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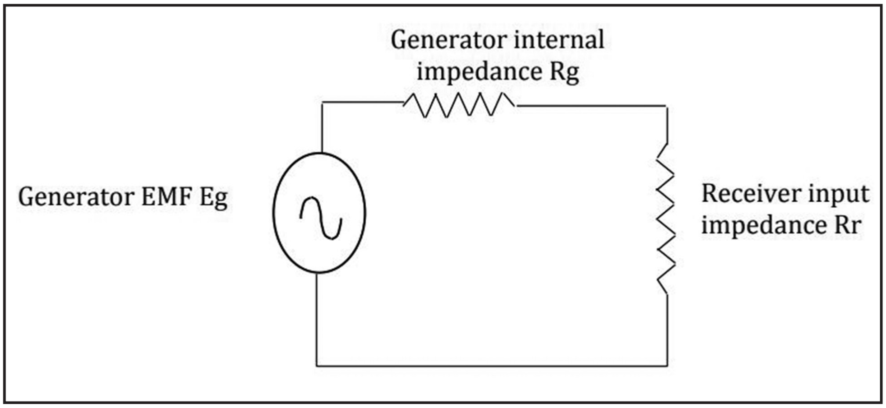
A Call for Enhanced Transmitter Purity

At the dawn of radio, transmitters were mainly spark technology, and a spark signal covered a lot of spectrum. When amateurs reached the "very short waves" of 200 meters with relatively modest antennas that in many cases looked something like maybe 10 Ω in series with 250 pF, one could expect a signal about 60 kHz wide at 3 dB and 600 kHz wide at 20 dB down. After the 1927 International Radio Telegraph Convention — a forerunner of today's ITU World Radiocommunication Conference — not only did amateurs get harmonically related bands but spark was to be phased out as quickly as possible, with no new installations in land or fixed stations after January 1, 1935, no new installations in ships and aircraft after January 1, 1930, unless the input power to the supply transformer was less than 300 W, and no spark transmissions on any frequency after January 1, 1940, except for ship installations with less than 300 W input.

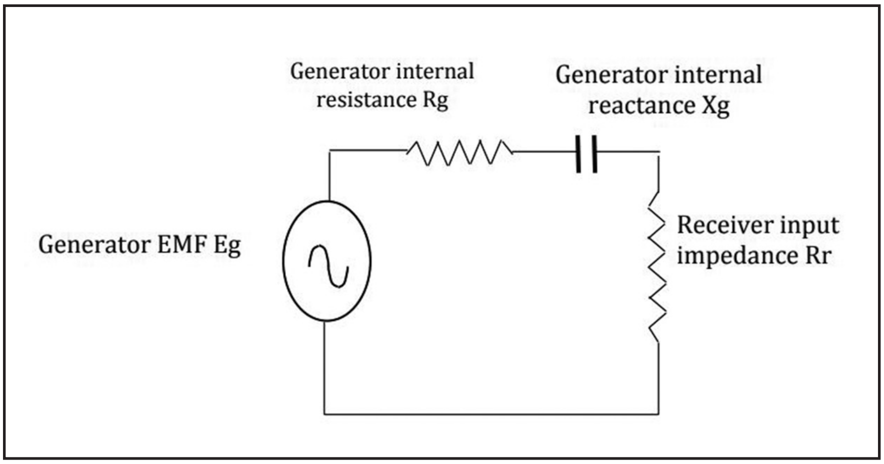
This has led to an interesting anomaly in the *Radio Regulations* even today: Article 3.15 states "The use of damped wave emissions is forbidden in all stations" while Article 4.9 states "No provision of these Regulations prevents the use by a station in distress, or by a station providing assistance to it, of any means of radiocommunication at its disposal to attract attention, make known the condition and location of the station in distress, and obtain or provide assistance."

As far as UK amateurs were concerned, spark was banned after 1924, while the use of spark transmitters by US radio amateurs was formally disallowed by the October 28, 1927 regulations issued by the Department of Commerce, Radio Division.

There were narrow-band transmissions, such as those from the Alexanderson high frequency alternator or the Poulsen Arc, but they were on much lower frequencies than those used by amateurs.



A 5-W SEO transmitter from the 1929 ***ARRL Handbook.***



Crystal control on 10 meters — G2OD in 1928.

Technology Advances

The move to vacuum tube transmitters led to much narrower signals. A crystal-controlled transmitter was described in *QST* in 1924, but there were a large number of SEO (self-excited oscillator) transmitters in the 1920s (see Figure 1). Although occupying less bandwidth than spark emissions, they were not "clean" by today's standards. Keying an oscillator without chirp or key clicks is not always easy to achieve. The power oscillator of Figure 1 even needed very careful adjustment to avoid frequency changes caused by the antenna swaying in the wind, while frequency drift as the tube and even other components heated was normal. So, the typical CW signal might be 1 or 2 kHz wide and a telephony signal some 20 or so kHz at the –20 dB points.

The Spread of Crystal Control

These problems led to the majority of amateur HF transmitters by the early 1930s being crystal controlled, although if the oscillator was keyed, chirp and sometimes slow rise times could be problematic and often were related to the crystal. A slightly earlier approach is seen in Figure 2, with doublers on the lower shelf. So, a typical amateur HF CW transmitter of the time would have a 3.5 or 7-MHz crystal oscillator, a frequency doubler stage or even two — often using twin triodes such as a 6A6 — and a PA stage. Frequency doublers were popular because at that time the HF amateur bands were 1.7, 3.5, 7, 14, and 28 MHz, and crystals of fundamental frequency at or above 14

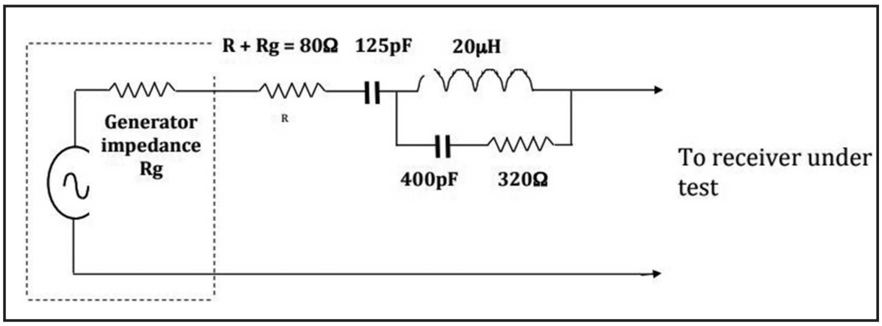
MHz were very expensive and fragile)

Before World War II, amateur radio HF telephony was almost 100% amplitude modulated (AM) double sideband, although there was some experimentation with SSB — initially known as SSBSC — single-sideband, suppressed carrier — following the publication in 1933 and 1934 in *R9* magazine by W6DEI of three articles dealing with SSB. About a half-dozen US amateurs were using SSB on 20 meters in the 1930s.

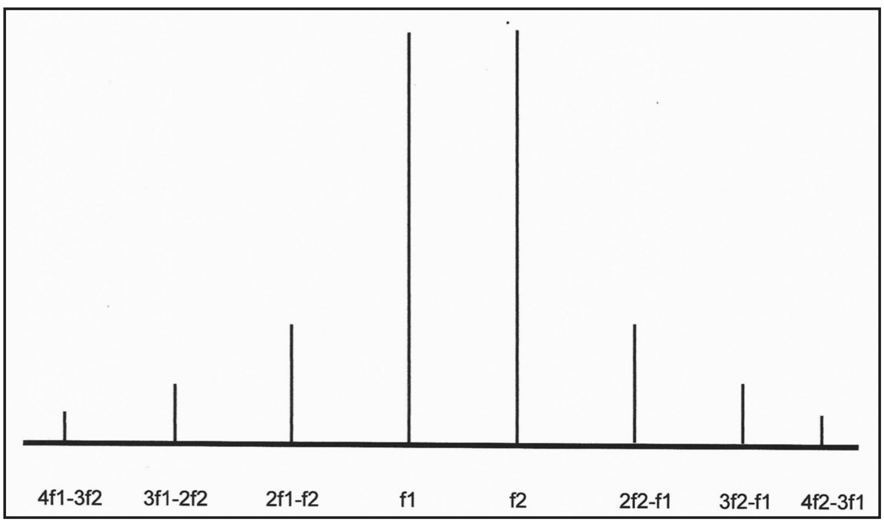
Overmodulation of AM transmitters was not uncommon, leading to interference on adjacent frequencies from what was generally known as "splatter," which was aggravated when speech clipping was used to increase the average power by reducing the peak-to-average ratio. This could be mitigated to some extent by good low-pass filtering following the speech clipper. Another problem in the days of free-running power oscillators was the amount of frequency modulation that occurred when AM was applied, even when buffer stages existed between the modulated final stage and the oscillator. This led to a broadening of the signal.

Post-World War II, HF transmitters typically were crystal controlled until about the late 1940s or early 1950s, when VFOs became popular. WW II surplus transmitters such the BC-610 (a militarized Hallicrafters HT-4 amateur transmitter) and the RCA ET-4336 provided a choice of crystal frequencies, and the RCA transmitter had an optional plug in VFO. The number of home-brew VFO-controlled transmitters still led to a number of drifting, chirping, and clicky signals.

In the late 1940s, television allocations in the lower VHF spectrum led to many problems for amateurs. Some were caused by inadequate harmonic suppression in the home-built and often largely unshielded transmitters, but deficiencies in TV receiver design and manufacture were by no means unknown, including the remarkably stupid practice of having a 3- or 4-MHz wide IF centered with an amateur or HF broadcast band. TV interference (TVI) problems led to the disappearance of many amateurs from the air during viewing hours, and, as these hours increased, major changes in transmitter design came about, including complete shielding, the use of pi-networks in power amplifier tank circuits, wide-band couplers in multiplier stages, and low-pass filters in coaxial coupling and feed lines. Some mitigation was obtained by the use of FM or phase modulation on the HF bands: This did not help reduce problems caused by harmonic radiation, but it did with direct demodulation in audio or video stages.



Linear transfer characteristic and the practical case.



The spectrum resulting from applying two signals to a non-linear stage.

Double-sideband AM signals were generally produced by modulating the final amplifier stage, typically running in class C. This could be high-level plate (and screen in tetrodes) modulated or, less common, an efficiency modulated stage using grid or screen grid modulation. Almost unknown in amateur practice was the use of low-level modulation followed by a linear amplifier.

By the mid-1950s, the widespread use of AM on the HF bands was leading to interference difficulties, so the ability of SSB to effectively narrow telephony signals to an occupied bandwidth of about 3 kHz plus an effective 4.8 dB power increase made the use of SSB attractive. Although circuit complexity and requirements were greater than with conventional double-sideband AM, the reduction in size, weight, and equipment cost that came by eliminating a high-power modulator made the mode increasingly popular.

There were three basic methods of SSB generation. The two basic ones were the filter method and the phasing method. Phasing had the advantage of lower cost, but it lacked long-term stability of sideband suppression, and it was not as capable as the filter method in providing a high degree of unwanted sideband suppression. The filter method was more expensive, although enterprising amateurs built filters on various frequencies using pot core inductors and military surplus crystals. Also popular were professional mechanical filters at 455 kHz and HF filters at various frequencies.

The third method of SSB generation was quite complicated, involving two channels with low-pass filters and balanced modulators within the speech passband. This technique never proved popular and suffered to some extent from instability in terms of component drift.

Production of SSB using digital signal processing techniques offers many advantages over the heritage approaches. Once produced, though, an SSB signal requires linear amplification.

Transfer Characteristics and Distortion

An ideal linear amplifier will have an output power directly proportional to the

Table 1 — IMD performance of the last tube-generation transceivers. Measurements are in dB.

Model	Input	3rd order	5th order	7th order
T-4XC	200 W	–36	–43	<–55
TS-820	200 W	–38	–46	No data
FT-101B	180 W	–35	–33	<–55
FT-101ZD	180 W	–38	–48	–58
TS-830	110 W	–33	–52	–65
FT-102	150 W	–43	–43	–57

Table 2 — IMD performance of early solid-state transceivers. Measurements are in dB. Note the very good performance of the IC-701, which was not carried forward in later models. ARRL product reviews did not include 9th-order IMD products until the mid-1980s.

Year	Model	Output	3rd-order	5th-order	7th-order	9th-order
1979	TR7	100 W	–34	–35	–39	No data
1979	IC-701	200 W	–46	–48	–56	No data
1979	Swan 100MX	100 W	–37	–39	–55	No data
1981	Astro 102 BX	108 W	–28	–40	–45	No data
1986	IC-735	120 W	–33	–39	–42	–47
1996	IC-706	120 W	–33	–31	–38	–45
1997	IC-756	100 W	–25	–34	–38	–42

Table 3 — IMD performance of some solid-state transceivers since 2014. Measurements are in dB.

Year	Model Output	PEP order	3rd- order	5th- order	7th- order	9th-
2014	Hilberling PT-8000	200 W	–35	–48	–54	–59
2015	ANAN-100D - ON	100 W	–52	–54	>–60	>–60
	ANAN-100D - OFF	100 W	–38	–38	–44	–52
2016	K3S	100 W	–35	–35	–48	–62
2016	Icom 7300	100 W	–42	–38	–46	–57
2016	IC-7851	200 W	–36	–52	–49	–61
2017	FLEX 6500	100 W	–39	–42	–49	–55
2018	IC-7610	100 W	–41	–37	–46	–61
2018	ANAN-8000DLE -ON	200 W	–54	–64	–60	–60
	ANAN-8000DLE - OFF	200 W	–30	–38	–47	–54
2019	TS-890S	100 W	–42	–42	–51	–62
2019	FT-DX101D	100 W	–42	–41	–48	–58

Notes on Table 3

1. In the case of the ANAN 100D and 8000DLE, 'ON' and 'OFF' refer to the state of the 'Pure Signal' pre-distortion facility
2. The RSGB review of the FT**DX**101D produced different numbers, generally worse than the QST review by up to 6 dB, and in the case of 160m, only -22 dB for the 3rd order.

Unfortunately, because different reviewers have different transceivers to test, it isn't really practicable to ship the same unit around the world. Unless it were possible to test a number of units, ideally from different production batches, review figures are of one piece of equipment, which may or may not be typical. The author has seen a run of over 100 nominally identical transmitters in which for the same 3rd order IMD performance, there was a 3 dB spread in output power.

input power, so that if 10 W input gave 100 W output, 20 W would give 200 W, 40 W would give 400 W, and so on. But there are limits to this when the amplifier output does not increase in proportion — and eventually the output will limit (see Figure 3). This is called gain compression.

Under these circumstances, applying a signal containing multiple frequencies and amplitudes will be distorted. Applying two frequencies produces a spectrum such as that seen in Figure 4, with added side frequencies, known as intermodulation products. The order of these products is the sum of the coefficients of the two frequencies involved, so $2f_1 – f_2$ is a 3rd order product, $3f_1 – 2f_2$ is a 5th order product, and so on.

Intermodulation products are formed when the transfer characteristic is not completely linear, which it never is with active devices. It can be very good when techniques such as negative feedback, polar — or Cartesian — loop, pre-distortion or suitable DSP feedback techniques are used. Until recently, other than analog negative feedback, these techniques had not been widely applied in commercial amateur equipment.

The problem with intermodulation products is the effect they have on adjacent signals by producing splatter. Historically, tube transmitters tended to be better in this respect than solid-state transmitters. This can be shown mathematically, for those so inclined. The tube case is evaluated from $(\sin f_1 + \sin f_2)3/2$, while the bipolar transistor case is $\ln(\sin f_1 + \sin f_2)$. This gives appreciable high-order products. This can be alleviated to a great extent by suitably applied negative feedback, although that can have its own problems, one of which is that when distortion starts, it tends to produce results worse than without feedback[1].

For a long time, SSB transmitters have been tested by feeding two non-harmonically related audio tones into the input. Results can vary, depending on the tone spacing. For example, very narrow tone spacing can produce considerably worse results, because the power supply is modulated by the current variation at the difference frequency of the two tones. A further difference is how the results are expressed — with intermodulation distortion (IMD) referred to the PEP or to the level of each tone. The results differ by 6 dB, appearing better when referred to the PEP, which is 6 dB greater than the power of each tone. ARRL measures IMD with reference to PEP. Other professional standards require measurement with respect to the power of each tone. As long as the reference is stated, either is valid.

A more useful method is one used in the 1950s with analog FDM (frequency division multiplex) telephone systems, where wide-band noise with a notch in the middle of the audio spectrum was used. The level of the noise in the notch at the measurement device gives a very good measure of the real in-service IMD. For SDR equipment, it is probably the only realistic measurement method, especially when testing receivers.

An analysis of more than 150 ARRL product reviews since the early 1970s shows 3rd-order products ranging from 24 dB below PEP (Yaesu FT-980) to better than 50 dB below for transmitters using pre-distortion. It should be noted, though, that 7th-order products are of the same order as those seen in the last generation tube PA equipment. These transceivers showed up very well in comparison to many early solid-state equipment (see Table 1).

The Effect of Linear Amplifiers

Transceiver IMD performance is not the whole story, because when a linear amplifier is introduced, there can be appreciable modification of the IMD products in the output of the combination, such as cancellation of some products and augmentation of others. This can be especially so if there is AM-PM conversion, caused, for example, by internal capacitance variation with the RF voltage swing.

Other Effects from "Dirty" Transmitters

Where a number of stations are in close proximity, such as during multioperator multi-transmitter operation or a DXpedition, wideband noise from transmitters, even those operating on other bands, can be a problem. The architecture of modern solid-state transceiver tends not to have the multiplicity of tuned circuits that existed in earlier transceivers and transmitters of the tube era, with the later gear using wide-band amplifiers and wide-bandwidth band-pass and low-pass filters.

In the days of HF maritime radiotelephone calls, where full duplex was required, some transmitters even had band-stop filters for the relevant receive band, and maximum separation between receive and transmit antennas. Filters capable of handling high power are not generally low in price or size. A perhaps extreme example of separation was seen in the 1936 Cunard White Star Liner RMS *Queen Mary* (GBTT), where the receiver room, completely shielded in copper, was 400 feet from the remotely controlled transmitter room.

Conclusion

It is interesting and encouraging that some of the latest amateur HF transmitting equipment is showing major improvement in the ability to generate a clean signal. One might say that it's about time. Regrettably, however, while the effects of interference from other transmitters is likely to further reduce in the future, the interference from the multiplicity of non-compliant digital devices is unlikely to drop, especially given the complacent attitude of some radio administrations.

Notes

1 "Second thoughts on radio theory," Cathode Ray, *Wireless World*, London, 1955, or "Negative Feedback," Cathode

Spectral Purity of HF Transmitters

We can all agree that overall receiver performance has improved greatly in the 21st century. Thanks to *QST* product reviews, manufacturers have developed a friendly rivalry to compete for "the best radio." This has resulted in higher dynamic range numbers, matching the needs of the most serious contester or DXer. Even some of today's entry-level transceivers have significantly better receiver performance than the best transceivers of the 20th century. That may be a good thing, but even the best-performing receivers cannot greatly reduce or eliminate undesired signal elements of a transmitted signal. A few years ago in *QST*, we cited the need for improved transmit quality. Many amateur radio equipment manufacturers responded favorably, improving their products with better transmit performance.

The key transmit signal parameters that the ARRL Lab closely scrutinizes are spectral content; CW rise and fall times, with the resulting CW keying sidebands, and transmit amplitude and phase noise levels, as measured from a transmitted continuous wave. For example, a quick rise-and-fall time (less than 2 milliseconds) will result in wider keying sidebands. Little to no rise and/or fall time will result in very wide keying sidebands. Such abrupt transmitted waveforms introduce key clicks above and below the desired transmitted frequency. Remember, the FCC requires amateur transmitters to be free of key clicks. The ARRL Lab will send a manufacturer back to the drawing board, if we observe key clicks and resulting wide keying sidebands. We also alert the manufacturer if a transmitter exhibits high transmit inter-modulation distortion (IMD) products in voice mode. It must be noted that IMD products are transmitted above and below the desired tuned frequency. That means while transmitting on upper sideband, 3rd, 5th, 7th, 9th order (and higher) intermodulation products are also transmitted where the suppressed opposite sideband would be. Monitoring ALC while speaking is necessary. Exceeding ALC upon transmitting increases the likelihood of increased IMD products dramatically, making the user unpopular on neighboring frequencies. Transmit phase and amplitude noise needs to be as low as possible. Transmitted noise, if strong enough, has the ability to raise the noise floor above and below the tuned frequency. It has been observed that all undesired transmit effects have been gradually reduced, thanks to the work of the ARRL Laboratory and the manufacturers who strive to advance the radio art. We will always be vigilant in reminding manufacturers to do better, when warranted. — *Bob Allison, WB1GCM, ARRL Assistant Laboratory Manager*