FM repeater separation — 20 kHz *Yes*, 15 kHz *No*

Proving the point through VHF FM receiver selectivity measurements

Amateur use of the 2-meter (144-148 MHz) band is now under nationwide scrutiny in an effort to determine whether the channel spacing for FM sections of the band should be set at 15 kHz or 20 kHz. The original 30 kHz spacing was divided, as band use increased, into 15 kHz channels to allow more channels; this division led to increased adjacent channel interference in many areas, which in turn resulted in the current proposal to increase the channel spacing to 20 kHz.

Changing to the 20 kHz spacing will, of course, change the frequencies of some of the channels and change the overall number of repeater "pairs" in the band. Only the technical — not the political or emotional issues implicit in these changes — will be addressed in this article.

In trying to become better informed on the issue and thus establish a more substantial foundation for our decision in northern Colorado, we examined the nature of frequency modulation and its transmission and reception, and then made some measurements on several popular transceivers. We hope this information will be useful to other repeater groups and coordinators as they weigh this issue for themselves.

Our measurements were made to establish the actual performance levels of Amateur ("consumer") and professional ("commercial") receivers, with respect to adjacent channel rejection and variation of sensitivity with transmitter deviation setting.

frequency modulation

One factor that complicates any discussion of FM channel spacing is the varied levels of the understanding from one person to another of just how FM works. The following brief review may help to clarify the subject and shed some light on interpretation of our data.

In FM operation, the radio frequency output spectrum components vary as a function of the modulating (voice) signal amplitude. The resulting signal consists of a varying amplitude carrier and sideband pairs. (In narrow-band FM-only, the first sideband pair and carrier are significant in amplitude.) The amplitude of the carrier and sidebands is described by a mathematical term called a Bessel function of the first kind. The only thing we need to understand here is how much power is spread over how much spectrum, and what determines the signal (spectrum) width. Note that regardless of individual sideband or carrier amplitude, the *total* power of the FM signal is constant.

A simplified FM signal spectrum is illustrated in **fig. 1**. With no modulation applied, a single carrier term at a frequency f_c is visible. As the amplitude of the modulating signal is increased (from zero), a sideband pair displaced $\pm f_m$ from the carrier frequency appears. In this simplified version, we have assumed that a single-tone modulating signal (at frequency f_m) is used. Further increases in modulating signal amplitude cause additional sideband terms (pairs) to appear. At the same time, the amplitude of the carrier decreases. It is worthwhile reiterating that the total power of the FM signal is constant. This power distribution is a function of the modulation index β, which is defined as the ratio of frequency deviation (swing from carrier frequency) to modulating frequency (f_m). For small values of β, the bandwidth occupied by an FM signal is simply $2 \times f_m$. As β increases, more sidebands appear (separated f_m in frequency from each other). A natural further complication is that voice modulation can be considered to consist of many tones of varying

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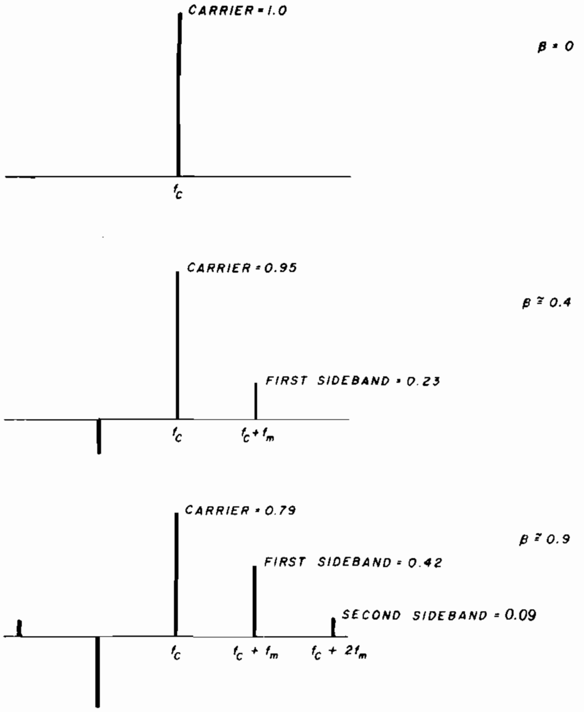


fig. 1. The spectrum distribution of an FM signal is a function of the modulation index β which in turn depends on the amplitude of the modulating (voice) signal. (*A*) the unmodulated carrier, (*B*) at a β of 0.4 a single sideband pair is evident with approximately 1/4 of the amplitude of the *un*modulated carrier, and (*C*) by increasing β to 0.9 a second sideband pair is also apparent. Notice that in both (*B*) and (*C*) the carrier power is reduced from its unmodulated value.

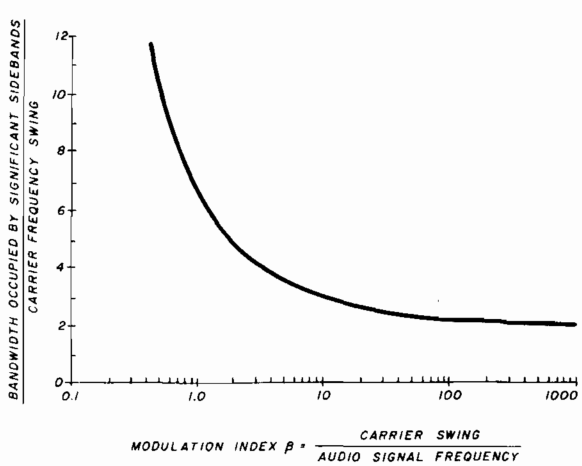


fig. 2. Bandwidth (normalized) versus modulation index β. (Adapted from C.E. Tibbs and G.G. Johnstone, *Frequency Modulation Engineering*, John Wiley & Sons, Inc., New York, as reproduced in *Reference Data for Radio Engineers*, Sixth Edition, Howard W. Sams, Inc., publisher.)

amplitudes. Consequently the total FM signal spectrum is quite complex.

For most VHF FM communications transceivers, this is 5 kHz deviation over 3 kHz maximum voice (modulation) frequency, or a β of 1.7 for high-pitched tones. Notice that lower deviation causes a lower modulation index. Using these figures, we find that 99.99 percent of the power in an FM signal will be contained in about 22 kHz of spectrum.[2] Depending on the assumed voice characteristics, this figure will change, and the older EIA specifications say that 99.99 percent of the power will occupy 19 kHz of spectrum.[3]

In the case of several FM signals, we do not have just narrow carriers that must be separated — we have finite bandwidth modulated signals occupying some spectrum.

For any given modulation frequency, we can decrease the modulation index, and thereby decrease the spectrum occupied, but not always in an exactly linear way. By increasing or decreasing the transmitter deviation control, the power ratios in the various sidebands will change, causing various effects on the radio channel and on the receiver.

effect of transmitter deviation on system performance

The Amateur 2-meter FM system is based on the commercial 5 kHz deviation FM system. System performance depends on the design and adjustment of the transmitters and the receivers used. However, design tradeoffs do exist.

Amateurs often discuss the effect of changing the deviation setting of ham transmitters, both in bandwidth and in effects on the receiver. We examined these two issues and made measurements of consumer gear and test equipment.

Figure 2 shows a curve of normalized significant bandwidth versus modulation index. Most Amateur transmitters adjusted for 5 kHz deviation will operate at a modulation index ranging between 3 and 6, depending on the operator's individual voice characteristics. The curve shows that in this range the curve begins to flatten, and that increasing deviation has less effect on bandwidth than at lower modulation indices. The "rules of thumb" used to roughly describe the bandwidth of FM signals involve a limited range where the slope of this curve can be considered constant. This is because as you decrease transmitter deviation, the modulation index for a given tone rises, changing the relative energy in each sideband.

Figure 3 illustrates the effect of the modulation index on the relative amplitude of FM sideband pairs. Consider the case of a 1 kHz tone, with the operator varying the deviation control on the transmitter. When the deviation control is at zero, all the RF power is contained in the unmodulated carrier. When the deviation rises to 1 kHz, the modulation index equals 1, and we

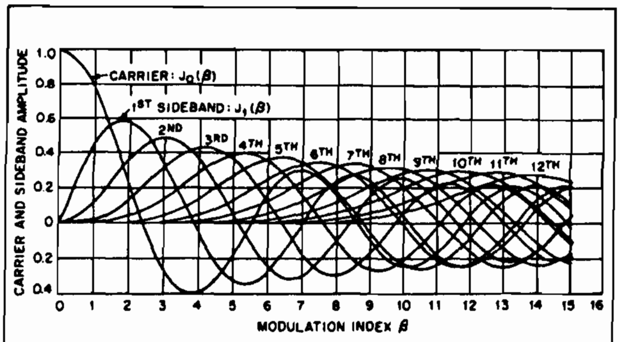


fig. 3. Plot of Bessel function of first kind as a function or argument β. (From P.F. Panter's *Modulation, Noise, and Spectral Analysis*, as reproduced in *Reference Data for Radio Engineers*, Sixth Edition, Howard W. Sams, Inc., publisher.)

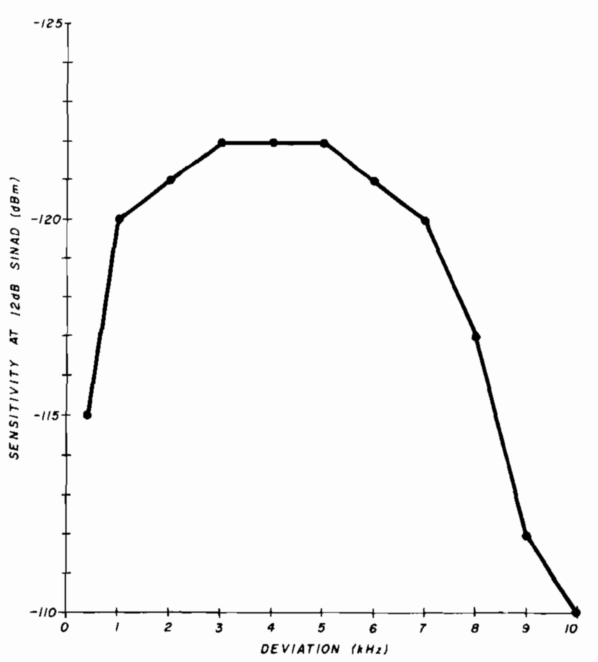


fig. 4. Effect of deviation on sensitivity for a popular Amateur 2-meter transceiver.

see a decrease in carrier power and increases in the first and second sidebands. In fact, there are increases in every sideband, but they are too small to show on this chart. At 1 kHz deviation, we see that the amplitude of the first sidebands has risen to about 0.44 times the original carrier level, and each sideband contains about 19 percent (0.44 squared) of the RF power. Now each of the second sidebands has about 1 percent (0.11 squared) of the RF power, and the carrier has only about 60 percent of the power.

As we raise the deviation to 5 kHz, the modulation index rises to 5 (5 kHz deviation/1 kHz modulation) and we can see that significant energy is now found in almost all sidebands up to the eighth. (Actually, there is energy present in other sidebands, but this chart cannot illustrate that.) The sidebands are spaced at intervals corresponding to the frequency of the modulating tone (1 kHz).

Note also how the modulation index varies with the modulating tone. Consider what would happen if we left the transmitter at 5 kHz deviation, but raised the modulating tone to 2000 Hz. The modulation index would drop to 2.5, and we would have to examine **fig. 3** at this new point to determine the relative amplitude of sidebands at the new index. Here, only the first five sidebands are noticeable — but remember, these sidebands are now 2 kHz apart. The bandwidth of the signal has increased, but it has not doubled.

It should be noted that this discussion of single-tone modulation is a very simplified version of what happens when voice is used to modulate the carrier. The voice is composed of many frequencies, and the composition changes with time. The components of the FM signal are many, and not just the sum of the voice frequencies. Consider a case of just two tones modulating the carrier. There will be carriers with amplitude of the Bessel function (J_0) at the deviation ratio of the first tone, the Bessel function (J_0) of the second tone, and sidebands having lines of all Bessel functions of f_1, f_2, $f_1 + f_2$, $f_1 - f_2$, $f_1 + 3f_2$, $3f_1 + f_2$, and so on.

If you now consider the complexity of the human voice, the problem of mathematically describing the bandwidth becomes unmanageable, at least for this author. For this reason the discussions here are limited to single-tone modulation.

The second aspect of performance affected by the deviation adjustment of the transmitter is how well the receiver is able to demodulate these signals. This is a very easily measured parameter. We checked the perormance of an Amateur receiver when receiving signals at different deviation values. In this test, we used a Hewlett-Packard 8640B signal generator and a SINADder. We measured the sensitivity of the receiver at the 12 dB SINAD point at deviations of 500 Hz, and 1 kHz through 10 kHz deviation in steps of 1 kHz. The results of the test are shown in **fig. 4**.

Notice that maximum sensitivity (−122 dBm at 12 dB SINAD) occurs at 3, 4, and 5 kHz deviation. The sensitivity is not affected by changes in deviation within this range. But above 5 kHz and below 3 kHz deviation, the sensitivity actually decreases. This result contradicts the popular notion that increasing the deviation of a transmitter increases range, and further indicates that reduction of transmitter deviation below 5 kHz does not reduce range (down to no less than 3 kHz, that is).

receiver selectivity

Although the performance of a receiver in rejecting

table 1. Level of isolation from interference experienced on channels separated from 10 to 30 kHz from an adjacent FM source.

Kenwood TW-4000A. On channel signal: −115 dBm, ±3 kHz deviation, 1000 Hz modulation.

interference modulation	30 kHz (dB)	20 kHz (dB)	15 kHz (dB)	10 kHz (dB)
400 Hz (EIA)	86	80	45	0
800 Hz	86	80	40	0
1200 Hz	86	80	33	0
2000 Hz	86	68	25	0

Kenwood TR-7800. On channel signal: −114 dBm, ±3 kHz deviation, 1000 Hz modulation

interference modulation	30 kHz (dB)	20 kHz (dB)	15 kHz (dB)	10 kHz (dB)
400 Hz (EIA)	87	82	65	2
800 Hz	87	83	57	0
1200 Hz	87	83	48	0
2000 Hz	87	79	37	0

Handheld 1. On channel signal: −115 dBm, ±3 kHz deviation, 1000 Hz modulation

interference modulation	30 kHz (dB)	20 kHz (dB)	15 kHz (dB)	10 kHz (dB)
400 Hz (EIA)	69	52	35	0
800 Hz	69	52	34	0
1200 Hz	69	52	30	0
2000 Hz	69	52	25	0

Motorola Syntor-X, 460.425 MHz. On channel signal: −107 dBm, ±3 kHz deviation, 1000 Hz modulation.

interference modulation	30 kHz (dB)	20 kHz (dB)	15 kHz (dB)	10 kHz (dB)
400 Hz (EIA)	93	85	53	13
800 Hz	93	85	53	13
1200 Hz	93	85	50	20
2000 Hz	93	84	43	8

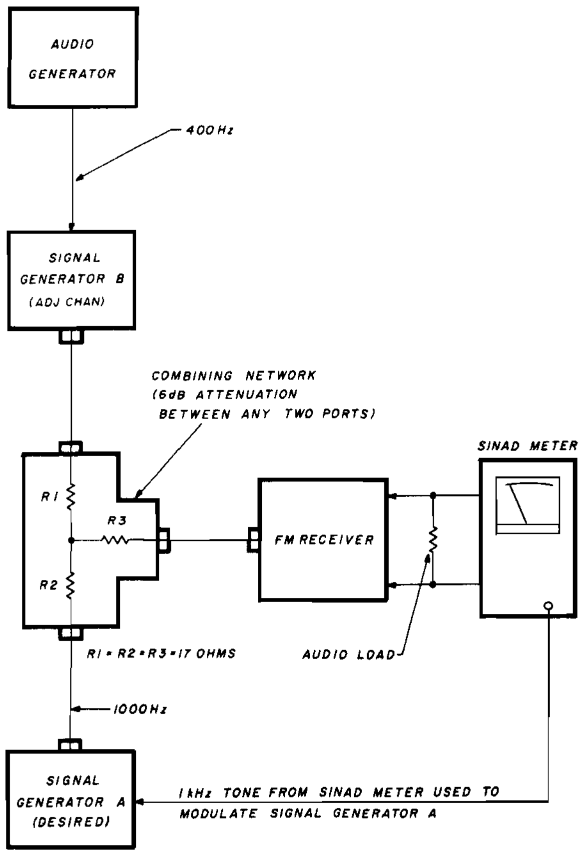


fig. 5. Setup is used to perform the adjacent channel selectivity tests. (From *Standard Radio Communications Manual* by Harold Kinley, © 1985, Prentice-Hall, Englewood Cliffs, N.J. 07632. Reprinted by permission of the publisher.)

off-channel signals is something that cannot be adjusted easily, it is a major element of any radio communications system. A receiver consists of RF, IF, discriminator, and audio sections with most of the selectivity provided by the IF filter section. Intermodulation products and images can be generated in the RF and mixer stages. However, these are not directly related to the problem of adjacent channel interference — the IF filter and discriminator are.

Most FM receivers use crystal or ceramic filters to narrow the IF bandwidth before the signals reach the discriminator, where they are demodulated (back) to audio frequencies. While it would be nice if we could build ideal filters that would pass all signals in the desired passband and completely stop all off-channel signals, this isn't possible. Filters actually have finite passbands with "skirts" that roll off signals more the further away from the channel center frequency they are. The filters are usually specified by their bandwidth at the −6 dB and the −60 dB points; this is also how most ham transceivers are specified for selectivity.

Because the actual performance of the radio depends on this and other, less easily described factors — including discriminator performance — commercial manufacturers have therefore elected to specify their receiver selectivity with a functional test that actually challenges the receiver with a signal in the adjacent channel and measures the result. This is the test we selected and performed to determine selectivity.

The Electronic Industries Association (EIA) has established an adjacent channel rejection test based on the ratio between the on-channel to off-channel signal strengths when the received signal-to-noise and distortion (SINAD) ratio becomes degraded by 3 dB by the adjacent channel signal. This test, part of the RS 204-C test, is performed by mixing the signals from two signal generators and measuring the SINAD of a 1000 Hz tone modulating the on-channel signal at 3 kHz deviation.[4]

The test setup used to perform the selectivity test is shown in **fig. 5**. The on-channel signal level is raised to obtain a 12 dB SINAD, then raised an additional 3 dB. The off-channel signal is modulated at 3 kHz deviation by a 400 Hz tone, and its signal level is raised until the SINAD is degraded back down to 12 dB. Then the ratio of the two signals' strength is calculated in dB. When this measurement is made for both the next higher and the next lower adjacent channels, the lower of the two figures is used.

When the EIA established these tests for selectivity, they also established standards they consider "mini-

the action is at the IF — not the RF — stages

When the problem of adjacent channel interference is examined, attention is focused on the filtering that takes place at the intermediate frequency (IF) stages of the receiver, not at the radio frequency (RF) stages. The reason the IF gets the attention is the very narrow bandwidth required to allow separation of channels within the receiver's radio frequency input bandwidth.

At the RF frequencies, cavity resonators are usually used by repeaters and helical resonators are found in commercial and some consumer receivers. These filters are used to control the receiver's RF bandwidth to improve performance in terms of sensitivity and reduction of out-of-band signal strength. By this filtering, desensitization ("desense") and intermodulation distortion ("intermod") are reduced. However, these filters are typically 50 kHz to several Megahertz wide, and match the input RF stages to the intended operating range of the receiver. These filters are therefore very wide compared to the spacing of the channels (15 or 20 kHz), and will not have any significant filtering effect on those adjacent channels signals.

In the IF amplifier chain, however, the very narrow filters required become practical, due to both the lower frequency used in the IF (typically from 0.455 to 10.7 Megahertz) and the fact that the intermediate frequency does not have to be varied as the radio changes operating frequencies. In the IF stages, crystal filters are most commonly used to obtain very high "Q" (resonant frequency divided by bandwidth), frequency stability and shape factor (bandwidth at −60 dB divided by −6 dB bandwidth). These filters are commonly built with very narrow passbands (12 to 20 kHz wide for FM, and as little as 250 Hertz wide for CW applications). Even these filters do not act as "brick-walls," passing all signals in the passband and completely stopping all signals outside of the passband, since their out-of-band attenuation increases as the off-channel signal moves farther away from the passband. The slope of this attenuation is another factor in the response of a receiver to the adjacent channel rejection test, and together with the filter bandwidth (3 dB bandwidth) is a major factor in determining receiver performance in the test.

The IF filter, then, plays a key part in determining the receiver's response to adjacent channel interference, while the filtering at the RF stages of the receiver has little or no effect on this problem.

mum acceptable" performance. For this test, performed on the adjacent channels, the minimum acceptable standard is 70 dB isolation from the adjacent channel.

In these tests, we used a pair of HP 8640B VHF generators, chosen for their spectrally pure output signals (SSB phase noise below −130 dBc), as the signal sources. The SINAD was measured using a Helper Instruments "SINADder 5."

After the normal RS-204-C tests, we also measured selectivity with different frequencies of modulating tone on the adjacent channel signal. We did this because we believed that the choice of a 3 kHz deviation and a 400 Hz modulation tone may not be realistic for direct comparison with the ham environment, since our DTMF tones and voices contain higher frequency components than 400 Hz, and our transmitters may be adjusted for greater deviation. While we did not change the deviation setting, we made additional measurements with tones of 800, 1200, and 2000 Hz at 3-kHz deviation.

We measured receiver performance in this way, at channel spacings of 10 kHz, 15 kHz, 20 kHz, and 30 kHz. The seven units we tested included one commercial and three consumer mobile transceivers as well as three handhelds.

results with consumer gear

The results with consumer equipment are shown in **figs. 6A, B,** and **C**. Note that at 10 kHz spacing, little or no adjacent channel rejection is evident, and signals within 10 kHz of the channel center frequency are treated as "on-channel" by the receivers. This gives some idea of the bandwidth of each receiver's IF filter.

At 15 kHz separation, the adjacent channel isolation (of an unmodulated carrier) is about 45 to 70 dB. With the introduction of modulation, the interfering signal component is up by as much as 30 dB from ideal.

At 20 kHz, the adjacent channel isolation is about 80 dB, and some adjacent channel modulation is still detected. In most cases, the 20 kHz measurement was within a few dB of the receiver's ultimate rejection (as measured at 30 kHz separation).

At 30 kHz, the adjacent channel isolation is about 85 dB, and there is no change in this figure because of modulation frequency change. This figure shows little variation among the mobile rigs, but the handheld unit shows slightly lower performance (70 dB).(See appendix for further details.)

results with commercial gear

Motorola loaned us a commercial UHF "SYNTOR-X" which tuned to 460 MHz. (A VHF unit was not available.) At UHF, commercial manufacturers and Amateurs use 25-kHz channel spacing, but shop personnel believe that both VHF and UHF radios have similar specs and IF designs. *We believe this test is* *therefore representative of commercial receiver performance at VHF.*

At 10 kHz, the SYNTOR showed slight rejection (see **fig. 7**), about 10 dB, of the interfering signal, indicating a slightly narrower IF filter than found in the consumer gear. Still, the low value means that receiver bandwidth is approximately 15-20 kHz total.

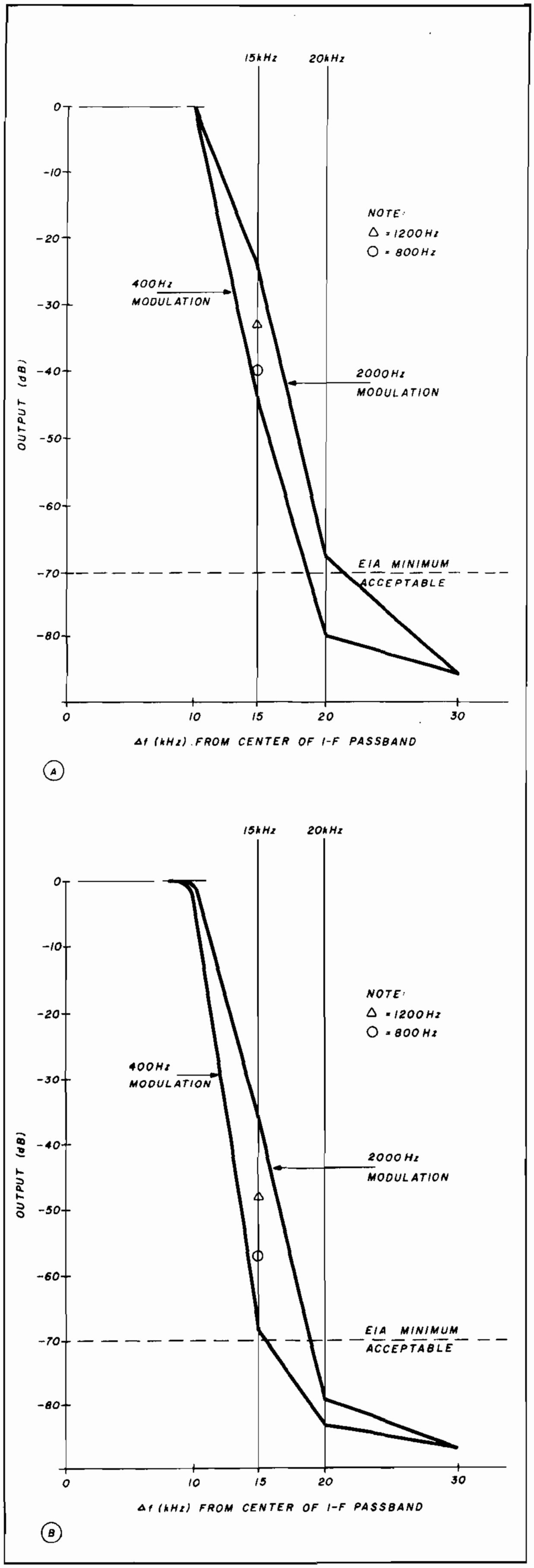
At 15 kHz, the SYNTOR showed 53 dB isolation, which was degraded by 10 dB when the modulating tone was increased to 2000 Hz. This again indicates, as in the case of the consumer gear, that we are on the skirts of the IF filter.

At 20 kHz, the isolation increased to 85 dB and was degraded only 1 dB by increasing the modulating tone to 2000 Hz.

At 30 kHz the SYNTOR showed 93 dB isolation, actually better than its specifications by several dB. Varying the modulating tone made no difference during the measurements.

discussion

Two major results are evident in this data. First, while commercial radio gear offers higher performance



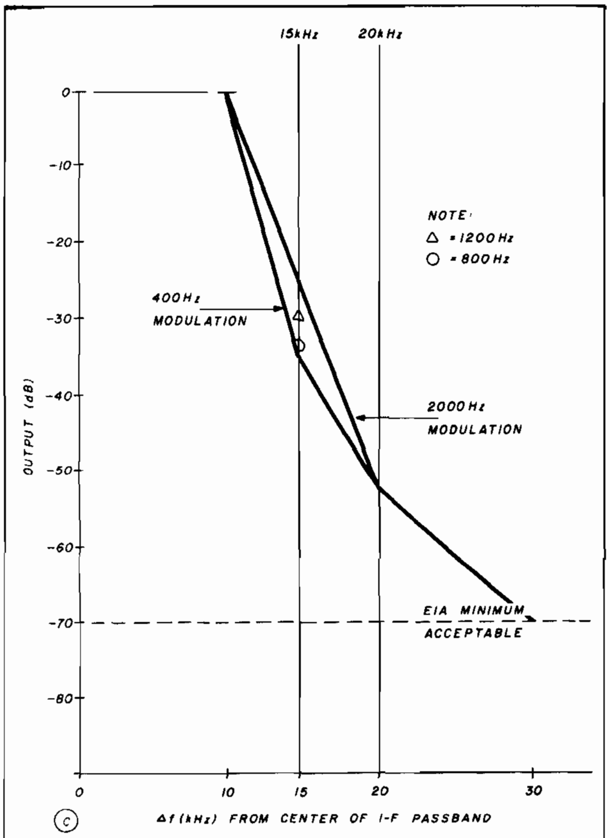


fig. 6. Effect of modulating frequency on selectivity test. Performed on three consumer (Amateur band) transceivers using 3 kHz deviation and 400 Hz (RS-204-C test), 800 Hz, 1200, and 2000 Hz modulation tones. (*A*) Kenwood TW-4000A, (*B*) Kenwood TR-7800, and (*C*) Handheld, HT1.

why do we use FM?

Considering the ongoing discussions of channel spacing and FM bandwidth, one might ask why hams use FM, which occupies such a large bandwidth compared with AM or single sideband (SSB). The answer lies in the improved signal-to-noise ratio (S/N) gained by the demodulator in an FM receiver. If you compare the signal-to-noise ratio of the demodulated signal with the carrier to noise ratio (C/N) of the radio wave before demodulation, you find that above a certain threshold, the demodulated signal shows a significant enhancement in S/N. The measurement of C/N must be made in a bandwidth equivalent to the IF bandwidth of the receiver, but within these constraints, we find an enhancement factor of: $E = 6\beta^2(\beta + 1)$ where β is the modulation index of the FM signal.*

To see how significant this enhancement is, consider the case of a 1000 Hz tone modulating a carrier at 4.5 kHz deviation, and a beta of 4.5, not unusual in Amateur voice systems. In this case, the enhancement is 668 times the carrier to noise ratio, or about 28 dB.

This enhancement, seen only above a threshold C/N, is one reason FM is popular for both commercial broadcasting and communications. Below this threshold, FM actually provides lower S/N than other modes, which is why weak-signal work is seldom done using FM.

*Simon Haykin, *Communications Systems*, John Wiley & Sons, 1983.

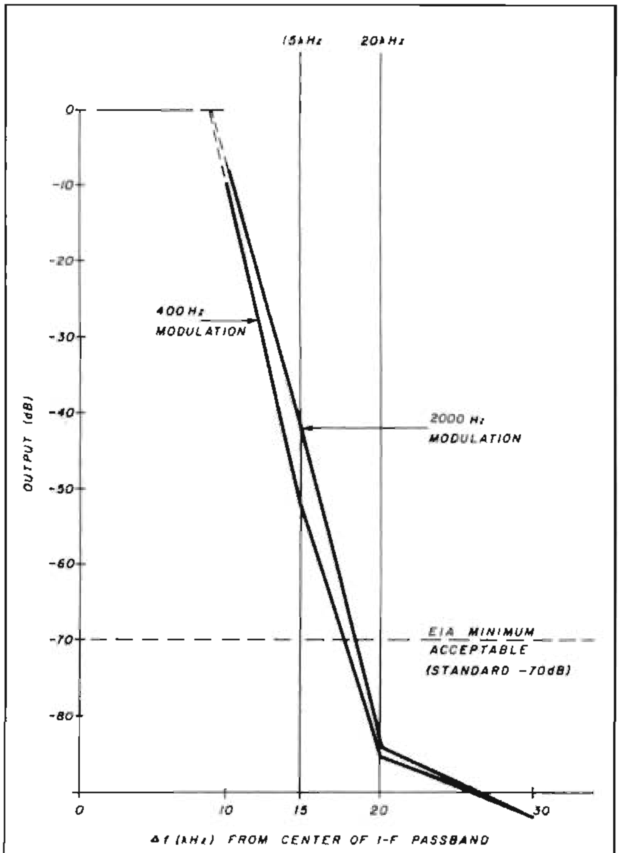


fig. 7. Selectivity test performed on a commercial UHF transceiver (Motorola "SYNTOR-X"). Both the EIA RS-204-C and 2000 Hz tones were used.

than consumer radios, the differences are not particularly large. Secondly, when operated at 15 kHz spacing, all these receivers will exhibit considerably degraded performance when compared to their use at 20 kHz.

On the first result, we wish to note that in the last several years, commercial radio suppliers have changed their radio designs from a relatively limited coverage radio to one that can cover channels separated by many Megahertz. This has been done by reducing filtering at the RF stages and enhancing the IF filters to maintain performance. While this reduction of the *Q* of the RF portion of the receivers does not alter the adjacent channel rejection, the enhancement of the IF stages does. The SYNTOR-X model is capable of covering the entire 450 MHz commercial band without retuning the RF stages, and represents first-class commercial radio equipment, with a price near $2800.

We expected, and found, excellent IF performance in the Motorola gear. The surprise was that the IF performance of the consumer gear *was actually quite similar*, and for most Amateurs the difference would not be significant — this was a surprise to us because we suspected that by adopting commercial standards for Amateur purposes, the interference problem could be solved. But the answer is clearly not that simple.

On the second result, we believe that when these radios are operated with 20 kHz channel spacing, they demonstrate performance which is near their ultimate design goal (as defined by their 30 kHz performance). At 15 kHz spacing, these radios *all* demonstrated very similar degradations in performance, and these degradations amounted to 30 to 40 dB. Furthermore, this degradation was significantly affected by the *bandwidth* of the interfering signal. Considering the conservative settings (3 kHz deviation, 400 Hz modulation) we believe the 15 kHz isolation numbers are generous compared to the Amateur environment, where 4.5 to 6 kHz deviation seems more common.

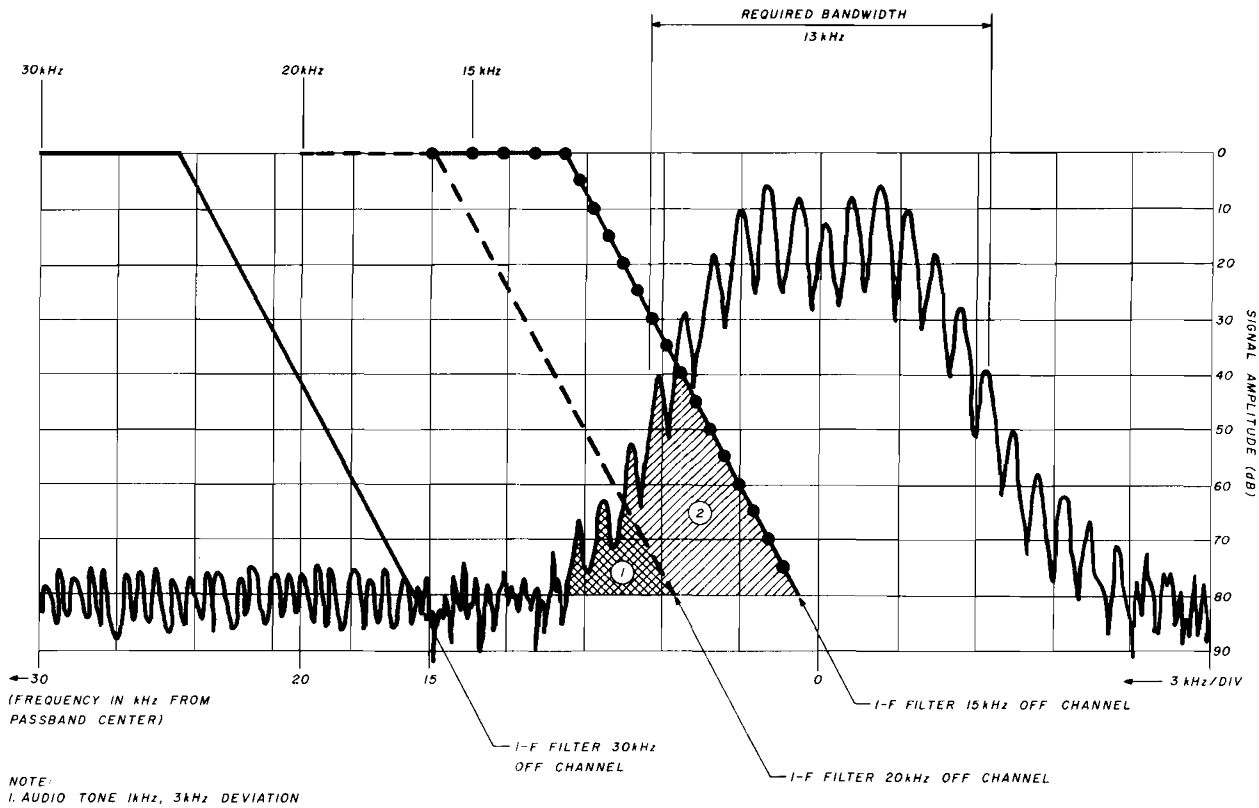


fig. 8. This graph clearly illustrates the need for at least 20 kHz separation between repeater channels.

Finally, when these results are compared with the EIA specification for minimum acceptable adjacent channel rejection, we see that all the receivers failed the test at 15 kHz spacing, and all but the handheld unit passed the test at 20 kHz spacing (see appendix).

The mechanism for this adjacent channel interference depends on both the nature of FM itself and the design of the receiver IF filters. What we believe is happening is shown in **fig. 8**. In this diagram, we have illustrated the shape of the FM signal resulting from a 1 kHz tone modulating a transmitter at 3 kHz deviation. First note the zone called "required bandwidth," which is the legendary 13 kHz wide. This zone shows the sidebands down to -40 dB from the carrier's unmodulated level. It is evident that some remaining sidebands are present, down to the -80 dB level, with the noise floor of the test instrument, an HP8568B spectrum analyzer.

On the left of the diagram, we have illustrated the filter shapes of typical consumer receivers spaced 30, 20, and 15 kHz away from the carrier frequency of the signal. Notice that at 30 kHz spacing, no power from the signal is entering the receiver's passband, down to the resolution of the instrument. At 20 kHz spacing, the edge of the receiver passband intersects a small portion of the signal, indicated by the area labeled *1*. At 15 kHz spacing, more of the signal is in the receiver passband, as noted by areas *1* and *2*. While it would be difficult to quantify the difference from this diagram, our tests have shown that this difference is in the range of 30 to 45 dB. If the more liberal EIA RS-204-C test were performed, using a 400 Hz tone, the receivers would pass at 20 kHz separation and *fail* at 15 kHz spacing.

We hope this report is informative and will be useful as you make your decisions on coordinating repeaters, both in frequency and geographical separation.

references

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