Synthesized communications receiver

Principles of a synthesized receiver together with a description of the Racal RA 1772 receiver

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The task of the communicator has always been to try to achieve a communication link for the highest possible percentage of the time. Use of the h.f. band, as an effective method of long-distance communication, increased rapidly as its possibilities became appreciated. Even with the introduction of submarine cables and satellites on high-density links, h.f. communication remains popular. A link is relatively inexpensive to set up, can be unobstrusive and ideal for medium-density traffic or person-to-person links. For military users the difficulty of interfering with a multi-frequency h.f. link is another attraction. Increasing traffic comes from maritime users because their requirement is both mobile and long-distance.

All of these reasons mean that the h.f. band is crowded and likely to remain so. Broadcasting, teletype, common carrier links, diplomatic channels and personal or amateur radio channels are only a few users of the band. In these conditions the engineer responsible for introducing or extending his radio equipment must try to ensure that the equipment does not have limitations which reduce the effectiveness of communication. Considering the task of the receiver which, when connected to a large antenna, may be faced with a mass of signals extending over 30,000kHz, requiring sometimes to be selective over a fraction of one kHz, with a range of signal levels which simultaneously may exceed 1,000,000:1 it is no wonder that the task is difficult, especially when the required signal is the smallest. Some specialist receivers are now in use which meet the requirements with limited flexibility. The receiver to be described meets the requirements with complete flexibility and some of its design considerations and characteristics are discussed.

Frequency selection

When assessing the requirements for a new receiver installation, the question of frequency selection is of prime importance. Most links are established on fixed frequency allocations and it is thus possible to consider crystal controlled receivers. An advantage of crystal control is frequency stability; a disadvantage is lack of flexibility. As the number of channels increases the attractions of frequency synthesis also increase.

Early synthesizer designs left much to be desired. The system of "direct" synthesis used a series of dividers and filters to produce the smallest required increments and then added, mixed and multiplied the resulting products to the output via yet more filters. This was bulky and expensive. The system is still used but although active filters have reduced sizes somewhat it is still expensive and it is only used where very fast frequency changing is a necessity. The "indirect" system of synthesis was introduced to counter the stringent filter requirements. A typical system works by using a voltage-controlled oscillator at the output frequency, mixing the frequency down with a selected one from a "comb" of frequencies and comparing it with a reference frequency which produces a locking voltage to the output oscillator. The system can be extended down to achieve the smallest frequency increment desired by a repetitive divide-and-add process. Whilst this system works adequately it still uses several filters and phase-lock loops and, as is the case with most linear circuitry, cannot easily be implemented in integrated circuit form without custom-built circuits. The advent of digital integrated circuitry provided the incentive to consider another method of "indirect" synthesis, where the phase-lock oscillator is merely divided down by a variable divider to a fixed frequency derived from the frequency standard. In the simplest system the comparison frequency is also the smallest incremental step, so that the complete synthesizer comprises one phase-lock loop. Using digital i.cs this can be compact, and ideal for packsets. With the present state-of-the-art it is possible to achieve variable frequency division from approximately 50MHz down to 100Hz and thus have 100Hz steps. Higher output frequencies, up to 100MHz, would require a prescaler of ÷ 2 and have a step size of 200Hz if the comparison frequency were maintained.

A more sophisticated form of digital synthesizer can be used which has a smaller step size than the comparison frequency; again, a divide-and-add system is employed. The advantage of the small size is maintained so that the synthesizer's inclusion within the framework of the receiver can be effected.

Oscillator purity

When used as the receiver local oscillator the synthesizer offers flexibility in the choice of frequency but an output must be produced which is pure enough to match the receiver requirements, because any spurious signals on the output will cause the receiver to have spurious responses. Fortunately with careful circuit design the output can be maintained to a purity of 100dB relative to the main output. Moreover with a digital synthesizer the number of spurious mechanisms is very small compared with those produced in a more traditional mixing-type system.

Noise on the output of the synthesizer is another form of spurious signal. This can also be minimized by ensuring that the maintaining circuit of the output oscillator has as high a Q as is practicable and by running the oscillator at the highest level possible. These requirements are somewhat contradictory in a semiconductor circuit especially when using varactors. Using a field effect transistor BFW 10 and maintaining an in-circuit Q of 50 it is possible to achieve a relative level of 100dB measured in a 3kHz bandwidth at 20kHz off. Reciprocal, mixing is another term for the adjacent channel noise effect where a large unwanted signal offset from the wanted signal mixes with the noise sidebands of the local oscillator to"produce a noise signal at the i.f., thus reducing the effective selectivity of the receiver filters as shown in Fig. 1.

One hazard which should be recognized in the simple, single-loop, digital synthesizer is the relatively "loose" method of control. Because the loop contains a high division ratio divider the loop gain is low. This means that any disturbance due to mechanical shock on the oscillator tuned circuits caused by sudden temperature changes may not be instantly corrected and this is true in any system with long intervals between correction. Correction can only occur at the comparison frequency intervals and faster or shorter-term errors remain uncorrected. For sophisticated transmission systems such as Kineplex a simple loop system is not good enough so that a multiple

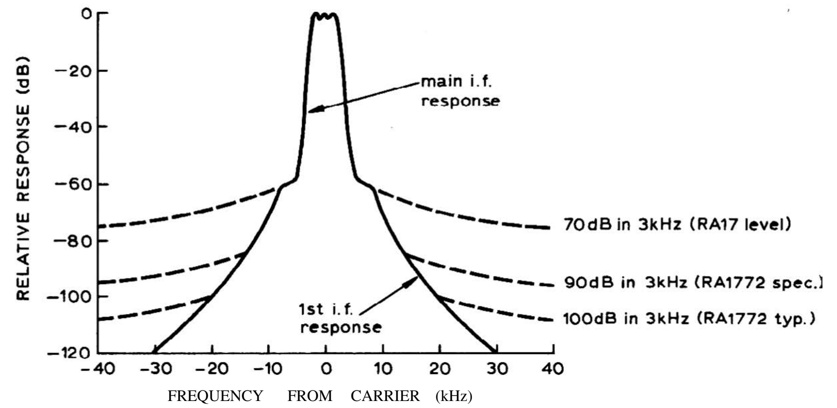

Fig. 1. Response of double superhet showing effect of reciprocal mixing, 3kHz bandwidth.

loop arrangement is required to maintain high speed correction and minimize the division ratio per loop. A further advantage of maintaining a high comparison frequency is that the speed of locking to a new frequency is also high.

The free-tune synthesizer

A synthesized receiver covering the h.f. band in 10Hz steps requires seven decadic switches which makes it difficult to tune in a s.s.b. signal. An alternative method of selection which is provided in the RA 1772 receiver shown in Fig. 2, consists of a shaft encoder coupled to a v.f.o.-type knob. The encoder changes the frequency of the synthesizer in 10Hz steps dependent on the rate at which the knob is rotated. In operation the illusion of a v.f.o. is obtained because the synthesizer locks very rapidly and the step size is small. For searching and monitoring, the free tune facility is provided whilst at the same time absolute frequency accuracy is maintained.

Receiver parameters

It is important to have a receiver which is sensitive to weak signals although there is a fundamental limit to sensitivity set by thermal noise in the receiver input circuits. Sensitivity is directly related to the amount by which thermal noise in the equivalent input resistance of the receiver is increased by the input circuits, the ‘amount being defined as the noise figure. A noise figure of up to 10dB is the lowest level which can be reasonably ‘specified in a h.f. production receiver although 7dB might be typical for the same equipment. This would be equivalent to a s + n/n ratio of 15dB for a 1μV signal using a 3kHz i.f. bandwidth or, providing the post filter noise is insignificant, 5dB for a 0.1μV signal using a 300Hz bandwidth. The latter figures demonstrate the reason for the continued popularity of c.w. over difficult links.

In practice, however, it is not normally the noise figure of the receiver which limits the detection of the' small wanted signal but the simultaneous existence of atmospheric and man-made noise on the antenna. A far more severe limitation comes from the large unwanted signals also present, whose effect is often disguised. It is not sufficient to provide a high degree of single-signal selectivity, the dynamic selectivity must also be of a high order. Cross-modulation is a recognized effect where a large unwanted modulated signal transfers its modulation to the smaller wanted signal. It is a broadband effect, due to front end non-linearities and occurs in many receivers with unwanted signal levels of a few millivolts. In this respect the transistorized receiver is at a definite disadvantage with respect to the older valve types because a bi-polar transistor is basically a non-linear device. Some benefit may be obtained by front-end tuning to reduce the number of large signals entering the receiver but real immunity is only achieved by designing for a very high linearity. In the RA 1772 this is obtained by using high-level field effect transistors achieving levels of 300mV. At this level the effect is no longer a problem unless co-sited transmitters are set up in duplex operation or a mile-long Beverage antenna is pointed near a broadcast station. Blocking is also a broadband effect which results in the reduction of the wanted signal by a large nearby unwanted signal. It has been traditional to specify the unwanted level at which 3dB of level reduction is measured; this now occurs at such a high level, 500mV minimum, that other effects disguise and can prevent more than 1dB reduction from being seen.

Intermodulation. A rather more insidious effect than those mentioned is due to intermodulation distortion between two or more unwanted signals which produce discrete unwanted products. The unwanted products for second order i.ps occur at $f_1 \pm f_2$ e.g. at 10MHz for unwanted signals of 4.5 and 5.5MHz or 10.02 and 20.02MHz. Fortunately one of the two unwanted signals must be at least one octave removed from the position of the product which is, if interfering, the tuned position, so that r.f. tuning can reduce the level of one signal and hence that of the product. Half octave filters are selective enough for this purpose and are commonly employed. Third order intermodulation products are more difficult to remove. These occur at $2f_1 \pm f_2$ e.g. at 10MHz for signals of 10.02 and 10.04MHz or 9.98MHz and 9.96MHz. Obviously it is impossible to remove these with conventional *LC* tuning and the only satisfactory solution is to arrange for a very low natural level of third order distortion. Specification methods vary but the most accepted method specifies the level of the two unwanted signals which together produce an unwanted product of 0dBμV (1μV). Most existing receivers if measured close-in (without benefit of r.f. tuning), would give a level of up to approximately 70dBμV (3mV). The equivalent performance of the RA 1772 receiver is 90dBμV (30mV), an order better. Since, however, third order intermodulation product levels increase at three-times the rate that the level of the unwanted signals increase, the unwanted level from a 70dBμV receiver when fed with signals of 90dBμV is at 60dBμV (1mV). Measured on this scale the improvement in level is three orders. It is only possible to assess the overall effect of third order intermodulation by analysing the total pattern of signals being received by the antenna. If the antenna is a large rhombic, for example, there may be several thousand signals received of levels up to 100mV and all these will combine in the receiver front end to produce many thousands of products. It is possible to deduce where the products fall, and at what level, from the pattern and level of the primary signals, and from the amount and degree of receiver preselection. Shown in Fig. 3 is the result of an analysis on a rhombic antenna where the highest level signals between 30 and 100mV were between 9 and 15MHz. The graph shows the mean

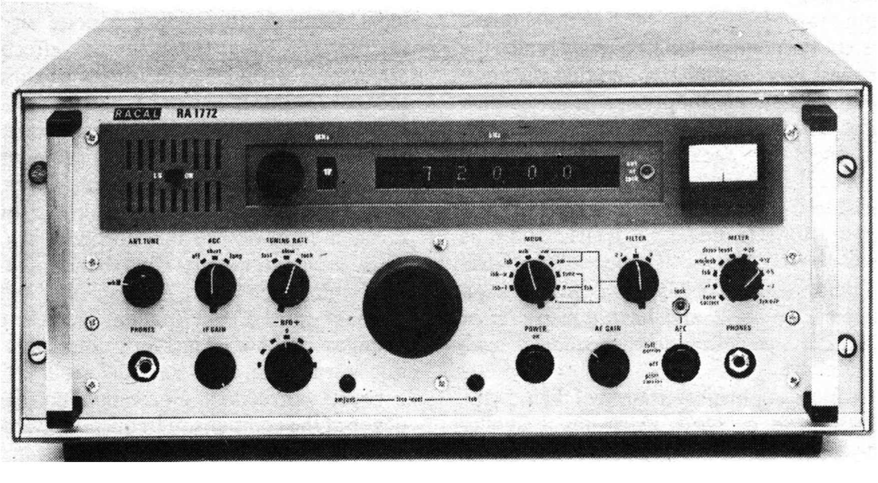

Fig 2. RA 1772 general purpose synthesized receiver.

signal strength requirement to overcome various effects and give a 10dB signal to noise ratio in a 3kHz bandwidth. The most obvious conclusion is that the 70dBμV i.p. receiver could not be used wideband on such a big antenna, (curve 4), even with 12% tuning, (curve 5), a mean signal of above 300μV must be arranged at around 11MHz. If an improvement in linearity to 90dBμV i.ps can be achieved then both curves 4 and 5 drop by 60dB to reduce the level to that of atmospheric noise. Curve 6 is that due to reciprocal mixing, a reduction in level of 30dB can be achieved so that, again, atmospheric noise becomes dominant. A common control in most h.f. receivers is the antenna attenuator. This control which reduces the level of all signals into the receiver is used since the intermodulation products fall faster than the wanted signal. It is, however, of little use if the wanted signal is already weak and near noise level. Fortunately at the level of performance achieved this can be dispensed with completely. A more detailed analysis with results are given in ref. 1.

It is not always evident that the receiver's limitations are preventing reception; as stated earlier, the effects are often disguised. One example is when a large unwanted signal intermodulates with a noisy signal or with atmospheric noise itself to give a noise-like signal on-tune. It is only the very experienced user who can determine that this is due to the receiver and not merely interference.

Receiver design

It is worth examining some of the ways in which the receiver design can be improved to the point of immunity from the problems mentioned. The h.f. superhet receiver has as its final i.f. a frequency convenient for large amounts of stable and variable amplification, typically up to 100dB. The frequency must also be one for which it is possible to construct narrow filters of defined characteristics. It is common to use crystal filters since these are stable and need no adjustment during the life-time of the equipment. No single frequency is standard but 1.4MHz is a good compromise because at this frequency the crystals are relatively compact and four to eight pole filters can be obtained in a package of 76 X 28 X 31mm. Single superhet receivers are constructed using a 1.4MHz i.f. but there is a problem of removing the image frequency at 2.8MHz off-tune and narrow r.f. filters become a necessity. It is often easier and more flexible to build a double superhet with a high first i.f. to remove the image from the h.f. band entirely. A first i.f. of 35.4MHz means an image frequency of 70.8MHz off-tune with the intermediate frequency also out of the h.f. band. A single low-pass filter before the first mixer which cuts above 30MHz is then all that is required to attenuate image and i.f. breakthrough to the specified levels, typically 90dB down (see Fig. 4).

Although it is sometimes beneficial to frequency selection it is never advantageous to the receiver performance if the first i.f. bandwidth is wider than the final output bandwidth. The highest possible amount of single–signal and dynamic selectivity are required both of which are obtained if the bandwidth is made narrow as soon as possible. It can be arranged for all frequency selection processes to be made in the first mixer, with fixed frequency injection in the subsequent mixer(s), so that a narrow first i.f. filter can be used. This filter can also be a crystal type so that its bandwidth need only be wide enough to pass the widest i.f. bandwidth envisaged, normally ± 6kHz. This allows protection to subsequent stages against signals farther off-tune than 10kHz and considerable protection at 20kHz off-tune. Having such protection we may concentrate on providing a very high linearity in the stages which are wide-band, particularly the first mixer and r.f. amplifier.

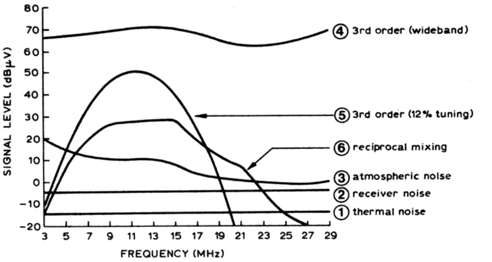

Fig. 3. Mean signal strength required for 10dB s/n ratio, showing effect of 70dB third order i.ps and reciprocal mixing with large rhombic antenna.

The front-end. The first mixer is the section where the greatest amount of development effort has been concentrated in recent years. The problem is to achieve mixing and maintain linearity to signals at the input in a function that is basically non-linear. The mixer must be non-linear to signals on two inputs but linear to signals on the same input. A solution lies with the switching type of balanced mixer in which the input signals are switched through to the output in-phase and out-of-phase alternately at the local oscillator repetition frequency. It is important to maintain this linear switching even at input voltages of several hundred millivolts which requires several volts for switching. All parts of the mixer are important when designing for the order of linearity described. The mixer transformers must be carefully balanced and non-linear ferrites avoided. If the frequency band to be covered is wide, then transmission line transformers are useful to maintain inductance whilst keeping core and self capacitance losses low–ref. 2. Balance is important not only to reduce the level of direct i.f. noise from the local oscillator but also to reduce the level of the oscillator appearing at the antenna input. The level of this "re–radiation" has to be kept very low in a communications centre (C.C.I.R. recommendation 10μV max.) particularly if several receivers share a common antenna

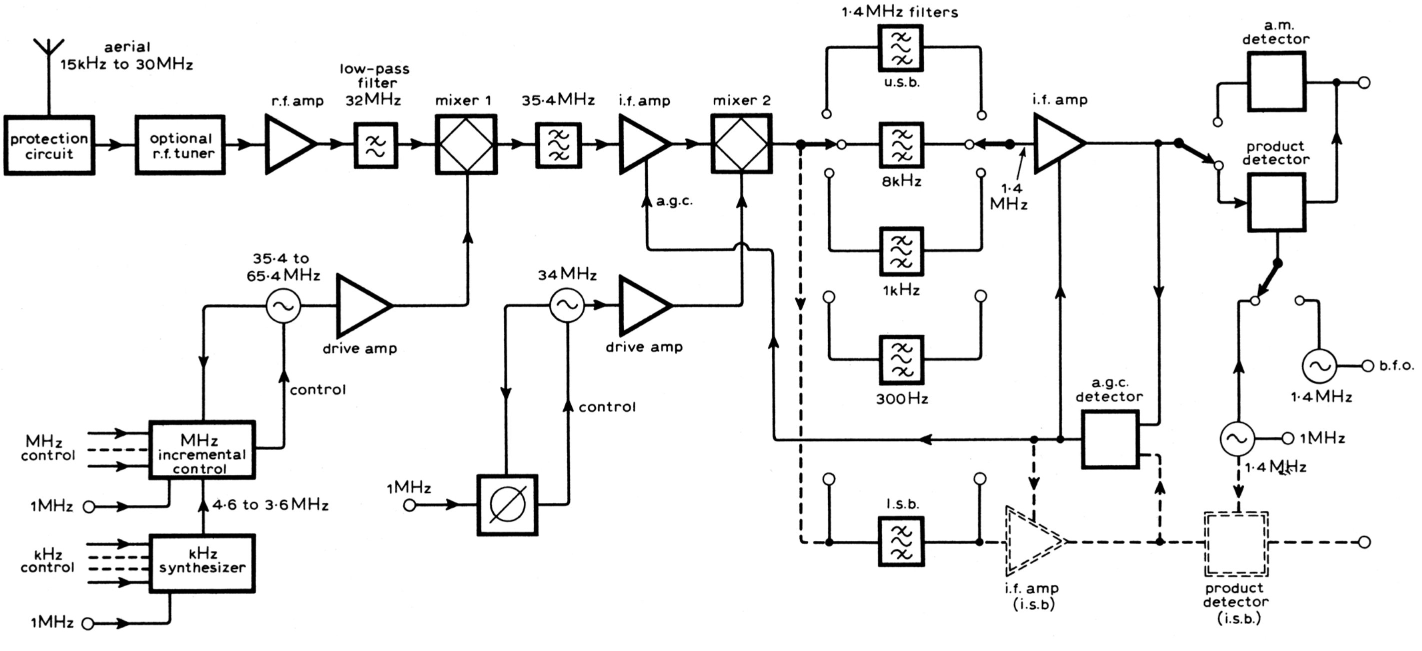

Fig. 4. Block diagram of the RA 1772 receiver.

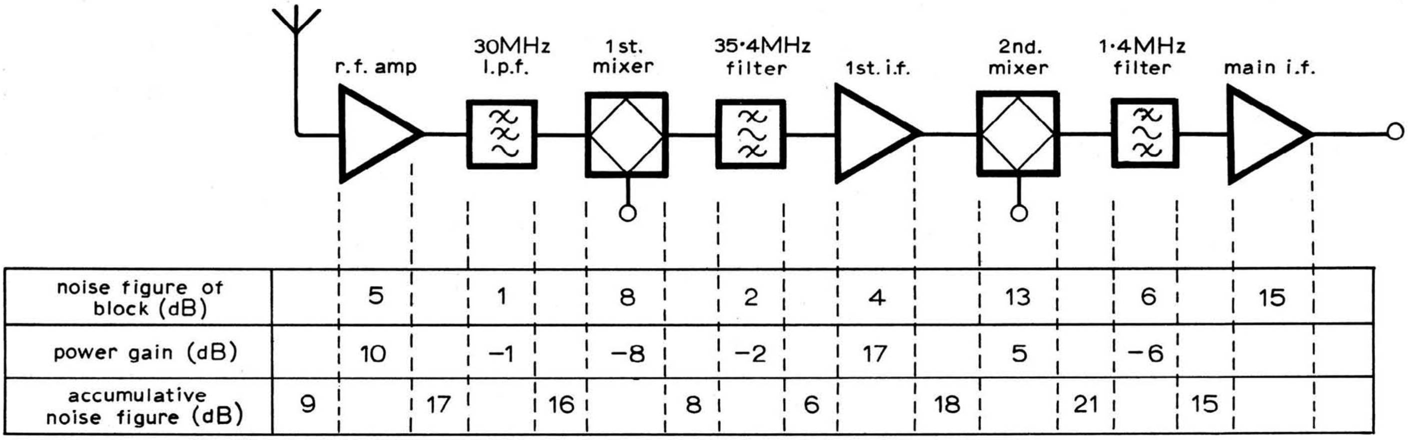

Fig 5. Typical level chart.

distribution network. Another advantage of the high i.f. is that the input l.p.f. gives a high rejection to all feedback of local oscillator frequencies, these frequencies being outside the h.f. band.

Designing for high linearity means attention to all parts of the system including those which normally do not give rise to i.ps. The first i.f. crystal filter for example; it might be thought that since this contains purely passive components no problems could arise. This has proved to be far from the case in the RA1772. Not only have all ferrite transformers had to be removed in favour of iron-dust but the crystals need to be manufactured very carefully to avoid any minute metalization to quartz discontinuities. Care must also be taken to ensure that the characteristics of the mixer are known from l.f. to u.h.f. because many mixer products up to frequencies of 1000MHz and beyond are produced of which only one is required. A noise figure around 15dB would be acceptable in most cases where the receiver is directly coupled to a receiving antenna, certainly up to 20MHz, because here the system would be atmospheric or man-made noise limited. If it is not directly coupled then a lower receiver noise figure is desirable. To achieve a worst-case noise figure of 10dB an r.f. amplifier is necessary which again needs a high linearity and signal handling capacity. In our case the gain as shown in Fig. 5 is 10dB so that the first mixer must provide third order i.ps of better than 90 for two 100mV signals.

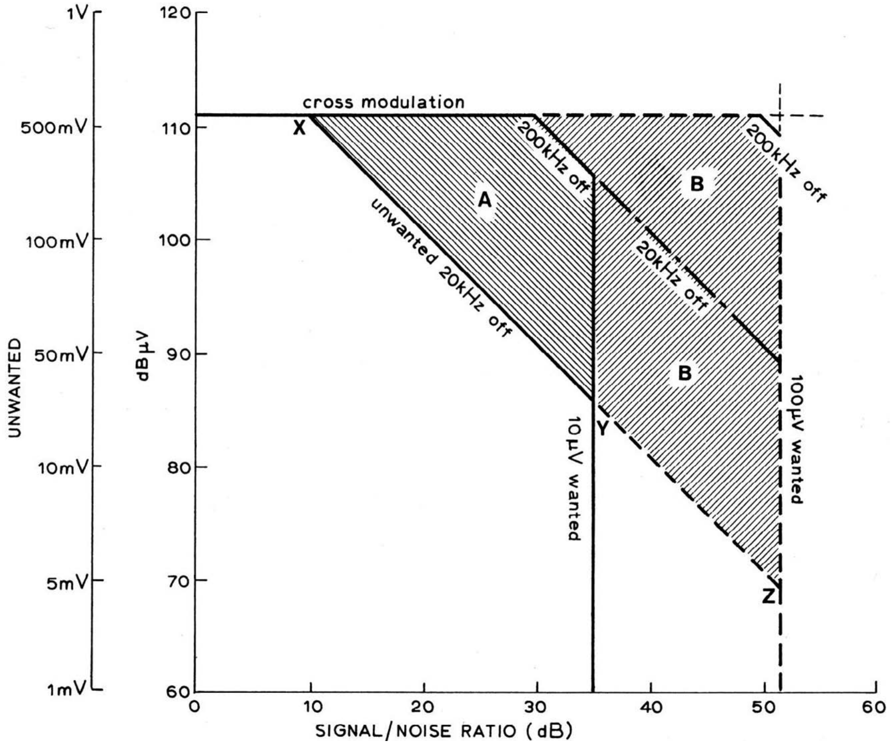

Fig. 6. Signal-to-noise ratio showing effect of reciprocal mixing and cross-modulation.

I.F. stages. Stages subsequent to the first i.f. filter are protected against signals off-tune but have to be capable of providing linear amplification to signals inside the passband. One measure of linearity is percentage distortion to the audio output after detection. The product detector as used for s.s.b. demodulation is capable of a higher linearity than the envelope detector and overall figures of 1 to 2% can be maintained. A.m. is thus often received using the sideband filters and product detector with, as a further bonus, the choice of sideband to minimize interference. Another measure of distortion is the in-band i.ps where the accepted minimum requirement is − 40dB. This limit arises because in a multichannel v.f.t. system unwanted products spread into the tone frequencies of another channel and cause errors. Large range a.g.c. is a requirement and, whilst it is agreed that the output level change should be as small as possible, there is disagreement over time-constants. For a.m. and f.s.k. signals both attack and decay times should be short, in the order of a few tens of milliseconds, whereas for c.w. and s.s.b. signals the decay time should be long. Therefore a choice of time constant is usual, “short” and “long”. Ideally in “long” there should be no a.g.c. decay when receiving s.s.b. until the transmission ceases, because otherwise an annoying increase in background noise returns between syllables of speech. A solution is to incorporate a “hold” period or decay time which lasts for two seconds, followed by a fairly fast decay of one second. The “hold” is readily achieved by storing the a.g.c. voltage on a capacitor which is fed to a high input impedance f.e.t. or m.o.s.f.e.t. until the end of the “hold” period when a discharge resistor is switched in. No a.g.c. is applied to the first i.f. amplifier until the signal reaches 300μV. This ensures that the signal-to-noise ratio increases with a signal strength as fast as possible until 50dB is achieved. Further requirements are a voltage/gain characteristic which is reasonably linear and defined, so that a.g.c. stability is maintained even with narrow filter bandwidths, and so that when using two receivers in diversity their two a.g.c. lines can be connected ensuring control of the higher signal strength receiver.

R.F. attenuation. No a.g.c. or attenuation is applied before the mixer, because with the linearity achieved in the mixer it is not necessary. This means that the small wanted signal is never attenuated. A method of extending the cross-modulation specification of a receiver is by using front end

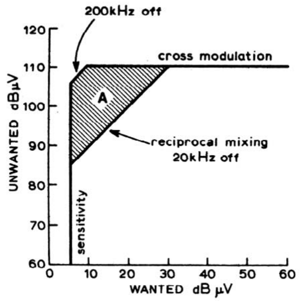

Fig. 7. Maximum unwanted signal level for 20dB s/n ratio.

attenuation determined by the level of the nearby unwanted signal. This is necessary if the natural cross-modulation level is lower than that of the anticipated signals but the result is of necessity a compromise. Shown in Fig. 6 is the s/n ratio achieved for two wanted signal levels against unwanted signals of different offsets. The diagonal limits are due to reciprocal mixing, the front-end attenuation would have to be arranged to follow the 20kHz line if the cross–modulation level was naturally lower than 300mV and specified at 20kHz. The disadvantage would be that unwanted signals further off-tune than 20kHz would also have the effect of causing the attenuator to operate and the extra signal to noise obtained in area A would not be obtained. Furthermore unless the attenuator was also coupled to the wanted level, line XY would extend to 2 and area B would also be lost. A more conventional representation, Fig. 7, shows the maximum level of unwanted signal for 20dB sin ratio as a function of wanted signal. The same effect is illustrated as in the previous figure, i.e. there is no real substitute for a very high real crossmodulation level to match a very low reciprocal mixing level.

The author wishes to thank the directors of Racal Communications Ltd for permission to publish this paper and credit is due to the members of the engineering laboratories who have contributed to the successful development of the receivers.

References

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Receiver for modulation studies

Facilities for s.s.b. and i.s.b.

The radio receiver in the picture looks quite conventional but is in fact rather special. It is designed for studies of the possibilities of new methods of modulation in the m.f./l.r. sound broadcasting bands–notably single-sideband and independent-sideband. Re-planning exercises for the European medium- and long-wave broadcasting bands (see August issue, pp. 266-271) have the unenviable task of attempting to maintain the present service, in which there are invested millions of broadcast receivers and associated transmitting stations, yet pave the way towards better spectrum utilisation and accommodating more radio channels. At present two technical expedients appear to go some way towards a solution of the above conflicting requirements. These are: (a) Place all the channels on a regular frequency spacing of 8kHz, with nominal carrier frequencies being an integral multiple of the carrier spacing. (This has the effect of reducing intermodulation and TV interference, making receiver design easier and allowing more channels.) (b) Consider the gradual introduction of independent single–sideband transmissions. (This makes possible stereo broadcasting compatible with a.m., later on two language channels, or ultimately double the number of channels.)

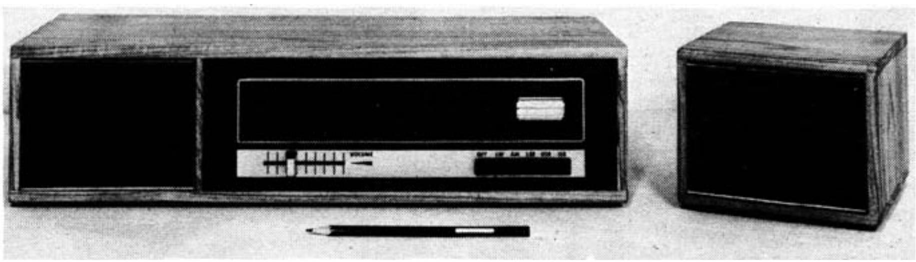
Incremental tuning

The receiver in fact contains battery powered circuits which respond to the two factors just described, but at the same time operates nearly conventionally on the existing m.f. sound radio transmissions. The differences introduced are as follows. First, the receiver tuning only settles down at 1kHz increments, even though controlled with a conventional continuous scale. The present channel frequency spacings are 8,9 or 10kHz, so the receiver can "capture" all existing stations. If the beneficial change to 8kHz comes about (by slightly retuning the existing transmitters) a simple change in the receiver's c.m.o.s. logic will make the receiver only settle on every channel – a very much easier thing to achieve, by the way, than on every 1kHz. Secondly, the push-buttons give listening mode options of a.m., lower sideband, upper sideband or independent sideband. Two loudspeakers are provided, as in unit audio, but in this equipment the lower sideband comes from the left-hand speaker and the upper sideband from the right-hand speaker. Sideband separation is accomplished by the phasing method of demodulation, with the receiver carrier phase locked to the incoming transmitted carrier.

Bi–aural listening

The overall sideband response is flat from 300Hz to 3000Hz, which compares well with a normal a.m. receiver. On present broadcasts one can listen bi-aurally, with a.m., or as i.s.b., or one sideband at a time in one speaker (if there is interference in the other). Apart from the fact that one soon recognises the potential of, say; two independent sideband broadcasts (expedient (b) above), the improvement in the quality of night-time broadcasts as received on the sideband method is a fact which has been recognised for some considerable time.

A single dual ‘output amplifier i.c. provides a total power of 1W, controlled by the single dual volume control. The front end of the receiver is conventional, with its tuned ferrite rod aerial housed in the receiver cabinet together with all the other circuits. A full description of the receiver is to be found in the June 1974 issue of the EBU Review (Technical), No. 145. The development of the receiver, in the Electrical and Electronic Engineering department of the University College of Swansea, was supported by a grant from the UK Science Research Council.



The experimental receiver, showing the two loudspeakers.