IMD in Transmitters

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IMD

What is it?

Intermodulation distortion is the creation of signals which are the result of mixing intended (and sometimes unintended) signals with each other. In SSB this causes many new signals because the voice contains many intended signals which mix producing new but unwanted signals at frequencies between the modulating signals and outside of them (adjacent to the intended bandwidth of the modulation signal). Upon reception, this sounds distorted, producing a “splatter” effect, where signals are being transmitted around and beyond the intended bandwidth of the intended modulation. This effect is obvious when watching a waterfall display as well as when listening to a signal on the air. In crowded spectrum conditions, in addition to distortion it also causes interference.

It is generally impossible to completely eliminate IMD. Even the very best radios have at least some of it. So, the offense caused by IMD is a matter of degree. Modern radios and amplifiers can produce large amounts of it and can be quite noticeable and cause annoyance by occupying unnecessary spectrum. As these signals proliferate – especially recently – the displeasure has raised discussions about what is acceptable and to that end the Clean Signal Initiative[1] has arisen, giving guidance in hopes of limiting distortion on the air

Everything is a Mixer

One of the primary sources of intermodulation is a mixer. So, if we fix (or at least minimize) the IMD from our mixer(s), then we have a clean signal, yes? No. Many components and subsystems in communication can contribute to IMD. This is primarily because many things act like mixers. Examples of mixers are Mixers, Detectors, Amplifiers, Switches, A/D converters, samplers, rusty or corroded connections, and ferrous materials in coax connectors. For the purposes of this discussion, I focus on conventional mixers and amplifiers because they are the primary source of IMD in transmitter chains (and receiver chains too). Note that just like transmitter induced IMD there is also receiver induced IMD. So, don’t be quick to blame your neighbor from whom you hear and see loads of IMD. Some of it can be your own receiver. I will mention a test for that at the end.

You might ask, why is an amplifier a source of IMD? Simply put, no amplifier is perfectly linear. Most circuits have some to a lot of negative feedback to reduce the non-linearity, but once the device is pushed into a high power range it will naturally compress, and that is a non-linearity that results in distortion (harmonic and inter-mod). Also, many power amplifiers are run in class B or some fudgy thing called “AB”. If the bias is properly adjusted, B and AB can compete with Class A while consuming far less DC power and making far less heat. However, they are not always adjusted that well, and the required optimum bias settings will drift with temperature.

Unless things are very carefully controlled, such as bias stability over power and temperature, the linearity will deteriorate. The lowest distortion comes from a Push-Pull amplifier running Class AB or A with lots of negative feedback, and well below the power levels that enter into compression. And, each side of the push pull have to be individually adjusted to provide the lowest distortion[2].

Lower power amplifiers (often called “Gain Blocks”) are usually single ended, run Class A, and are kept well below their saturation knee to avoid compression. But in amateur radio products, even these low level amplifiers might be operated with parameters to achieve high gain and output level rather than lowest distortion.

How is IMD Manifest?

IMD in an RF signal is apparent mixing of any (and usually every) pair of signals. When you look at a spectrum of a USB modulated signal of say 28.1 MHz (typical IF for some VHF Transverters), you will see any particular tone as 28.1 MHz plus the modulating frequency. If that is 700Hz, then 28.1007 MHz will appear on the analyzer. Except for harmonic distortions and internal LO mixing products in the transmitter, the hopefully clean output of the transmitter is just one frequency. Without other frequencies present, there is no IMD, and any distortion is harmonics of 28.1007 MHz such as 56.2014MHz. For the moment I will ignore harmonics, but they will become important shortly.

When a second tone is added to the modulation in the Transmitter such as 2 KHz, then in the analyzer we should see two signals, namely 28.1007 (call this IF_1) and 28.1020 (call this IF_2), and NO others (except their harmonics). So, in and around the typical modulation passband of about 3 kHz we have two and only two signals. Others are harmonics way up at 56, 84 MHz and so on and can be reduced to nearly zero with a simple low pass filter. When I put this signal into the IF port of a standard high quality mixer along with a 194 MHz LO to produce a USB signal at 222.100 MHz, how come I see some other signals above and below the two desired tones, now at 222.1007 and 222.1020? (please ignore the lower peaks between the 8 larger ones)

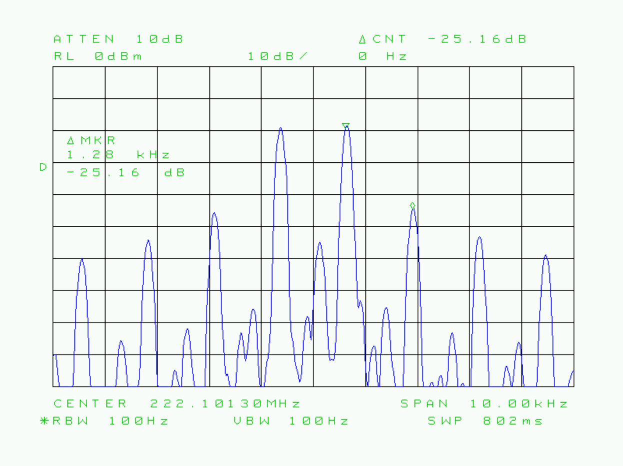

Figure 1. Spectrum of a mixer output (adjusted levels to emphasize the intermod products)

Harmonics Matter

The mixing products of those two tones are their difference 222.1020 – 222.1007 = 13 kHz and their sum 222.1020 +222.1007 = 444.2027 MHz. Both of these are way far away from the area inside and nearby the 222.1 USB receive bandwidth. So where what is generating the very close in “comb” of signals spaced 1.3 kHz apart? Here is where the harmonics come in. Mixers generate not only LO + IF and LO – IF (generally what we want) but also 2xLO +IF, 2xLO – IF, 2xLO + 2xIF, 2xLO-2xIF, and so on.

One of the mixing products is a desired output (LO+IF$_1$) and another is a harmonic of the other desired output 2 x (LO+IF$_2$). Although they are written as LO+IF, they are just two frequencies 13 kHz apart in the 222 MHz band. Now, mixers take sums and differences and multiples. In this case is will be a difference between the first desired output and the second harmonic of the other desired output.

In our case

First desired output is (LO+F$_1$) = 194 + 28.1007 = 222.1007 MHz

Second desired output harmonic is

2 x (LO+ IF$_2$) = (2xLO+2xIF$_2$) is 2x194 + 2*28.1020 = 388+56.2040 = 444.2040 MHz

444.2040 – 222.1007 = <u>222.1033</u>

This mixer product is inside the receiver passband. It is 1300 Hz above the IF$_2$ (2 kHz) modulation tone (222.1020 + 0.0013 MHz = 222.1033 MHz). The difference between the two desired tones is also 1300 Hz. Similar arithmetic will end up with a comb of tones spaced 1.3 kHz apart below and above the two original tones in the spectrum around the passband. As the multiple of 1300 Hz increases the power decreases.

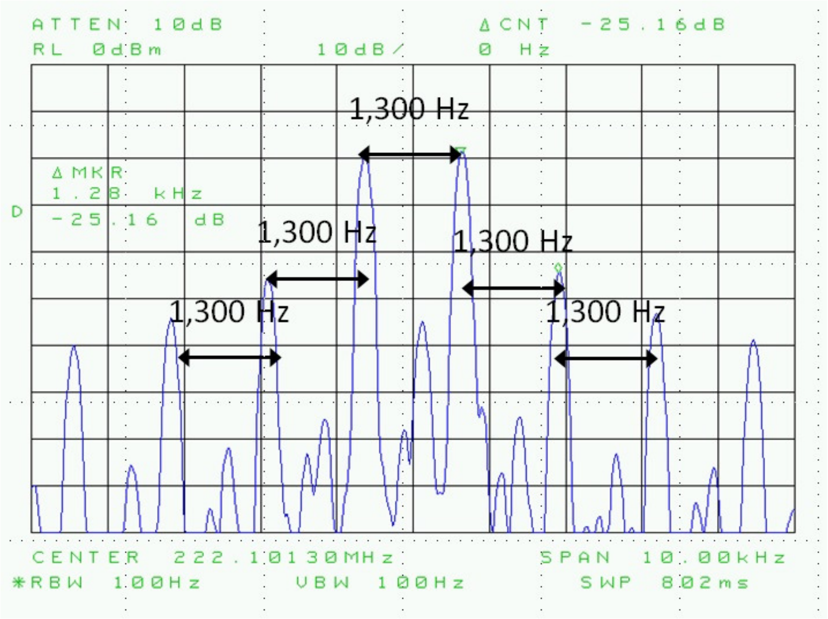

Figure 2. The spacing of IMD products is multiples of the difference between the two tones

IMD is measured by taking the signal level of one of the desired tones, and measuring the difference in power to the first non-desired tone (in our example, at 222.1033 MHz). The difference is negative dB as compared to the “carrier” which is in fact a tone in the modulation. Two examples are shown in Figure 3. The greater this difference (the larger the negative number) the better, as larger negative numbers indicate lower unwanted distortion products. Therefore an IMD might read “-25dBc” which means that the first undesired IMD product is 25 dB below the desired signal. The military and some communications engineers use this as the IMD value. The ARRL prefers to “add” 6 dB to this number, actually making the negative number more negative. Therefore in our example the ARRL Labs would report “-31 dBc” instead of -26 dBc IMD. One idea is that these tones represent a signal some 6 dB greater than PEP during voice modulation. I will use the measured value, and the reader may adjust as appropriate. To further simplify, some publications don’t use the negative sign and simply report “IMD is 31dBc” or “IMD is 31dB”. Note, the “3rd order intercept” IMD product of an amplifier, (although also quantifying IMD) is a different measure, showing the relationship between the amount of distortion and the output power. I did not produce or report those values.

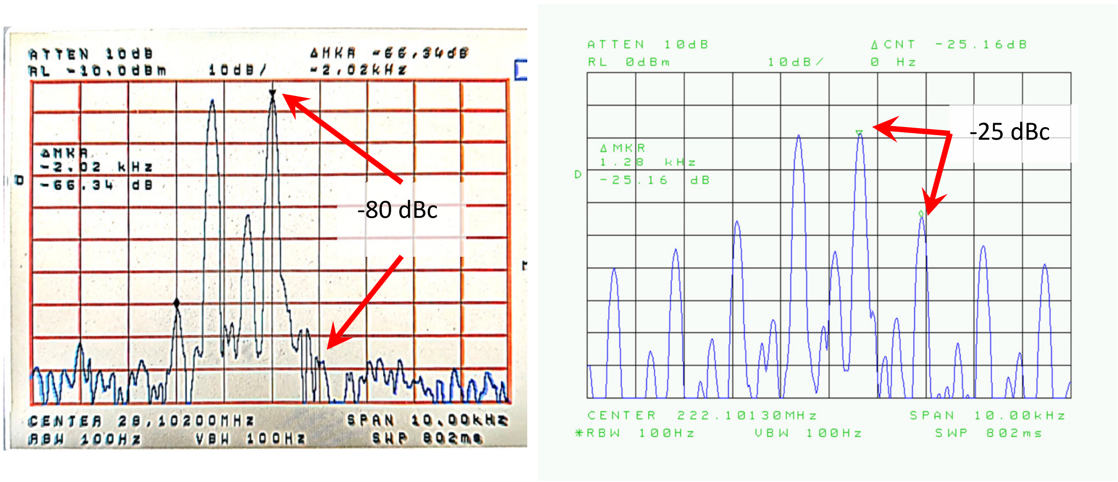

Figure 3. IMD is measured from an original tone peak to the first distortion peak

From the above analysis we can see that harmonics in the mixer are contributing factors in generation of IMD. It has been observed during the development of high power transmitters, especially where excessive IMD is very detrimental to performance of a communication channel, such as broadcast and communications systems, attention to termination of harmonics is helpful and sometimes critical to achieving success.

This is a well-known situation in broadcast transmitters where the simple addition of low pass or band pass filters (to assure compliance of low harmonic radiation is met) has caused significant IMD. The problem arises when the harmonics are reflected by the filter back into the power amplifier, which (acting as a mixer) produces significant IMD in the normal broadcast bandwidth. Although harmonic radiation compliance is met by adding the low pass filter, the quality of the signal is compromised. Amateurs commonly use low pass filters on their power amplifiers to achieve low harmonic and spurious emission, and rightly so, as compliance with interference regulations demand it. But, just as with broadcasters, IMD can suffer.

Broadcast amplifiers often employ specialized filters which go by several names including “Harmonic Loading”, “IMD Cleanup”, “Out of Band Load Dumping” and others. There are a few ways this is accomplished. The most common is by employing a duplexing filter of some sort, where a low pass or band pass portion of the filter allows the primary signal to pass, and the high pass or band reject portion of the filter feeds a termination load. A paper appeared in QEX by William Sabin W0IYH (SK)[3] which showes how to construct a bank of filters, one for each HF amateur band. A few bands were grouped together. IMD performance was shown to have improved. Subsequently, the FLEX Radio Power Genius legal limit HF amplifier has among other advanced features a “harmonic filter” capable of absorbing 400 watts!

Non-Linearity

The other primary cause of IMD is the operation of an amplifier or mixer at amplitudes where compression takes place. If an amplifier (or any circuit) is not linear, then harmonics and intermodulation are generated. Some components (diodes, transistors, spark gaps, light bulbs) are inherently non-linear. To make them more linear (at least the transistors) various methods are employed, often involving negative feedback where an error voltage is used to reduce the non-linearity. This can be as simple as a “ballast resistor” between a transistor emitter and ground, or as complicated as using the topology of an operational amplifier.

In good low level amplifier circuits, sufficient compensation can usually make them quite linear, and IMD levels as low as -50 to -40 dBc can be achieved up to some reasonable power level. That power level is where (despite various forms of compensation) the gain function changes from a straight line to a curve, and the amplifier begins to compress. In my experience, for most amplifiers the point where this becomes a problem is around 7 dB down from the P1dB point. That P1dB point is often provided in the datasheet for amplifiers, and in some ways suggest a maximum power where significant enough distortion takes place to limit use as a linear amplifier.

Another method is to “pre-distort” the signal entering the amplifier so that the output overcomes non-linearity. The pre-distorter lowers the waveform amplitude where the amplifier has greater gain than required, and vice versa. These circuits are difficult to implement in analog but simplified if the signal is digital. I will not address pre-distortion. But realize that this “fix”, once only affordable in very expensive military and commercial systems is becoming a reality in amateur radio equipment in the digital age.

Note, this care to reduce power does not apply to CW, FT8, Q65, or any common digital mode where there is only one carrier present at any instant and there is no amplitude modulation. In those cases there should be only one carrier being sent which is frequency and phase (but not amplitude) modulated. In such cases there is no IMD. Many FM transmitters employ very non-linear class C power amplifiers that provide a clean signal and achieve lower initial cost, operating cost and heat.

Investigation

Setup to test measure IMD

In order to understand and quantify IMD in a transmitter, I constructed a “bench transmit converter”. This consisted of off-the-shelf amplifiers and filters, and in some cases home brew filters. During the construction I had to qualify and quantify the gain and IMD of amplifiers at different power levels and selected components and amplitudes which maintained a low level of IMD as I progressed through the chain of components. To simplify, I use “MCL” as shorthand for Minicircuits Labs.

Two Tones

I first built a two tone generator from Pacific Antenna[4]. It has two 9 V batteries, an output for each tone, a combined output, and balance and a level control. The combined output was quite high, so I put it through a 20 dB audio attenuator and an unbalanced to balanced converter to plug into the balanced mic input to my FLEX Radio 6700 Transceiver. The output of the transceiver was set to XVERTER 0 dBm 28.1 MHz and displays as 222.1 MHz. The generator had some audio harmonics visible on the analyzer, but the frequencies of just over 700 Hz and 2000Hz were not harmonically related and were a good distance apart for clear analysis. I connected the output of the transceiver into the HP 8653 spectrum analyzer which showed the IMD to be about -80 dBc (somewhat mixed with noise, so perhaps -75 to -80 or maybe even lower). For my purposes, this was clean.

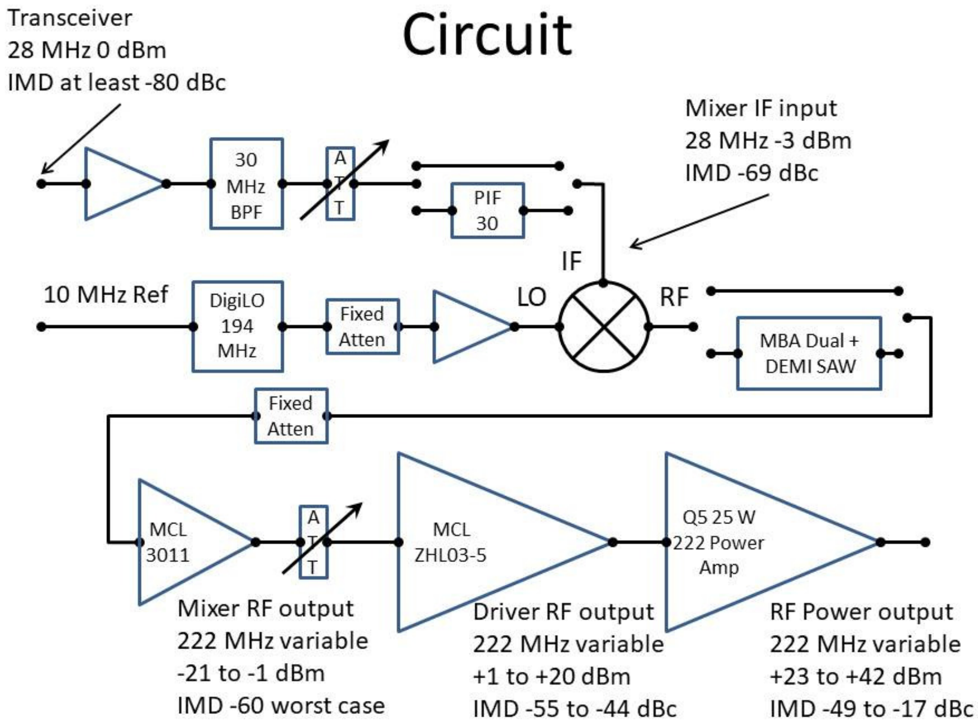

Figure 4. The overall bench circuit with power and IMD levels

An amplifier was needed in order to bring the IF 28 MHz level high enough to deal with losses in a 30 MHz bandpass filter and other filters prior to the input of the MCL (Minicircuits) SRA2H-10 mixer. I chose this low IMD mixer because eventually I would also use it as a down converter. Originally an old Pasternack 1500 amplifier was used as an IF amplifier but the IMD was excessive as it was pushed near compression in order to produce a +6 dBm output to overcome the subsequent filter losses. A MCL ZFL-1000VH was substituted with an input 6 dB pad. The result was sufficient power and IMD of –69 dB.

Mixer IF Port

The IF port of a mixer should be terminated at all frequencies. The preceding output of the IF amplifier passes through a 30 MHz BPF that reflects out-of-band signals in order to simulate a typical transceiver RF input/output. The amplified and filtered IF signal was connected to the mixer IF input in two ways. One was through an attenuator and other through a constant impedance bandpass filter MCL PIF30. The connection between the filters (or direct connection) and the mixer IF input port was measured through a coupler in the line and once adjusted, left alone.

Then the output of the mixer (at the 222 band) was monitored.

When the IF input was connected from the amplified filtered source:

- directly to the mixer IF it showed an IMD of -39.3 dBc,
- through a 3 dB pad delivered in IMD of -51 dBc,
- through the PIF filter IMD of -42.5 dBc., and
- though a 3 dB pad and the PIF filter resulted in an IMD of -52 dBc

That final selection was chosen for the mixer input. Eventually, to keep the mixer input IF port signal level down and achieve good IMD at the mixer output, the input to the IF amplifier was further reduced by increasing the amplifier input attenuator to 10 dB, resulting in the IMD out of the filters reduced from -52 to about -60 or slightly better (some error in measurement do to noise).

At this point, the final IF port input IMD was -60dBc at a level of -2 dBm terminated into a wide bandwidth spectrum analyzer input.

The LO port was driven by a wideband amplifier which has an excellent wideband S22, so it would absorb various reflected products. Adding pads to this port (and adjusting gain to keep the amplitude constant) did not make any difference in the 222 MHz IMD.

Mixer RF Output Port

The RF (output port) of the mixer was then terminated in various ways to observe effects on 222 IMD. Because the RF port should be bandpass (or at least high pass) filtered in order to prevent subsequent circuits from passing, amplifying or mixing unwanted mixer products and also to meet out of band emissions compliance, a quality BPF was inserted. The DEMI 222 BPF was selected[5]. This excellent filter has sharp skirts, and does reflect some energy outside the passband. Those reflections could add to IMD in the mixer. MCL does not make a 222 constant impedance or duplexing filter, so I designed a simple one of my own.

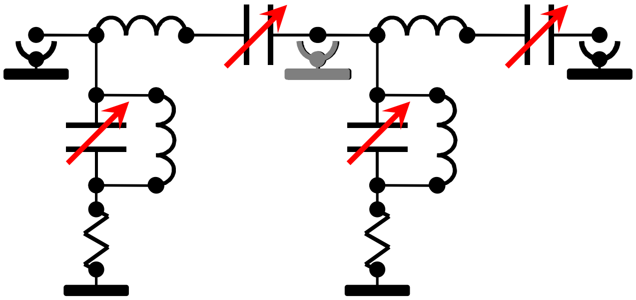

Figure 5. First 222 constant impedance filter topology (built as 2 filters)

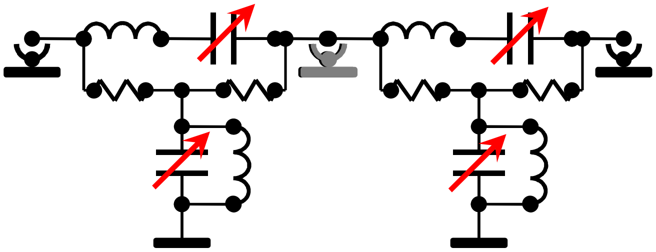

Figure 6. Second 222 constant impedance filter second topology (built as two filters)

My talents are limited in this regard and found that I had to replace the fixed with variable capacitors in order to tune out the parasitics and achieve a modicum of acceptable performance (figure 5). Eventually I redesigned the filter to a second topology (figure 6), and by adding and substituting capacitors achieved acceptable performance when two were cascaded. This second design was employed in the test setup.

The IMD at 222 following the DEMI BPF was

- Direct - With no BPF (and a good terminating amplifier) -51.3
- With only DEMI BPF -53.1 (comment – surprised this is so good, but it is)
- With cascaded HB filter followed by DEMI BPF -59.6

The output level was -12 dBm which accounted for mixer conversion loss and filter IL. Following the filtered mixer, several amplifiers were tried. The best performance was had by feeding a MCL Z60-3011 with 4 dB of input attenuation. Although this amplifier is not specified below 400 MHz it works very well.

After this amplifier a variable attenuator was inserted to control drive for levels in the subsequent higher power stages. The variable attenuator consisted of 2 HP 355 series 1 dB steps from 0 (which was measured as 1.3 dB – always good to check surplus devices) to 132 dB using one decade and one units switch attenuator in series.

The two subsequent power amplifiers were a 10 watt rated P1dBm, 60 to 300 MHz, MCL ZHL03-5 followed by a Q5 Signal 25 Watt adjusted for 100 mW (+20 dBm) for full output. The Q5 consists of a RA30H2127M1 Mitsubishi MOSFET “brick” amplifier biased for linear performance.

Because these amplifiers were being driven by a signal source with very low IMD levels, the vast majority of IMD present in their outputs is caused by these power amplifiers and not the driving sources.

Driving and First Power Amplifiers

The first amplifier following the mixer, buffer and attenuator is the MCL ZHL-03-5, capable of 10 watts at P1dB. It was driven and plotted across a range of input power that resulted in output power capable of driving the subsequent 25 W power amplifier from a very low level to its maximum output. The Power Output, Gain and IMD of the MCL ZHL-03-5 is plotted in figure 7. As can be seen, the output rises above -50 dBc IMD at -20 dBm input corresponding to +12 dBm output, and rises above -46 at -13 dBm input corresponding to +20 dBm output, the approximate input level for the subsequent 25 Watt amplifier. All of these values are considered quite low IMD for these power levels. They are achieved by the MCL amplifier by using it at a maximum power level nearly 20 dB below its rated output power. Perhaps a quality but less expensive 1 Watt amplifier could be used and still achieve very low IMD for driving the subsequent stage. The possibility of obtaining sufficient output from this MCL amplifier for directly driving a high power amplifier will be explored in the future.

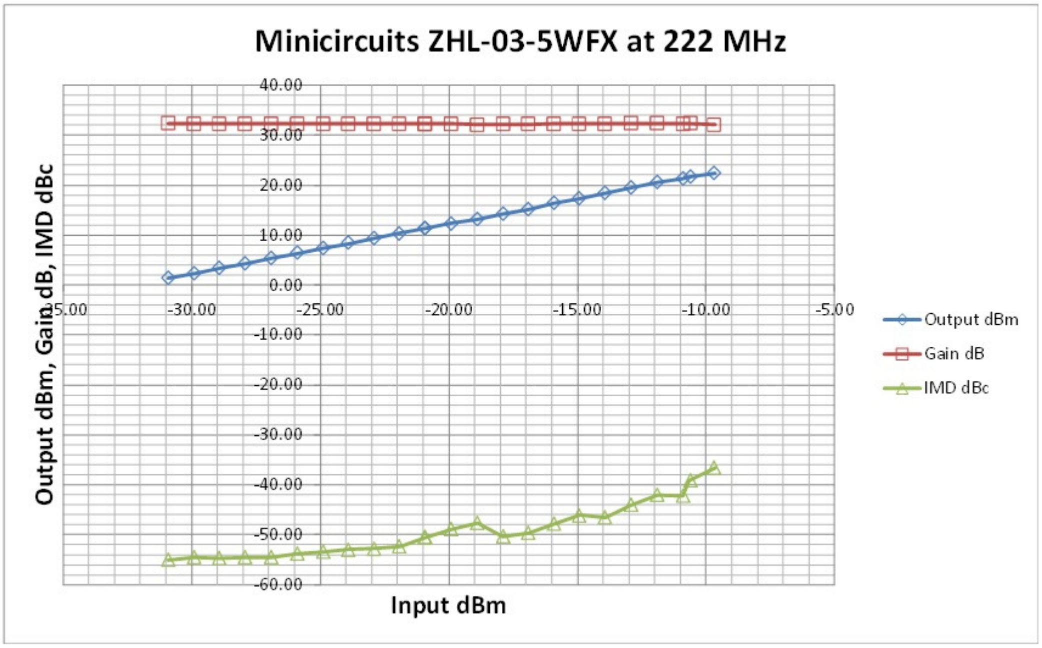

Figure 7. Minicircuits ZHL-03-5 Input dBm showing Output Power, Gain and IMD

The output of this driving amplifier was connected directly to the input of the Q5 25 watt amplifier. With full knowledge that at compression levels around 20 dBm of input power (100 mW) this 25 watt amplifier would be in compression and therefore have relatively high IMD. The input attenuator of the driving amplifier was adjusted in steps in order to produce a Gain, Output and IMD plot. This is shown in Figure 8.

It can be seen in this plot that the gain is in a slight downward curve at the lower levels which indicates some limited amount of non-linearity. As the power increases, the non-linearity in output (starting to curve more) and the gain (also starting to curve more), is indicating a P1dB at 7 to 10 watts output. This is also the region where the IMD increases to -30 dBc and worse. This operating point is 6 to 7 dB below maximum power, but equal to the P1dB point rather than below it.

Because the primary use of a power amplifier is to produce sufficient power for communications, some degree of IMD is tolerated in SSB and AM modes. Although I have not read any specific comparison between levels of IMD and human hearing sensitivity to voice quality, I can hear IMD effects right around 30 dBc, and it becomes very noticeable around -10 dBc. The Clean Signal Initiative suggests a range of -30 dBc as a goal for the first product and even a lower level for signals further out. Personally, I would have no problem at all running an amplifier with -30 dBc IMD and perhaps occasional voice peaks exceeding this level. The full power of the amplifier is there for CW, FT8 and other modes for which IMD is not relevant and maximum DX can be obtained.

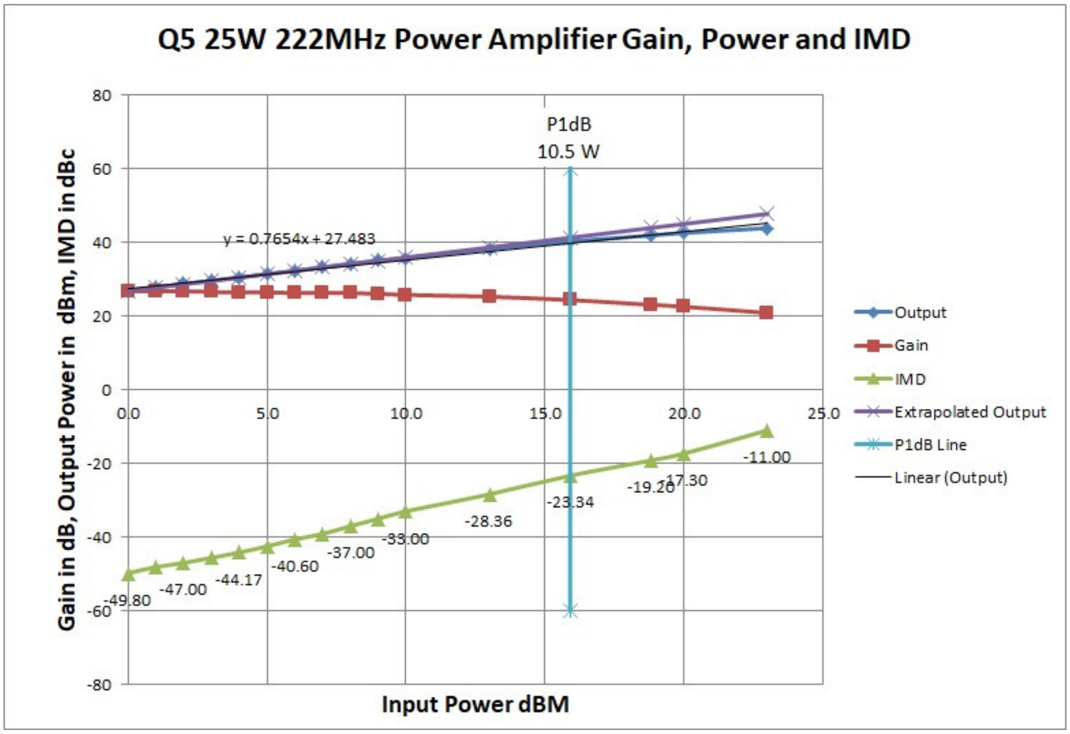

Figure 8. Q5 Signal 25 W, factory adjusted for 20 dBm input to deliver max power

Filtering subsequent to the output amplifier.

I plan to introduce a 500 watt LDMOS amplifier to be driven by this 25 Watt amplifier at about 7 watts peak power. All LDMOS and other amplifiers have output low pass filters to suppress harmonics and other spurs to levels acceptable to the FCC.

My next effort will be to construct a filter to provide a load to those output signals instead of reflections back into the amplifier where mixing might increase IMD. My first attempt at building a high power duplexing filter failed, but I had very little time to debug and adjust values to tune out parasitics. In future work I intend to do just that. In preparation, however, I placed a "line stretcher" between the output of the 25 Watt amplifier and a Low Pass Filter. A line stretcher is a coaxial version of a "trombone slider", allowing the length of a piece of coax to be varied in circuit. I found that I could tune at least 2 dB of IMD "away" by stretching the line. This implies that the phase angle of the return signal affects IMD, and therefore a constant impedance load filter might reduce the power amplifier IMD.

Receiver IMD

One way to help decide whether the IMD you are receiving from a neighbor station is their transmitter or your receiver chain is by changing the amplitude of the signal you are receiving. This test is somewhat subjective (not quantified). Observe a waterfall and/or spectrum display of the received signal. Note the difference in signal level between the voice peaks and the out-of-band sidebands immediately adjacent to the modulation. If it is an upper sideband signal, look at frequencies below the suppressed carrier. Then rotate your antenna. As the signal grows and fades, note the level difference between the voice peaks and the adjacent unwanted sideband. If that difference stays the same, it is the transmitter. If it changes, then at least some (if not all) of the IMD is in the receiver. This will take several goes because voice peaks and characteristics change over time.

If you have a calibrated spectrum display (as many SDR's are these days), you can directly measure the level difference in dB. If it is 30 dB or more, then it could be an acceptably "clean signal", even if it is bothersome. Most ham voice communication is conducted with less than 30 dB signal/noise, and in that case the unwanted IMD is buried in the noise.

Conclusions and Advice

Signal Converters / Transverters

If you can't measure IMD, then design with constant impedance filters at the IF and RF ports of every mixer. A 10 dB pad between the port and a reflective filter provides excellent constant impedance, but unfortunately attenuates by 10 dB. Even a 3 dB pad can make a very measurable improvement in IMD.

Try to run all gain block amplifiers at maximum power levels at least 7 dB below the P1dB point.

Power Amplifiers

In the future, I will try to run Power Amplifiers at 6 to 7 dB below maximum output, or a couple dB below the P1dB level when operating SSB, especially when other hams are likely to hear my signal more than 30 dB out of the noise. If I am far enough away and/or in a direction with blockage, or I know for sure the nearby amateur is not operating, IMD becomes less important as an interfering spectrum hog, but more important as an audio quality issue. When my signal is relatively weak to everyone, I can be a reasonably good neighbor and still approach the higher end of my amplifier output level using SSB. To reduce the IMD of a PA further, there are some ways to improve linearity, including increasing bias to class A, balancing bias across all power devices in push-pull amplifiers, auto-adjusting bias across temperature, and managing bias differently between SSB and CW/FT8. Note that these ideas are based on VHF and above operations, where it is possible to predict the received power of a signal based on distance and obstacles. On HF signals can be quite strong at great distances, and the spectrum is generally more crowded. Therefore, advice for HF operation would be more cautious about running power levels that produce IMD greater than -30 dBc.

References

1. ARRL Clean Signal Initiative, QST May 2024, pp26, and https://www.arrl.org/arrl-clean-signal-initiative

2. Go to Rob, N4GA Website for a good read on this subject with respect to LDMOS power amplifiers http://www.n4ga.com

3. William Sabin W0IYH, “Diplexer Constant Impedance High Power Filters”, QEX July/August 1999,

4. Pacific Antenna, QRP Kits https://www.qrpkits.cm/twotonetest.html

5. Down East Microwave, BPF 222, https://www.downeastmicrowave.com