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RECEIVER IM-ENFORCING THE SQUARE LAW

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PAPER No.

ECX-527

A CONFERENCE PAPER PRESENTED AT:

19th IEEE Vehicular Technology Conference
San Francisco, CA
December 3 and 4, 1968

ECX-331

RECEIVER IM - ENFORCING THE SQUARE LAW

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Summary

The mathematics of IM generation are surveyed, and it is shown that, for Land Mobile receivers, worst case IM is a third order effect occurring in the first mixer. The importance of relating the IM specification to the receiver sensitivity is pointed out. RF gain reduction or elimination, selectivity at both RF and IF, and the new square law mixing devices are all mentioned as techniques used for receiver IM reduction. The new diodes and F.E.T.'s are looked at in greater detail. Their advantages of low noise and high burnout resistance are contrasted with the problems of conversion gain and high required L.O. power levels.

Introduction

"Nothing is certain but death, taxes, and intermod."

Benjamin Franklin? Well, not quite. While this represents a slight expansion on Ben's original statement it is not far from the truth for many of today's vehicular radio users. In our crowded Land Mobile spectrum some intermodulation (IM) is certain, but we designers of vehicular communication equipment and systems can greatly minimize the problem by proper application of our engineering knowledge and skill. It is the intent of this paper to bolster that knowledge and improve that skill by imparting a better understanding of receiver IM and of the receiver design techniques utilized to minimize it. To achieve this intent this paper will: impart a broad understanding of the receiver IM problem; review some of the time tested methods of reducing IM in receivers; and introduce some of the newer tools available to the receiver designer which better enable him to "enforce the square law".

The Receiver Intermodulation Problem

Receiver IM is the result of two undesired carriers reaching a nonlinear element in the receiver. The carriers mix in the nonlinear element; and if the frequency spacings are proper, an output on the receiver desired frequency occurs. If the amplitudes of the undesired carriers are high enough, the amplitude of the mix may be sufficient to override the receiver noise and produce an output.

An examination of the general mathematical relationship which describes the output of a nonlinear element in terms of its input aids in understanding the intermodulation process. A simplified general equation of the transfer characteristic for such a device is as follows:

$$i_2 = A_0 + A_1 i_1 + A_2 i_1^2 + A_3 i_1^3 + \dots A_n i_1^n$$

where i_1 is the instantaneous input current

i_2 is the instantaneous output current and

A_0, A_1, A_2, etc. are coefficients determined by the type of device and its operating point.

If two signals, F_1 and F_2, are applied to this device, currents flow in the output circuit. The relative amplitude of these currents is determined by the coefficients A_0, A_1, etc. The frequencies of these currents can be determined from the equation and are given in Table I:

Term	Frequencies of Output Currents	Type of Transfer Characteristic
A_0	Zero	DC Component
$A_1 i_1$	F_1, F_2	Linear
$A_2 i_1^2$	$2F_1$, $2F_2$, $F_1 \pm F_2$	Second Order (Square Law)
$A_3 i_1^3$	$3F_1$, $3F_2$, $2F_1 \pm F_2$, $F_1 \pm 2F_2$	Third Order
...		
$A_n i_1^n$	nF_1, ... $F_1 \pm (n-1) F_2$	Higher Order Curvatures

TABLE I

If a "low intermod" linear amplifier is desired, the designer will attempt to select a linear device and bias it in such a way as to make A_1 as large as possible and all other coefficients as small as possible.

If a mixer is desired, and we consider F_1 and F_2 to be the frequencies to be mixed, then it is apparent that $F_1 \pm F_2$ is the desired output frequency and only the square law characteristic is required. The device selected should be biased to make A_2 as large as possible while keeping the other coefficients as small as possible. This is no small task.

What stage limits the IM performance of a receiver? Usually the troublesome stages are considered to be the RF amplifier(s) and the mixer since selectivity can generally minimize the problem in succeeding stages. Due to several factors, the mixer is the prime generator of intermodulation products. The first factor is signal level. The RF amplifier is less prone to IM since it receives lower level signals from the antenna than it delivers to the mixer. A second factor results from the A_3 coefficient (which, as we shall see, is the major cause of IM problems in Land Mobile receivers). This coefficient is automatically larger for the square law biased mixer than it is for the linearly biased RF stage. Comparing the difference in performance of the two types of stages is difficult. Generally, the mixer generates detectable IM products at input signal levels 6 to 10 db lower than would be required for detectable IM output from the RF stage.

There is another mathematical relationship, derived from the n^{th} term of the expansion of the general transfer equation, which helps in understanding receiver IM. The frequencies which produce IM are related according to the following general formula:

$$\left| m\ F_1 \pm p\ F_2 \right| = F_{IM}$$

where m and p are integers.

If F_1 and F_2 are frequencies such that, with given values for m and p, F_{IM} equals the receiver operating frequency (F_0) then conversion to the intermediate frequency will take place. Receiver output due to intermodulation then occurs.

Several things should be noted about this formula. First, if m and p are equal and of low value, very wide frequency spacings between F_1 and F_2 are required to produce the condition where $F_{IM} = F_0$. For example:

let m and p = 1 and F_0 = 150 MHz

then $\left| F_1 \pm F_2 \right| = 150$

This equation can be satisfied by any number of values for F_1 and F_2, but at least 75 MHz spacing is required between them. In Land Mobile receivers with their excellent front end selectivity, this type of IM is only occasionally a problem. Incidentally, this is second order intermodulation (the order is determined by the sum of m and p) and cannot be improved by the use of a square law mixer. Selectivity is the only answer for this type of IM.

Secondly, as the values of m and p are raised, higher order coefficients of A become involved and the conversion efficiency of the mixing is decreased. Higher level inputs are then required to produce F_{IM} at a level sufficient to cause undesired output from the receiver.

If selectivity protects the receiver from second order IM (equal values of m and p), and if high values of m and p don't generally cause trouble, then the IM problems in Land Mobile receivers must be caused by unequal and low values of m and p. Such is indeed the case. For example, consider a 150 MHz (F_0) receiver and:

let m = 2, p = 1, F_1 = 151 and F_2 = 152

then (2) 151 - 152 = F_{IM}

$302 - 152 = F_{IM}$

$F_{IM} = 150 = F_0$

This third order IM product on F_0 is then converted to the receiver IF by the receiver's normal mixing action.

Note that, in addition to this type of frequency relationship, there is an important power relationship which is also based on the general transfer equation. This power relationship can be briefly stated as follows: The IM product power is proportional to the signal power at F_1 raised to the m exponent times the signal power at F_2 raised to the p exponent. The proportionality is determined by the coefficient A corresponding to the order of the IM product. Thus, in the above example for third order IM, the important coefficient is A_3; and the power at 151 MHz is twice as important in determining the IM product power as is the power at 152 MHz. Using this relationship it is easy to see why IM products often appear so strong and also why just a little attenuation is often so effective in "knocking out" an undesired product.

An example can also be constructed for fifth order IM as follows:

let m = 3, p = 2, F_1 = 152 and F_2 = 153 MHz

then (3) 152 - 2 x 153 = F_{IM}

$456 - 306 = F_{IM}$

$F_{IM} = 150 = F_0$

The signal levels required to produce fifth order IM are generally about 15 db greater than those required to produce third order IM.

A word about IM specifications and absolute levels is in order here. The generally accepted methods of measuring IM in Land Mobile receivers state the IM performance of the receiver in terms of db above the receiver sensitivity. There is nothing wrong with this method of specification. Unfortunately, people do not take the time to relate the IM and sensitivity specifications of a receiver to see what level signals result in receiver IM problems. Table II relates these two specifications to give the resulting IM level:

12 db SINAD Sensitivity - Microvolts	IM Spec - db above the Sensitivity	Resulting IM Level - Microvolts
0.35	65	630
0.55	69	1600
0.35	80	3500
0.175	75	1015
0.175	70	560

TABLE II

As you can see by comparing line 2 of the table with lines 4 or 5, the highest IM specification does not alone guarantee a receiver with the best immunity to intermodulation interferences. The sensitivity must also be considered. It should be noted that the "threshold of annoyance" for IM interference is really related to the critical squelch opening sensitivity rather than the 12 db SINAD sensitivity shown in the table. Unless the receiver sensitivity is limited by ambient noise the "threshold of annoyance" occurs with even lower signal levels than those shown in the table.

As a point of calibration in looking at Table II; two one-third KW transmitters with unity gain antennas at 100 ft. will each produce approximately 3500 microvolts at the input jack of a mobile receiver 0.8 mile from each transmitter. The receiver designer's best efforts are none too good.

History and the Designer's Tools

The Land Mobile receiver designer's task is not an easy one. He has many choices to make in arriving at a receiver design which is the best overall compromise for the intended service. If he pushes too hard on any one of the several areas of receiver performance, one or more of the others is bound to suffer. For example, sensitivity can be traded for IM performance but only to a point, after which the user finds the resulting sensitivity unsatisfactory for his application.

For 20 years designers made these choices with probably no more than a 15 db variation in the IM specification. Early receivers with multiple RF stages had unspecified IM performance but were probably in the 50 to 55 db region. Later on, techniques improved; and the emphasis shifted somewhat from sensitivity to interference rejection. As a result, IM performance improved to 60-65 db; but 65 db seemed to represent the practical upper limit. Beyond this limit there was really very little that the designer could do for improvement. The required "trade-offs" were just too unattractive as far as the other areas of receiver performance were concerned.

During all these years with an essentially fixed upper limit on the IM specification, a number of other changes took place which made the IM problem much more severe. Using High Band as an example: Receiver sensitivities were improved by 10 db or more. Transmitter power outputs were increased from the 10-50 watt level to the 75-330 watt level. The channels were split from 120 to 60 to 30 KHz, and many new systems were authorized. These changes resulted in a greater number of higher level signals reaching the IM generating mixer.

To offset these negative factors, there were some design improvements over the years. The first of these came when IM was recognized as a problem, and steps were taken to reduce the number of RF amplifier stages and minimize the RF signal level at the input to the mixer. These changes were responsible for the improvement to the 60 to 65 db specification level previously referred to. Later, coupled helical resonators were introduced as a step in the trend toward better RF selectivity. They restricted the RF bandpass of the receiver which minimized the number of offending carriers reaching the mixer and thus reduced the probability of IM. Crystal filters were introduced for the high IF selectivity. They effectively removed the second mixer as a source of IM even at the 30 KHz channel spacing.

Unfortunately, there was one small backward step during these years. The introduction of the bipolar transistor mixer was accompanied by a slight loss in IM performance. It was just enough, at the maximum, to show up as a 5 db loss in the IM specification. The other advantages of the bipolar transistor mixer were many: low noise figure, low D.C. power requirements, high conversion gain, etc. Overall the advantages outweighed this one disadvantage, and the solid state Land Mobile receiver replaced its vacuum tube counterpart.

The steps taken to improve the receiver performance by the use of helical resonators and crystal filters were not really getting at the root of the problem. What was needed was a mixing device, or devices, which could be biased for square law operation with significantly less higher order curvature than exhibited by either the bipolar transistor or vacuum tube mixer. It was also essential that a low noise figure be secured at this same operating point.

Some steps, or partial steps, in this direction were suggested, and perhaps even used by some, as a means of combating receiver IM. These included parametric converters and the use of power tubes as mixers. The demand, however, was for simple solid state receivers and these ideas never really caught hold for the Land Mobile Service.

Some New Design Tools

It remained for the introduction of two new devices to allow receiver designers to break the "65 db barrier". These devices are the field effect transistor (F.E.T.) and the Hot Carrier or Schottky Barrier diode. Each has its advantages and disadvantages when used as mixers in land mobile receivers, but both can be operated as essentially square law devices. On top of excellent square law characteristics both of these devices are capable of such low mixer noise figures that it is possible to design very sensitive receivers without the use of an RF amplifier stage. This is quite advantageous since, for a given sensitivity, it permits lower signal levels at the mixer input which in turn aids in achieving good IM performance. Receiver designers have been quick to take advantage of this feature, and Land Mobile receivers without RF stages are now quite common.

The Hot Carrier or Schottky Barrier diode combines several desirable features for a mixer diode. It is a low noise device on par with the best point contact diodes. More important, as far as intermodulation is concerned, this low noise figure is not degraded by the high levels of local oscillator power required to maintain the square law transfer characteristic at high levels of input signal. This diode also is capable of withstanding higher levels of transient pulses before burnout occurs.

The local oscillator (L.O.) injection requirements for a square law diode mixer are quite high since it is necessary to keep the L.O. power level at least 10 db above the largest expected signal if square law operation is desired. In addition, excess L.O. power is sometimes required to make up for the loss encountered in coupling the L.O. into the diode. This loss occurs because of the difficulty associated with properly terminating the diode at both the signal and the L.O. frequencies. Since there is no RF stage, signal power must be preserved if the best sensitivity is to be obtained. As a result, the design usually favors correct terminations for the signal frequency at the expense of increased L.O. power requirements.

In addition to the single unbalanced diode mixer, there are several balanced configurations possible. Balanced operation permits the L.O. to be coupled to the diodes with correct termination for both signal and L.O. frequencies. As a result L.O. power requirements can be less for balanced mixers. The reduction of certain receiver spurious is an additional benefit of balanced operation.

For minimum overall receiver noise figure, it is essential that the diode mixer be followed immediately by a very low noise IF amplifier. This requirement means that low loss, and hence generally wide band, matching circuits must be used between the diode and the amplifier. Therefore, the amplifier is subject to multiple inputs restricted only by the RF selectivity of the receiver. The conversion loss of the diode mixer does, however, reduce the signal level at the input of the amplifier by several db over that present at the diode input. Even with this loss, linearity requirements are stringent for this amplifier and a field effect, or large geometry bipolar grounded base, transistor stage is required for best IM performance.

In spite of their obvious advantages as mixing devices, Hot Carrier or Schottky Barrier diodes have not found much use in Land Mobile receivers. There are two good reasons for this situation. Compared to an F.E.T., the diodes have been considerably more expensive, and they exhibit a slightly (1-2 db) inferior noise figure.

The field effect transistor has come to be the favored device for achieving superior IM performance in many types of receivers. The N channel junction and the single or dual insulated gate MOS (metal-oxide-semiconductor) devices are the most popular for RF applications. The junction F.E.T.'s have the edge on noise figure performance, but the dual gate MOS devices may offer some advantages associated with coupling the L.O. into the device via the second gate.

The junction F.E.T. is one of the lowest noise mixing devices that receiver designers have ever had to work with. It will consistently produce overall receiver noise figures of about 5 db at 150 MC. Even with the addition of the preselector loss, this noise figure performance permits 12 db SINAD sensitivities of 0.35 microvolts without the use of an RF amplifier stage. Concurrent with this low noise performance excellent square law mixer operation is obtained, and third order IM is reduced by 15 to 20 db over that obtained with a bipolar transistor mixer.

RF burnout due to nearby high power transmitters, or leakage across antenna relays in high power stations, etc. has sometimes been a problem with small signal bipolar transistors. Frequently, diodes have been used to protect the bipolar transistor from damage under these circumstances. The IM generated by these diodes is inconsequential in a receiver with a 60 or 65 db IM specification but would severely limit the intermodulation performance of an F.E.T. mixer receiver. Fortunately, F.E.T.'s are better able to withstand this type of overload, and no diodes or other devices are required to protect receivers with F.E.T. front ends.

The field effect transistor is not quite as easily applied as a VHF-UHF mixer as was the bipolar transistor. In the case of the junction F.E.T. the main problems are: (1) L.O. power requirements of up to 10 MW versus 1 MW or less for bipolar devices; (2) the best conversion gain and best square law mixing are not obtained at the same operating point.

The high L.O. power requirement problem is very similar to the problem which was mentioned for Hot Carrier diodes. Figures 1 and 2 illustrate the problem.

Figure 1 shows a mixer using gate injection. Capacitor C2 must be kept at an optimum value (large) if the signal power from the antenna is to be transferred to the F.E.T. with minimum loss. Capacitor C4 should also be large if the L.O. power is to be efficiently transferred. However, they cannot both be large, for then the input tuned circuit (L1, C1) and the injection tuned circuit (L2, C3) are closely coupled together. Under these conditions the signal will be shunted to ground through L2, C3 and the L.O. will be shunted to ground through L1, C1. Capacitor C4 is usually made much smaller than optimum to prevent these shunting losses. As a result, the L.O. power requirement is increased. Figure 2 shows a mixer using source injection. The problem is similar. If the tap on the injection coil is raised to obtain more injection voltage, the source is no longer well bypassed for the signal frequency. On the other hand, if the tap is lowered the source return for the signal frequency is better; but sufficient L.O. voltage is difficult to obtain. In practice the tap is usually set at a point which permits a good return for the signal frequency, and the L.O. power is increased to raise the voltage at this tap.

This problem is really not much different than that which exists for bipolar mixers. However, since it is coupled with the requirement for 0.5 V or more gate-to-source injection voltage compared to 0.06 to 0.15 V emitter to base injection voltage for bipolar transistors, the over-all problem of providing L.O. power is quite difficult. The brute force approach is used as a method of meeting this requirement, and many of the new Land Mobile receivers contain the equivalent of a little transmitter to generate this power. This is not the only solution to this problem. Future receiver designs may use dual gate MOS devices, or an RF stage, to minimize the L.O. power requirements.

The balance between conversion gain and square law operation must be optimized for each particular receiver design. This optimization usually favors square law operation. Additional gain, if required, is obtained by the use of a highly linear F.E.T., or large geometry bipolar grounded base, IF amplifier stage. In this manner excellent IM characteristics are maintained while providing the gain required to override the noise existent at the IF input.

"Wrap-Up" Observations

Receiver IM specifications have recently been quite "dynamic" after having been "static" for a number of years. Are further "dynamic" improvements likely? This paper would be incomplete without some observations on the future of the receiver IM problem.

First, the F.E.T. is here to stay as a general purpose mixer. It is already a low cost device, and ways will be found to minimize the application problems so that it can be applied to low cost broadcast receivers as well as high quality vehicular units.

Second, the recent improvement in the IM specification, which came with the introduction of the F.E.T. mixer, is not likely to be soon duplicated. The next 20 db will come more slowly.

Third, IM is not the only interference problem. Transmitter noise, receiver desensitization, and sometimes even transmitter IM at today's levels, would limit system performance long before advantage could be taken of another 20 db IM improvement.

Fourth, the receiver designer needs the help of the application or systems engineer to make further headway in reducing receiver generated IM. Approaches to system design which deemphasize high power, co-located transmitters in favor of the use of lower power and multiple remotely located transmitters and receivers should be encouraged. This "tailoring" of the coverage to the desired areas would lower the signal levels existent in the center of the city and hence help in reducing IM.

Acknowledgment

The author wishes to thank Mr. R.T. Myers for his helpful suggestions and for permission to use material from his paper "Selectivity and the Performance of a Mobile Receiver".

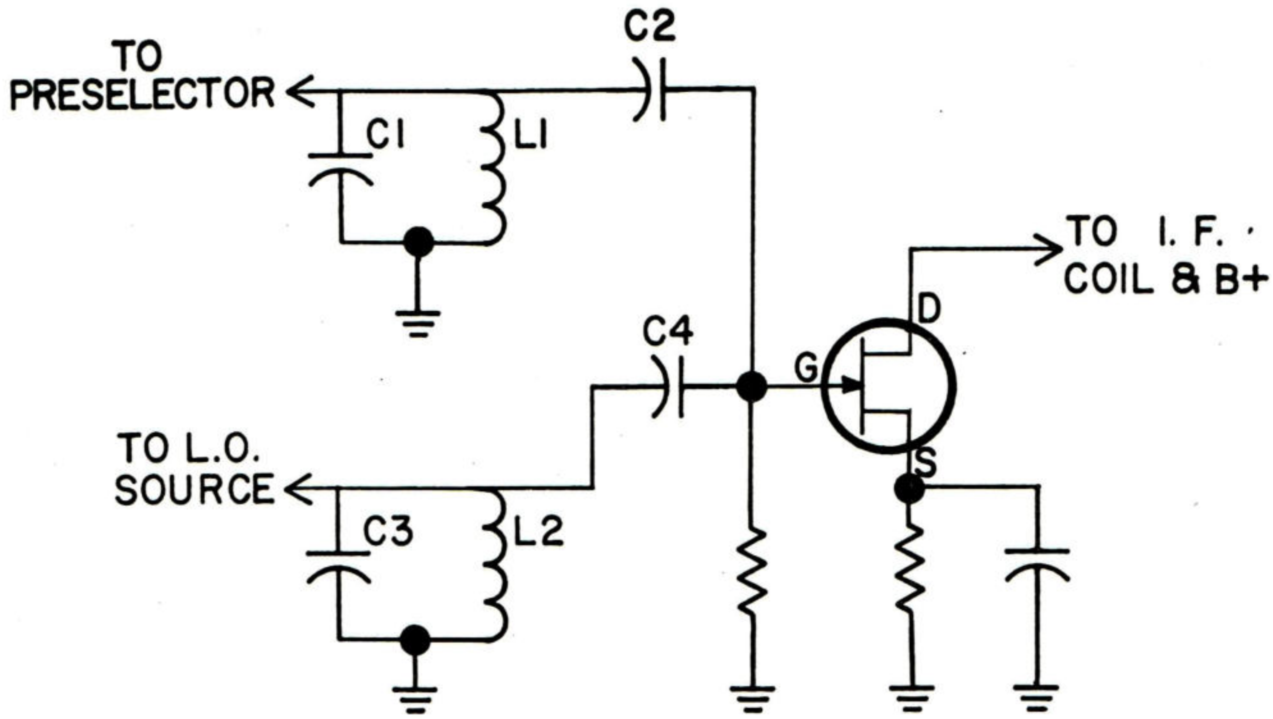

FIGURE 1

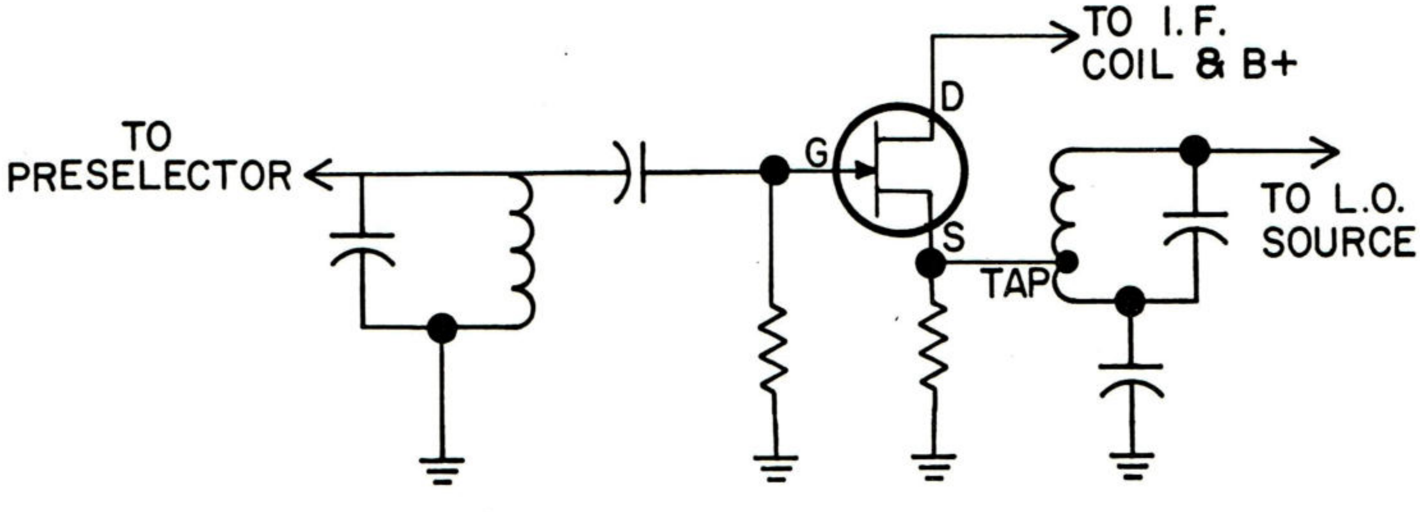

FIGURE 2