designing communications receivers for good strong-signal performance

Many modern amateur receivers perform poorly in the presence of strong signals — here are some sound design ideas for solving this problem

Ray Moore, 116 Walnut Street, Walpole, Massachusetts 02081

"Current receivers... perform poorly under exactly those conditions that are most important, when the desired signal is weak and the undesired signal is strong" is the way Squires began an article on receiver front-ends in 1963.[1] Since then, solid-state receivers have become the standard in new design, increasing the difficulty of obtaining adequate signal handling characteristics. Outstanding strong-signal performance is one of the more difficult and expensive characteristics to design into a receiver; the least expensive characteristics are sensitivity and gain. This is why most receivers are "hot" enough to rattle the walls on noise alone.

The price for low noise figures on the high-frequency bands is paid, not in dollars, but in poor to mediocre strong-signal performance. Top professional receivers in the $5000 to $10000 price range are often designed for noise figures of 10 to 12 dB, the excess noise-figure performance being traded for signal handling ability.

What are the symptons of poor strong-signal performance? Under actual on-the-air conditions a receiver which cannot handle strong signals can have its performance so deteriorated that its static sensitivity and selectivity figures are meaningless. The receiver may go completely silent in the presence of a strong, unwanted station, or its gain and sensitivity may be so reduced that you can not copy the weak, desired station.

The amateur bands may appear to

be full of weak commercial stations *which are really operating outside the* bands — heterodynes, birdies and broadcast stations appear. Strong ssb stations produce less obvious effects which make the bands seem noisy and full of splatter. All these conditions are produced by deficiencies *within* the receiver.

There are a number of ways in which strong, undesired signals outside the i-f passband can interfere with reception. Some require only a single undesired signal to be present; others require two or more signals. Single signal effects include adjacent channel interference, image interference, i-f breakthrough, strong-signal spurious responses, desensitization and blocking. Multiple signal effects include cross-modulation and rf intermodulation.

single-signal interference

Adjacent-channel interference is caused by a strong, undesired signal close to, but outside of, the receiver's i-f passband. This is the fault of the main selectivity determining filter. The filter either has a poor shape factor or the ultimate attenuation (stop band) is not deep enough. Some filters, for instance, have skirts that go down to only 50 or 60 dB before they flatten out. One solution to this problem is cascading two or more filters. Care in matching filter center frequencies and proper isolation produce ultimate attenuations of 120 dB or more and shape factors approaching 1:1.

Image frequency interference is a function of rf selectivity and the frequency of the first i-f. Secondary images between the first and second i-f stages of multiple-conversion receivers are also possible. Many current receivers have image rejection ratios as low as 50 dB on at least one band. However, with an i-f in the megahertz range, image ratios of 100 dB or more are possible if economy is not an overriding factor. Up-conversion to an i-f above the receiver tuning range in conjunction with a front-end low-pass filter is also very effective.

I-f breakthrough occurs when a signal on the frequency of the i-f rides through *the front-end and into the i-f by brute* force. The i-f rejection ratio of a receiver is a function of its rf selectivity, and runs in the range of 50 to 70 dB for amateur receivers and up to 70 to 100 dB for professional and military receivers.

The problem is much more severe with *variable* first i-f receivers than with *fixed* first i-f receivers because it is difficult to find a 500- to 1000-kHz slice of the spectrum with no strong stations, and further, because simple traps can reduce i-f breakthrough in fixed i-f receivers where band elimination filters are required for variable i-f receivers. Up-conversion with a low-pass filter is one of the most effective solutions to the i-f breakthrough problem.

Strong-signal spurious responses are produced in two ways. First, strong signals can ride through the front end and mix with harmonics of the first oscillator to produce the i-f. Second, a nonlinear rf amplifier or mixer can generate harmonics of a strong signal which beat with the local oscillator. Rf selectivity and filtering of the injection frequencies are the cure for this problem.

The best receivers have strong-signal spurious responses of 100 dB in relation to a 1-μV desired signal. That is, it takes a 100-mV undesired strong signal to produce a receiver output equivalent to the output produced by a 1-μV desired signal. A 0.3 mV signal (50 dB relative to 1 μV) can produce strong signal spurious responses in less expensive receivers.

Desensitization and blocking are different degrees of severity of the same problem. In desensitization a strong signal outside the passband reduces the gain of the receiver which may make it impossible to hear a weak desired signal. In blocking, the gain is reduced to such an extent that the receiver goes silent. Both desensitization and blocking are caused by a signal which rides through and is rectified by the first active device causing a shift in the operating point of the device. If the first device is also connected

to the agc system, the rectified voltage can be fed back through the agc line to affect other stages as well. These problems are most common in the immediate vicinity of transmitters.

Professional class receivers specify desensitization and blocking in terms of the unwanted signal level required to cause a 3-dB drop in receiver output when tuned to a 1 mV desired signal. 100 mV is a typical desensitization specification for such a receiver. These characteristics are seldom specified on lower priced receivers but tests have shown that some will completely block at 35 mV or less.

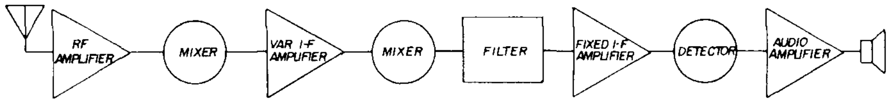


fig. 1. Signal path through a typical modern communications receiver.

cross-modulation

Cross-modulation is a mixing effect that is produced when a desired signal and a strong, undesired signal are applied simultaneously to a device with third-order curvature of its input-vs-output transfer characteristic. The first and second mixers are the stages most likely to produce cross-modulation but very strong signals can also produce it in the rf amplifier. The result of cross-mod is that the modulation of the undesired signal is superimposed on the desired signal and cannot be removed by subsequent processing. Cross-mod is aggravated in the first stage of a receiver by the popular gain control methods which change the operating conditions of the device (see **fig. 5**). Any attenuation ahead of the offending stage is beneficial even if the desired signal is also attenuated, because 1 dB of attenuation reduces cross-modulation by 2 dB. Of course, attenuation of the undesired signal by rf selectivity without affecting the desired signal is preferred, but this is not always possible if the undesired signal is close to the passband.

Cross-modulation is seldom specified except in professional receivers and even there a lack of standard conditions and levels makes direct comparisons impossible. The undesired signal required to produce a certain level of cross-mod is specified, but the reference cross-mod level is variously given as −10 dB, −20 dB or −30 dB relative to the desired signal output, as 3% cross-mod, or as "negligible". More important, the spacing of the undesired signal from the desired signal may be anywhere from 10 to 100 kHz or may be expressed as a percentage up to 10%. Cross-mod performance is improved by use of greater rf selectivity and more linear active devices. A given active device can often be made more linear by optimizing its operating conditions.

intermodulation

Rf intermodulation (IM) is, like cross-modulation, the result of third-order curvature of a device. If there are two strong undesired signals, f_1 and f_2, they will produce two third-order products, one at $f_1+(f_1-f_2)$ and the other at $f_2-(f_1-f_2)$. Fifth-order curvature can also produce much weaker IM products spaced $2(f_1-f_2)$ from the two offending signals. As an example, two strong signals, one at 3450 kHz and the other at 3490 kHz, can produce two IM products in the 80-meter band, a third-order product at 3530 kHz and a fifth order product at 3570 kHz. Two other IM products fall outside the amateur band at 3410 and 3370 kHz. Perhaps this is why the 80 meter band on

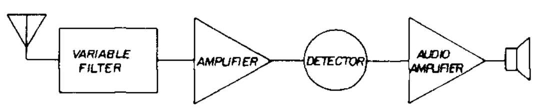


fig. 2. Ideal receiver signal path for handling strong signals.

your receiver sounds full of RTTY and other commercial stations.

There are two ways in which IM is specified in professional receivers. One is to tell how far the IM product is below the level of the two signals which cause it. Third-order IM, for example, can be specified as, "at least 60 dB below two 10-mV undesired signals." IM can also be specified as the undesired signal level to produce an IM product equivalent to a 1-μV desired signal. The better professional and military receivers require from +70 dB to +100 dB relative to 1 μV to produce third-order IM equivalent to a 1-μV desired signal. Improvement in IM performance is accomplished by the same means as for cross-modulation.

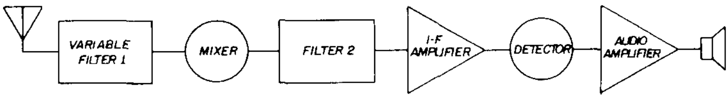


fig. 3. Compromise receiver signal path for handling strong signals.

receiver signal path

The typical modern communications receiver (**fig. 1**) has a signal path which is not ideal from the strong-signal standpoint. The problem with this design is that four stages are exposed to strong undesired signals before the passband-determining filter can reduce them to harmless proportions.

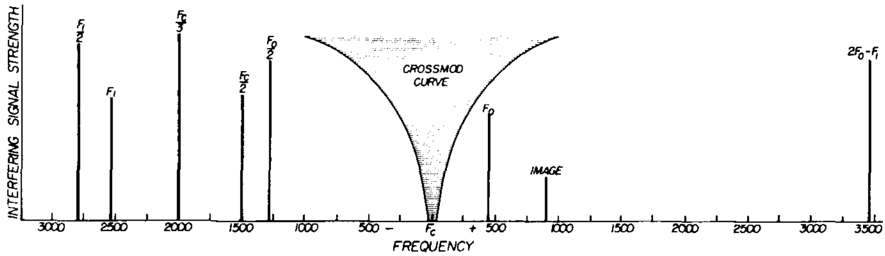


fig. 4. Plot of strong-signal responses in a typical communications receiver. Frequency f_c is the center frequency to which the receiver is tuned (3000 kHz), f_o is the oscillator frequency (3455 kHz), and f_i is the intermediate frequency (455 kHz).

The ideal receiver configuration for handling strong signals (**fig. 2**) is a throwback to some of the TRF receivers of the 1920s which had all their tuned circuits lumped between the antenna and the first rf stage. The filter in the ideal receiver, however, must be adequate to provide adjacent channel selectivity to modern standards – a shape factor of 2:1, 2.5 kHz bandwidth, ultimate rejection greater than 100 dB, insertion loss 1 or 2 dB. Such a filter would stop the strong undesired signals before they got into the receiver, unlike the two or three tuned circuits in most receivers which allow signals 50 or 100 kHz off frequency to ride through with little attenuation. High-frequency crystal-lattice filters which meet these requirements for single frequencies are available, and receivers such as this, covering one or several fixed frequencies, are in use.

A practical, tunable receiver which can approach the ideal in performance is shown in **fig. 3**. The objective is to provide maximum adjacent-channel selectivity as close as possible to the antenna. The mixer must be low noise and as linear as possible; FL1 should consist of two to four tuned circuits, depending upon the noise figure of the mixer and the target noise figure for the entire receiver. The i-f must be high enough so FL1 can adequately suppress images and low enough

to be practical, say, in the range of 1.5 to 50 MHz.

Higher intermediate frequencies remove the i-f from the receiver tuning range and permit the use of up-conversion in conjunction with a low-pass filter ahead of FL1. The disadvantage of the higher frequencies is that filters, while available, may be expensive and difficult to locate. The stability and constant tuning rate usually associated with the variable first i-f, multiple-conversion receiver can be achieved with this configuration by deriving the injection frequency for the first mixer through the pre-mixer technique. In this case, complexity has been removed from the signal path and added to the frequency determining circuits where it can do no harm to the signal.

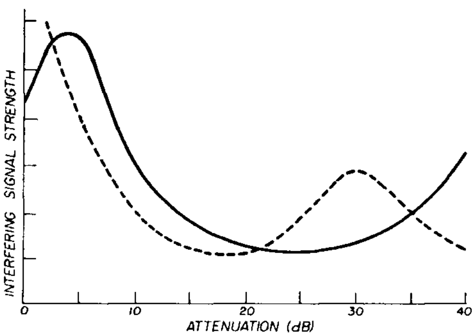


fig. 5. Interfering signal level required to produce 1% cross-modulation in two different active devices.

receiver design trends

The receiver design trends of the last twenty years have, almost without exception, been in the direction of poorer strong-signal performance. One of the innovations of that period is all solid-state receiver design. In general, semi-conductors do not handle strong signals as well as vacuum tubes, and the use of semi-conductors in stages ahead of the adjacent-channel selectivity filters degrades strong-signal performance.

Multiple conversion, another design innovation, results in two mixers and three to five total stages before there is appreciable selectivity to protect the amplifiers and mixers from strong undesired signals. Broadband and variable i-f stages are susceptible to i-f breakthrough.

Furthermore, the newer low-noise devices, both tubes and semi-conductors, tend to be less linear than the older vacuum tubes. The low-impedance (50-ohm), tightly-coupled primaries on modern antenna coils compound the strong signal problem because they degrade the Q of the tuned circuit. They also present higher signal levels to the active device than did the old medium-impedance (200- to 500-ohm) primaries.

evaluating strong-signal performance

The best method of evaluating the strong signal performance of the receiver is that used for military and professional receivers. Two signal generators are used to plot cross-mod and spurious responses as shown in **fig. 4**. In plotting the cross-mod curve one generator feeds in a desired signal (10 to 100 μV) at the frequency to which the receiver is tuned; the second generator is swept out from the desired signal frequency, first in one direction and then the other, representing a strong undesired signal. The amplitude of the undesired signal necessary to produce the reference cross-mod level is recorded at enough points to produce the curve shown in **fig. 4**.

The first generator is removed from the circuit and the second generator is swept through the spectrum again. Any

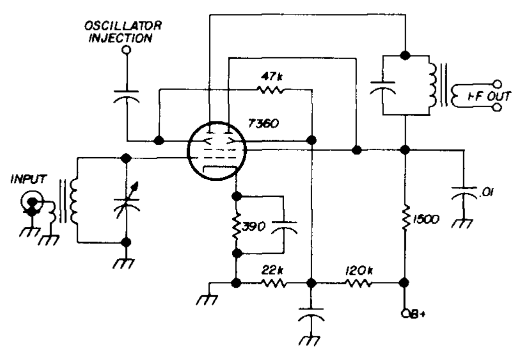


fig. 6. Unbalanced 7360 beam-deflection mixer circuit.

discrete responses such as image and i-f breakthrough are recorded. The undesired signal strength required to produce a response equivalent to a 1-μV desired signal is recorded for the discrete responses.

Since there are an infinite number of signal combinations which can produce IM, you must be content with spot checks in evaluating this characteristic. Set one generator at f_c plus 30 kHz and the other at f_c plus 60 kHz. The amplitude of both generators must be the same. Increase the amplitude of the two generators until a response appears at f_c equivalent to that produced by a 1-μV desired signal. The level of either generator is then the IM response level and may be expressed in dB relative to 1 μV.

There are only two ways to improve the ability of a receiver to handle strong signals: Reduce the strength of the undesired signals or, in the case of cross-mod and IM, improve the linearity of mixer and amplifier devices in the stages ahead of the adjacent-channel selectivity filter.

Reducing the strength of the undesired signals is the method used in the receiver configuration in **fig. 2.** If the undesired signals can't get into the receiver, they can't do any damage. In most receivers you have to get along with something less than ideal rf selectivity, but strive for the maximum practical selectivity. Reducing the undesired signal by 1 dB will reduce cross-mod by 2 dB and IM by 3 dB, so even a small amount of additional selectivity can make a decided improvement.

If ideal rf selectivity isn't available then the linearity of the amplifier and

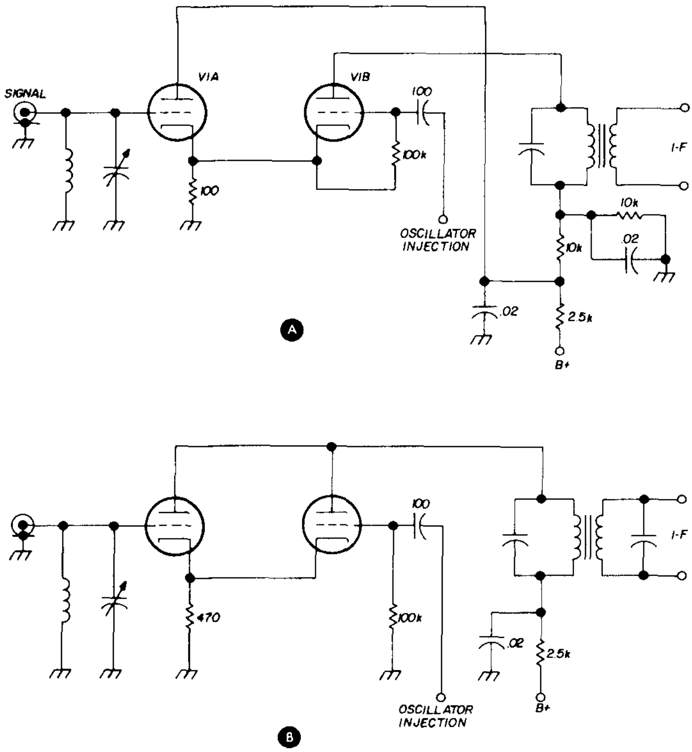


fig. 7. Two dual-triode mixer circuits. The circuit in (B) is not as sensitive as the circuit in (A), but (B) will handle larger signals. These circuits are suitable for vacuum tubes such as the 12AU7, 12AT7 or 6DJ8.

mixer devices becomes important. Not only should the most linear devices and circuits be selected, they must be optimized for strong-signal performance. Each active device has an optimum point at which it is least susceptible to cross-mod and IM. This is illustrated in **fig. 5** which shows generalized cross-mod-vs-attenuation curves typical of active devices when attenuation is produced by changes in bias.

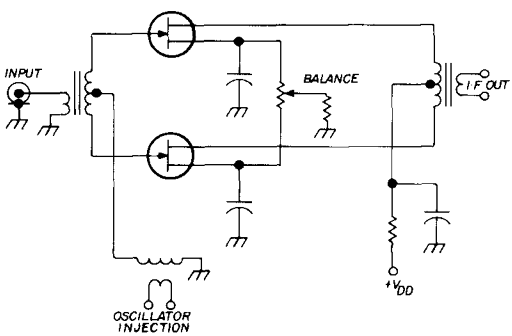


fig. 8. Balanced mixer circuit using a field-effect transistor.

Most amateur receivers suppress all strong-signal effects from out-of-passband signals by a minimum of 50 dB. The suppression of military and professional receivers runs from 70 to 100 dB or more. The noise figure of amateur receivers runs from 5 to 8 dB, that of professional receivers is usually around 10 dB. The cost of amateur receivers is $250 to $800, professional receivers $5000 to $10,000 and up. Obviously, sensitivity is cheap while strong-signal performance is expensive.

It can not be stated too often that good strong-signal performance in modern receivers is the result of painstaking design work. It is not enough to pick out a signal path configuration and the circuit for each stage. Each stage must be experimentally optimized for operating point, voltages and injection levels. If there are two or more circuits under consideration for a given stage, each must be optimized, and then compared.

strong-signal performance

The following paragraphs detail the steps which are necessary in the design of a receiver with superior strong-signal performance.

First of all, determine the maximum acceptable noise figure. Many professional receivers are designed for a noise figure of 10 to 12 dB. If the input device of the receiver has a noise figure of 6 dB the designer then has an excess of 4 to 6 dB to use in providing additional rf selectivity, to keep the gain low ahead of the adjacent channel selectivity filter, and to allow optimum strong-signal biasing of stages.

For amateur work where it is possible to take advantage of the rare occasion when a 5- or 6-dB noise figure is usable the best idea is to have an auxiliary low-noise preselector that can be switched in ahead of the receiver. It is easy to add a preselector to a receiver that has sacrificed noise figure for superb strong-signal characteristics, but it is difficult to improve the strong-signal characteristics of a receiver that has been designed for low noise.

Next, select the signal-path configuration. For general use the arrangement of **fig. 3** is recommended. A low-gain rf amplifier can be added if the mixer does not have the required sensitivity. Note that it is *not* necessary to go to the variable first i-f approach to achieve the vfo type tuning we expect in modern receivers.

mixers

The mixer stage is the key to the design of a superior strong-signal receiver. If the configuration of **fig. 3** is to be used to its fullest, the mixer must provide low noise, high conversion transconductance and exceptional linearity. Fortunately, there are devices and circuits which possess these characteristics to a much greater degree than the mixers found in the average medium-priced receiver.

The problem with many mixers is that the device is biased to an operating point where it is not linear so that the required

second-order (sum and difference) frequencies are generated. However, at that point the device is also likely to be an efficient generator of third- and higher-order products which cause cross-modulation and rf intermodulation. Following are some recommended mixers which have been used in professional or military

Squires' original balanced circuit had a noise figure of 5.5 dB at 29 MHz and handled undesired signals up to 1.5 volts.

Various dual-triode mixer circuits perform well because they are low noise and require little or no gain ahead of them. The 12AU7, 12AT7 and 6DJ8 are some of the tubes which have been used.

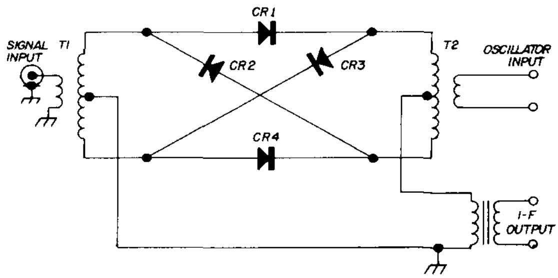


fig. 9. Diode balanced mixer has approximately 8-dB noise figure and handles large signals well. Diodes CR1-CR4 are hot-carrier diodes; transformers T1 and T2 are toroidal types.

receivers or which are of unusual interest.

Squires developed a mixer circuit with the 7360 beam deflection tube in 1963 which has been used in a number of amateur receivers and at least one commercial receiver.[1] An unbalanced version of the circuit is shown in **fig. 6**. The tube is set up for linear operation between G1

In the circuit of **fig. 7A** V1B is a triode mixer with the signal injected at the cathode and the oscillator at the grid. V1A is a cathode follower which provides isolation between the signal and oscillator circuits. The 10k resistors in the plate circuit of V1B form a voltage divider to reduce the plate voltage because V1B

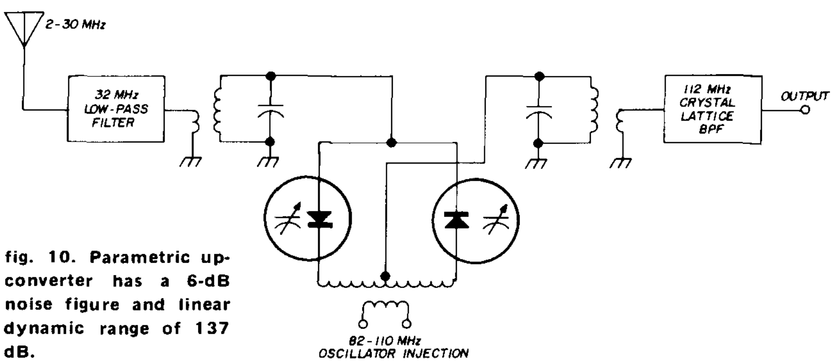


fig. 10. Parametric up-converter has a 6-dB noise figure and linear dynamic range of 137 dB.

and the plates; the signal is switched between the active plate and the grounded plate by the oscillator voltage appled to deflection plate.

Another source indicates that superior performance is obtained from the circuit with a fixed bias (about 1.9 V) and with an oscillator injection of 7.5 volts.[2]

must have a much lower transconductance than V1A. A somewhat different circuit is shown in **fig. 7B**. Sensitivity of this circuit is not as good as that of **fig. 7A** but it will handle larger signals.

The fet balanced mixer (**fig. 8**) is a good choice for use in the circuit of **fig. 3**. When used with suitable devices (such

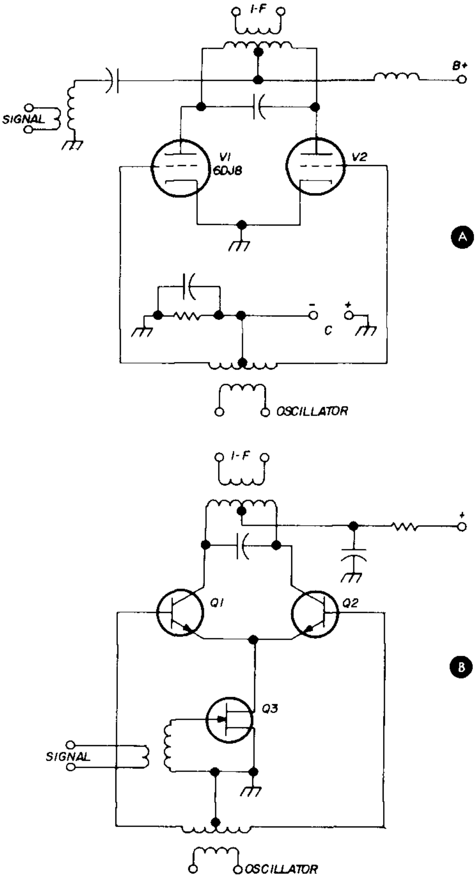


fig. 11. Vacuum-tube (A) and transistor-type (B) switching mixer circuits.

as the 2N4416) it has a noise figure of 4 to 5 dB and handles large signals fairly well. The noise figure is low enough to allow a rather elaborate rf filter to be placed between it and the antenna.

The diode balanced mixer using hot-carrier diodes in **fig. 9** has a noise figure around 8 dB and handles strong signals well. However, it requires high local-oscillator power level and has conversion loss, so it must be preceded by an rf amplifier in order to achieve an acceptable overall noise figure. These are both disadvantages.

A parametric up-converter **(fig. 10)** is used in the National R1490/GRR17 wide dynamic range military receiver.[3,4] The specified linearity of the circuit is 137 dB and the noise figure is 6 dB. All external spurious responses, images, i-f breakthrough, cross-mod, IM, etc., are down more than 100 dB. The 112-MHz filter sharply attenuates all undesired signals more than a few kHz outside the i-f passband. Adjacent-channel selectivity is provided in a later stage at 5 MHz.

Up-conversion is advantageous because a simple low-pass filter can be used to increase the rejection of the i-f and image frequencies without the added complexity or loss that additional tuned circuits would bring. The up-conversion technique can be used with any of the other mixer circuits as well.

The 7360 mixer operates as a very linear switching circuit. Attempts have been made to improve the technique and to develop semiconductor equivalents. Perhaps the ultimate performance so far was also by Squires with a dual-triode switching mixer **(fig. 11A)** in a receiver that handled 3-volt rms signals within 10 kHz of the desired signal, and 25-volt signals 10% removed, without cross-mod.

He used a 6DJ8 tube and the oscillator injection had a square-wave characteristic. The tube was biased as a class-C amplifier and the oscillator had sufficient amplitude to drive the grids positive. The signal was alternately switched to ground through the two tubes by the oscillator injection voltage. A stage of rf amplification was used ahead of the mixer which worked into a 6-kHz wide filter. A somewhat similar scheme using semiconductors **(fig. 11B)** has been tried, but details on its performance are not available.[5] The signal is amplified in Q3 and alternately switched to ground through Q1 and Q2 and the output transformer.

rf amplifiers

If an rf amplifier must be used, the rule is to use only enough gain to override the mixer noise, using any excess gain to provide additional rf selectivity either by adding tuned circuits or tapping down on the existing tuned circuits to improve Q. In general, the best rf amplifier devices are vacuum-tube pentodes or triodes in the cascode circuit. Next in order are fets,

and last are bipolar transistors. When receivers *must* be all solid-state, circuit designers have gone to power fets and power bipolars for rf amplifiers in order to improve strong signal performance.[3,6]

Rf amplifiers must be adjusted experimentally to determine the best bias, plate, screen, drain or collector voltages. If the gain is higher than required it should not be reduced by changing the operating conditions, but by adding rf selectivity through additional tuned circuits, looser coupling or tapping down.

gain control

The method by which the front-end gain is controlled is important to strong-signal performance. As shown in **fig. 5**, if a conventional gain control method is used which changes the operating point of the device, it results in serious degradation in the ability of the device to handle strong signals. The preferred method of manual gain control is a resistive attenuator ahead of the first active device (**fig. 12**).

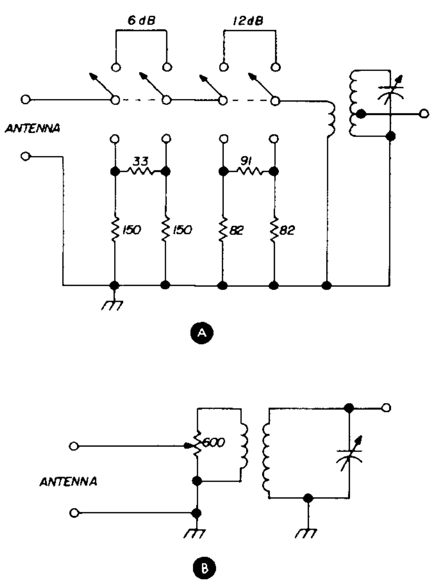


fig. 12. Two types of attenuators which may be used to control signal input to communications receivers. Step attenuator is shown in (A); simple potentiometer attenuator is shown in (B).

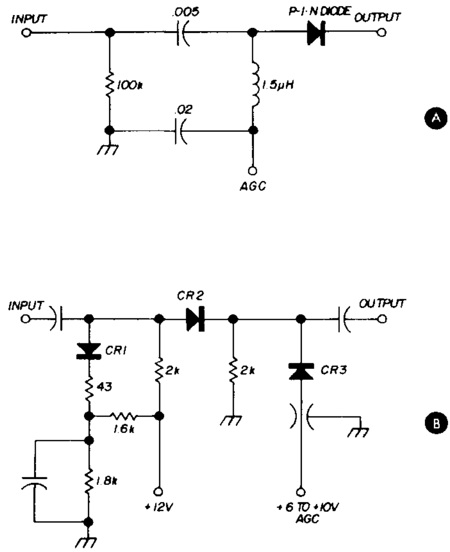


fig. 13. Agc voltage-controlled attenuator circuits using PIN diodes. In the circuit in (B), with +6 volts on the agc line, minimum attenuation is 1 to 2 dB (CR1 and CR3 off, CR2 on). With +10 volts on the agc line, miximum attenuation is 38 dB (CR1 and CR3 on, CR2 off).

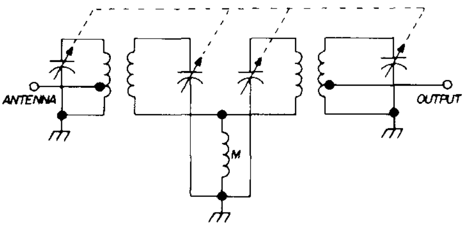
voltage-controlled attenuator using PIN diodes ahead of the first stage. A single diode attenuator is shown in **fig. 13A** and a more complex three-diode version with both forward and reverse biased diodes is shown in **fig. 13B**.[7,8] The designer must be alert to the possibility that the cross-modulation level of the diodes can be less than that of the amplifier or mixer device that they are intended to protect.

selectivity

Rf selectivity is important in the search for the ultimate in strong-signal capability since a perfect rf filter will eliminate all forms of strong signal interference. Crystal-lattice filters are available throughout the high-frequency range and are the near perfect answer for fixed frequency operation.[9,10] Unfortunately, if you are interested in more than a few fixed channels you must go on to less perfect filters.

Helical resonators are perhaps the next best rf filters (**fig. 14B**). They are not easily adaptable to continuous tuning and

they become quite bulky in the high-frequency range, but they can give Qs of 1000 or more which results in bandwidths of 1 kHz per MHz; 14 kHz at 14 MHz for example.[10,11,12,13]



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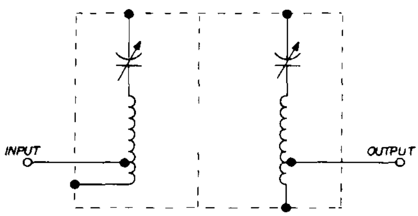

B

fig. 14. Four-circuit rf filter (A), and helical resonator (B).

Cascaded tuned circuits are also effective and most modern receivers have at least two such circuits between the antenna and first stage, and some have as many as four. One arrangement is shown in **fig. 14A.**

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