of redundant bits. Digital modulation techniques are discussed in Chapter 22.

Problems

Problem 7.1. The FM broadcast band extends from 88 to 108 MHz. Standard FM receivers use an IF frequency of 10.7 MHz. What is the required tuning range of the local oscillator?

Problem 7.2. Why are airplane passengers asked not to use radio receivers while in flight?

Problem 7.3. Two sinusoidal signals that are different in frequency, if simply added together, will appear to be a signal at a single frequency but amplitude modulated. This "beat" phenomenon is used, for example, to tune two guitar strings to the same frequency. When they are still at slightly different frequencies, the sound seems to pulsate slowly at a rate equal to their frequency difference. Show that

$$\sin([\omega_0 - \delta\omega]t) + \sin([\omega_0 + \delta\omega]t) = A(t)\sin(\omega_0 t)$$

where

$$A(t) = 2\cos(\delta\omega t).$$

(Note that this addition is a linear process; no new frequencies are generated.)

Problem 7.4. Using an AM receiver in an environment crowded with many stations, you will sometimes hear an annoying high-pitched 10 kHz tone together with the desired audio. If you rock the tuning back and forth the pitch of this tone does not change. What causes this?

Problem 7.5. When tuning an AM receiver, especially at night, you may hear "heterodynes" or whistling audio tones that change frequency as you slowly tune the dial. What causes this? Can it be blamed on the receiver? (Answer: Yes.)

Problem 7.6. Using modern components and digital control, we could build good TRF radios. What advantages would such a radio have over a superheterodyne? What disadvantages?

Problem 7.7. You may have observed someone listening to distorted sound from an AM radio whose tuning is not centered on the station. Often this mistuning is done deliberately when the listener has impaired high-frequency hearing and/or the radio has insufficient bandwidth. What is going on here? Why would a radio not have sufficient bandwidth and why would insufficient bandwidth cause some listeners to tune slightly off station?

Problem 7.8. Design a direct-conversion AM broadcast receiver using digital processing of the I and Q signals. Assume that the L.O. frequency may not be set exactly equal to the frequency of the desired station. Hint: compute the input signal amplitude from the digitized I and Q signals. Then feed this stream of amplitudes into a D-to-A converter.

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