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RTTY Spectrum Measurement

This article investigates the transmitted RTTY spectrum using different modulation methods. The motivation has little to do with the debate over keying methods — ie, sound card-driven AFSK as opposed to on/off keying using a radio's internal FSK tone generator — and everything to do with spectrum usage in a crowded contest environment. This investigation will try to answer these questions:

1. What does the transmitted bandwidth of a RTTY signal look like?
2. What can we do to decrease that bandwidth?
3. Does any of this really matter in practice?

This experiment looks at a transmitter's internal FSK generator and various forms of AFSK transmission as well as power and transmit filter bandwidth. I address FSK wave shaping for the purpose of reducing bandwidth but not the issue of signal-to-noise degradation due to such wave shaping. This research is ongoing, although I believe the methods discussed in this study do not result in any meaningful loss of SNR at the receiving end. In practice, most contesters are listening through a 500 Hz or narrower filter, so any keying energy transmitted outside this range is wasted anyway.

Wave shaping can be thought of as altering the rise and fall times of the tones, much like shaping a CW waveform to reduce key clicks (it may be helpful to think of RTTY as two on/off keyed signals 170 Hz apart). Wave shaping can also be accomplished by passing the tones through a carefully chosen narrow filter. From that point of view, the "ringing" of the filter shapes the mark and space tones. No matter how one conceives of wave shaping, the net result is an amplitude envelope over the mark and space tones that applies a rise and fall time to the mark and space bits. This reduces keying sidebands in the same manner that shaping a CW signal reduces key clicks.

I encourage readers to draw their own conclusions from the data I present. I also recommend reading W7AY's RTTY FSK sideband discussion (**www.w7ay.net/site/Technical/RTTY Sidebands/sidebands.html**) for an overview of different FSK generation methods.

Test Setup

The test setup (see Figure 1) used an Elecraft K3 as a transmitter and a FlexRadio Flex 5000A as a spectrum analyzer. I chose the K3, because it is a popular contesting transceiver that includes an internal phase-continuous FSK synthesizer as well as several configurations to transmit AFSK. The K3's transmitted intermodulation distortion is probably a little worse than that of some other popular contest radios (we'll see why this matters in a moment), but on the whole much of the analysis here applies equally to other radios. The K3 transverter configuration was adjusted to transmit on 14 MHz, which allowed bypassing the radio's internal power amplifier. A variable attenuator was placed in line to keep the signal strength constant at the receiver.

FSK Excitation

FSK excitation was generated with the terminal function K3 *Utility* software. The radio was set to use FSK-D. Transmitted

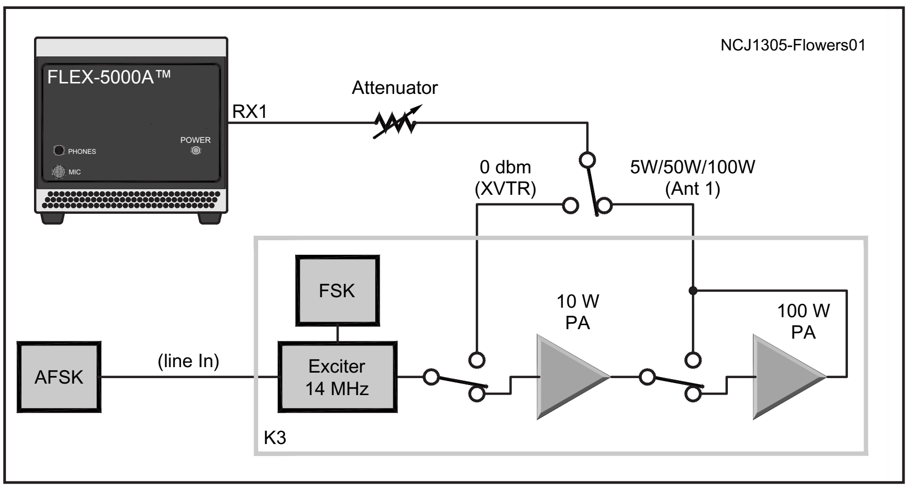

Figure 1 — A diagram of the test setup

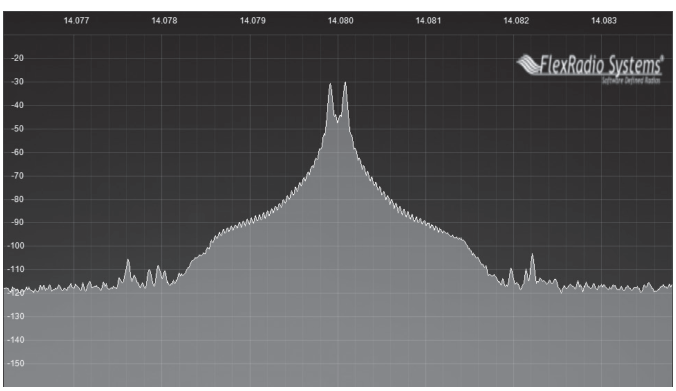

Figure 2 — Internally generated FSK at 100 W

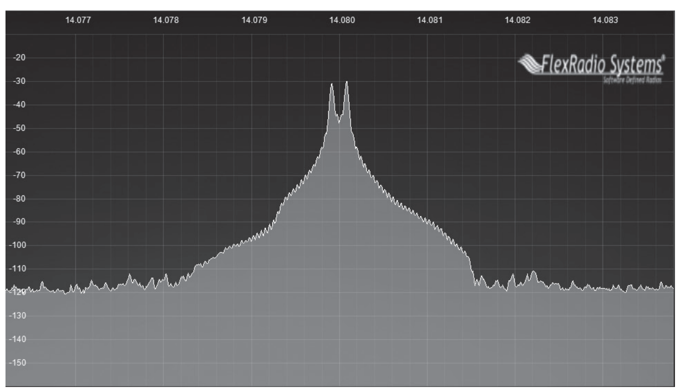

Figure 3 — AFSK with *MMTTY* with TX filter disabled, 100 W

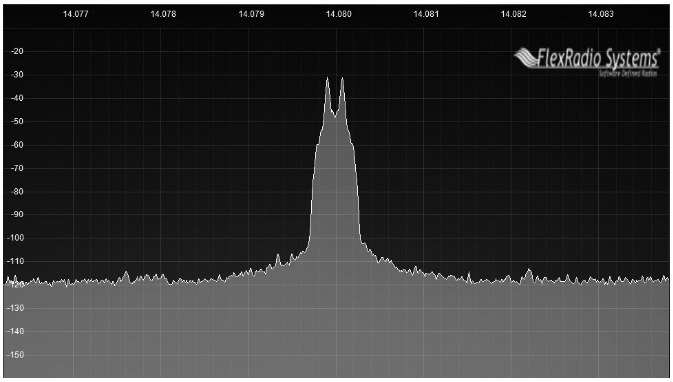

Figure 4 — AFSK with *MMTTY* using a 512 tap TX BPF with a passband of from 2000 to 2400 Hz, 0 dBm

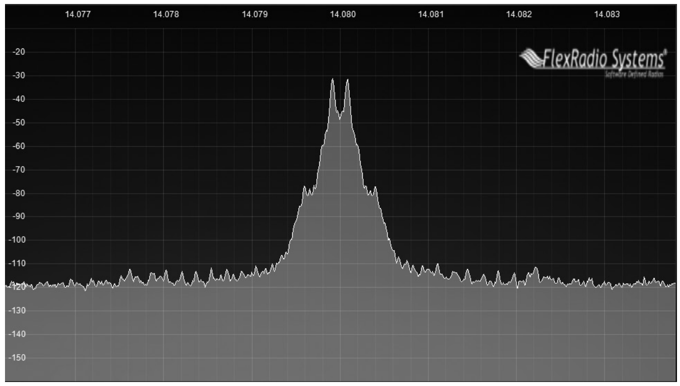

Figure 5 — AFSK with *MMTTY* with 512 tap TX BPF, 100 W

data consist of a continuous string of "RY" at 45.45 baud with 2 stop bits. The data clock is entirely contained inside the K3 and does not rely on the *Windows* timer as it would with some other forms of external keying.

AFSK excitation

AFSK excitation was generated using these software configurations:

1. *MMTTY* with no software transmit filter
2. *MMTTY* with the default 48 tap transmit filter
3. *MMTTY* with the 512 tap transmit filter
4. G3YYD's *2Tone* v12.12a with "AM" transmission (default, wave-shaped output)

The K3, was set to use FSK-A mode and high tones. The transmitter was configured to use the 8 pole, 2.8 kHz SSB transmit filter with the "AFSK TX" filter turned off. The K3's line in gain was set to 3 and showed 3 bars on the ALC meter, which, on this radio, indicates no ALC applied to the PA. No power creep was noticed, indicating an appropriate drive level for the DSP's ALC ahead of the exciter.

Measurement Method

Ten seconds of transmitted data were sampled using the *peak hold* spectral display in the *PowerSDR* software. The sample does not include on/off keying of the transmitter, in order to avoid any spectral contamination ("pops") at the beginning and end of the transmission. In all cases the relative power seen by the receiver was kept 30 dB below full scale. All plots represent the spectrum of an equally strong signal from the point of the receiver and well below the clipping level of the analog-to-digital converter in the FlexRadio (approximately S-9 +40 dB).

FSK Bandwidth Measurements

The internal FSK generator does not perform any RF waveform shaping; it appears to be phase continuous, ie, it avoids instantaneous jumps in voltage at the beginnings and endings of bits. The spectrum rolls off at about 6 dB per octave, in line with what we'd expect for this keying waveform. In FSK-D mode, the K3 places the signal in the middle of the IF filter; you can see the "knee" at ±1400 Hz, where the 2.8 kHz filter stops the sidebands from continuing.

In practice there is very little difference between the FSK spectrum with and without the PA chain. Since there is no signal wave shaping and, therefore, no overlap of mark and space tones, transmit IMD ("splatter" in the conventional sense) is not a factor. The second harmonic energy at about 2.2 kHz from the carrier could be due to the numerical precision of the mark and space generator or a DSP artifact. As this is about –78 dBc, it is unlikely to be noticed.

AFSK Without Wave Shaping

With no wave shaping the AFSK signal bandwidth, like that of the internal FSK generator, is limited by the passband of the of the K3's transmit filter. Even with the K3's AFSK transmit filter disabled, it still places a low-pass filter on the audio spectrum with a cutoff at around 3 kHz, which explains the asymmetrical spectrum. This is likely radio specific, and other radios probably will have a slightly different spectrum, depending on just where the tones lie in relation to the IF filter. *If no bit shaping takes place during AFSK modulation, the signal will be identical to that of the FSK generator.*

AFSK Bandwidth With Wave Shaping

At the time of this writing, the only method of creating wave-shaped FSK was to use soundcard-based AFSK. A few pieces of RTTY software do some wave shaping by default. The default setting in *MMTTY* uses a 48 tap filter centered on the transmitted tones. The net result is a very slight overlap of mark and space pulses, due to ringing in the filter. Figure 4 shows more aggressive filtering using a 512 tap filter with a passband of from 2000 to 2400 Hz — essentially a 400 Hz DSP "brick wall" filter.

Wave Shaping with the K3 PA

The bandwidth of a signal can be reduced significantly using wave-shaped FSK, at least when the transmitter's IMD is low. Because the wave shaping causes an overlap between mark and space during the bit transitions, transmitter IMD potentially can undo some of that work. Like all radios, the K3's exciter is not perfect, and you can just start to see some IMD sidebands coming into play in Figure 4. Running the K3 at typical output, we begin to see the spectrum degrade. It's noteworthy that the K3 appears to have better third order IMD at 50 W than it does at 5 W, while the final PA may be contributing more to higher-order IMD. This is probably due to the 10 W driver amplifier being driven in a more linear region. This will vary from radio to radio, and many competition-grade radios will exhibit better transmit IMD performance.

An important point: Even given the K3's transmit IMD, the occupied spectrum using shaped FSK is much narrower than that when using the internally generated FSK synthesizer. FSK keying sidebands are not unique to the K3; every radio that uses phase-coherent for its internal FSK generator will generate a wider spectrum at essentially any power level. The only differences will be in cases where the IF filter cuts off the sidebands.

As an experiment, I decided to see just how wide I could make my signal by overdriving the K3's line input. I cranked the PC's headphone output to 100 percent and drove the ALC as hard as I could by setting the line input gain to maximum (see Figure 7). Some strange spurs show up in the spectrum, but even those are below the keying sidebands of the FSK transmitter (see Figure 2). Even trying to transmit absolute trash I wasn't able to make the AFSK signal as wide as that of the internal FSK generator. The rise in the noise floor over the 2.8 kHz bandwidth occurs, because the K3 amplifies noise from somewhere; at this gain setting it is present whether or not anything is plugged into the K3's line in jack. This behavior is almost certainly specific to the K3, because the K3 scales audio in DSP before it ever enters the RF stages. Other radios are not going to protect you from yourself nearly as well, so you might expect harmonic distortion and other bad things with no limiting prior to the point of RF modulation.

FSK with 400 Hz Transmit Filter

One way to wave shape an internally generated unshaped FSK signal is to transmit through a narrower filter at the IF frequency. It is possible to trick the K3 into transmitting through the 400 Hz roofing filter. Early versions of the K3 firmware allowed this, but this was disabled in subsequent versions. If you're careful to center the tones in the filter passband, you can transmit a much narrower signal and still use a keyed FSK key line or the internal FSK modem. Let me emphasize that I do *not* endorse this procedure and offer it for information only. It could be a very bad thing to do. I have not measured the group delay in the crystal filter, which could increase inter-symbol interference over the normal transmit filter. There is a more than 20 dB improvement beyond 200 Hz from each tone, so the internal FSK generator would yield a much more neighbor-friendly signal.

While this method of cleaning up an FSK generator may be a little tricky to adjust, it may be the only option to clean up radios that generate FSK by directly altering the radio's RF oscillator. Crystal filters often have pass-band ripple, and the tones need to be of equal amplitude. Still, even a 600 Hz or 1 kHz transmit filter would help in cleaning up most of the unnecessary energy.

Effect of the K3 AFSK Transmit Filter

Rather than hacking the K3 to transmit through a narrow roofing filter, an equal or better result can be had by simply enabling the AFSK transmit filter in the configuration menu. This places a 400 Hz filter before transmit audio arrives at the RF modulator (this only applies to AFSK-A mode, not DATA-A mode). This filter is centered around the tones configured under the radio's PITCH menu. The effect is similar to what *MMTTY* and other programs do in their software, but this is done in the radio's DSP firmware.

The radio's manual says this filter can serve to filter any noise that might be on the audio input, and it certainly will do that, but it has the additional benefit of filtering keying sideband energy. Figure 9 shows the result of *MMTTY*'s unfiltered phase-continuous AFSK audio into the K3 with the K3's AFSK filter enabled. Comparing Figure 9 with Figure 3 demonstrates the effect of the K3's AFSK filter, as both have exactly the same audio input to the K3.

Attempts to overdrive the radio resulted in no significant change in signal bandwidth. Even when transmitting wideband noise into the K3, the AFSK filter limits the bandwidth. While it is possible to transmit trash that is difficult or impossible to copy, the K3's AFSK filter makes it unlikely that it would generate much interference on adjacent channels. I suspect that other

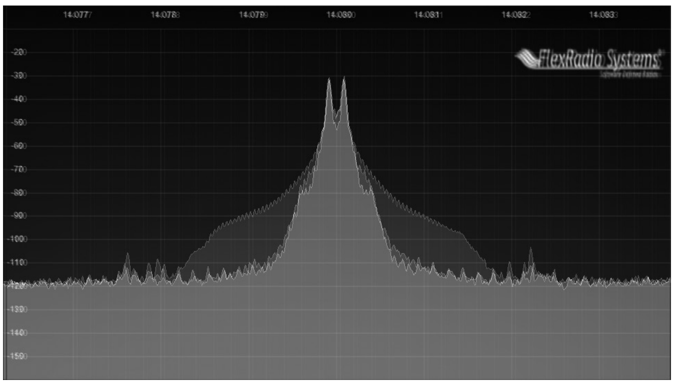

Figure 6 — Comparison of *2Tone*, *MMTTY* (512 tap) and FSK at 100 W (thanks to W7AY for putting together the composite images)

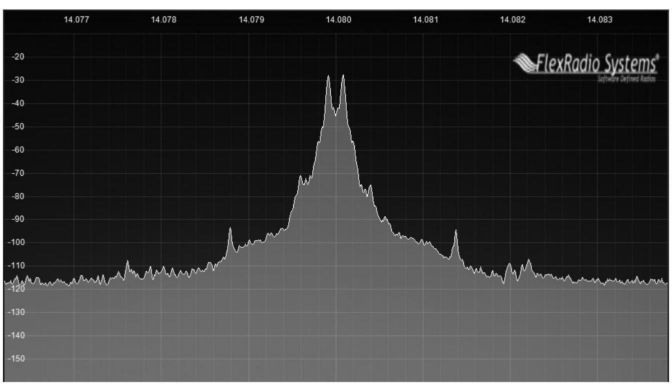

Figure 7 — Badly overdriven AFSK with using *MMTTY's* default configuration

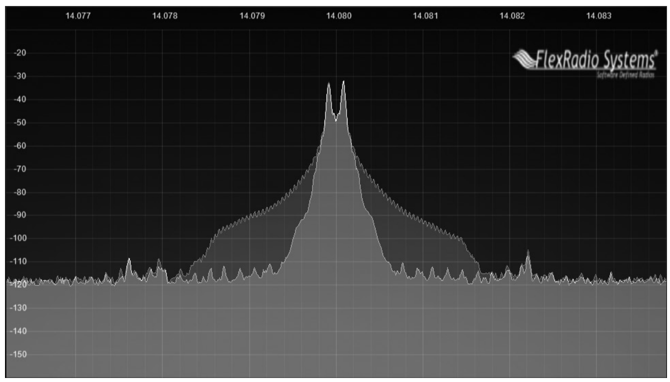

Figure 8 — Comparison of internally generated FSK in the K3 using the 2.8 kHz filter and the 400 Hz filter for transmitting. Transmitter output is 50 W. Since this article was written, Elecraft has released a firmware update for the K3 to provide wave shaping in its interal FSK.

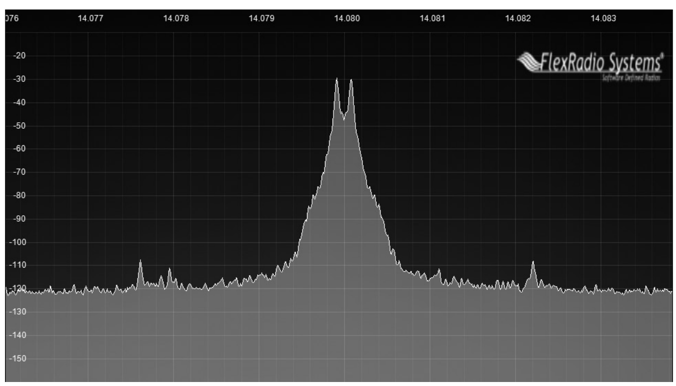

Figure 9 — Unshaped AFSK with the K3's AFSK filter enabled, 100 W. The K3 was set to use the 2.8 kHz SSB filter for transmit (compare with Figure 3).

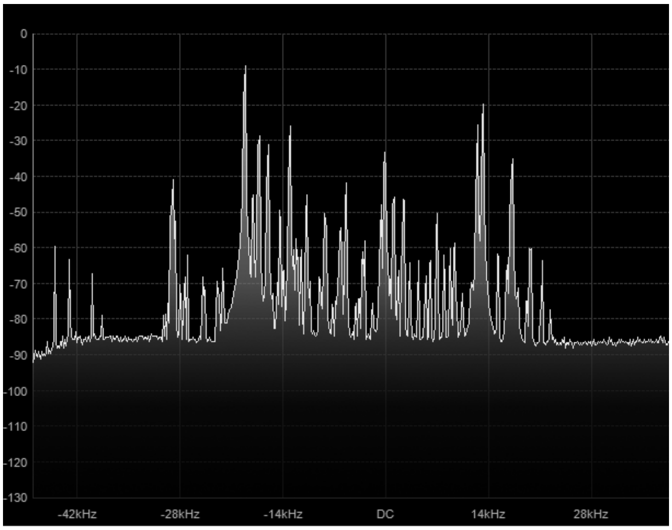

Figure 10 — Spectrum of the 2012 ARRL RTTY Roundup centered at 14,100 kHz. These signals were received with a low dipole. *SDRSharp* (http://sdrsharp.com/) was used to capture the spectrum.

radios that let you place a DSP filter ahead of the modulator would behave similarly. This appears to be an excellent safeguard against causing wideband QRM while also reducing the bandwidth of a properly transmitted signal.

Does Any of This Matter?

The discussion so far has compared FSK modulation techniques in the lab. We have seen that it is possible to transmit a much narrower spectrum than possible with simple phase-continuous FSK; to my knowledge most radios transmit phase-continuous FSK when configured to use their internal FSK generators (see Figure 3). We've shown that keying sidebands could be drastically reduced outside about a 400 Hz passband. At this level the phase-continuous FSK sidebands flare out and decay very gradually between –40 and –70 dBc and are eventually limited by the transmitter's IF filter (assuming it is using one). Does this make any practical difference on the air?

Real Contest Signals

Figure 10 is a snapshot of a swath of 20 meters during the 2012 ARRL RTTY Roundup, recorded in a noisy suburban neighborhood; clearly many locations will have lower noise floors and stronger signals. This was at a time when 15 and 10 were wide open, so the band is not nearly as full as it could have been. The noise floor, is about –85 dBFS. At this moment there are:

- 14 signals with a 40 dB SNR or higher
- 8 signals with a 50 dB SNR or higher
- 4 signals with a 60 dB SNR or higher
- 1 signal with a 75 dB SNR (and it's 800 miles away!)

Zooming in on that 75 dB signal we can easily see the keying sidebands raising the noise floor by >10 dB out to about 1 kHz on either side. The other spikes in the keying sidebands are other stations buried under the keying sidebands — in fact two more are closer to this transmitter, but we can't see (or copy) them at all until the transmitter stops; even so they are more than 10 dB above the noise floor.

There is nothing abnormally "dirty" about this signal, though. These keying sidebands are the result of phase-continuous FSK without any shaping or filtering, and are typical of what the vast majority of radios generate in FSK mode. All of the big signals seen in the recording likely are running unshaped phase-continuous FSK, very likely using the radio's internal FSK generator. Most are

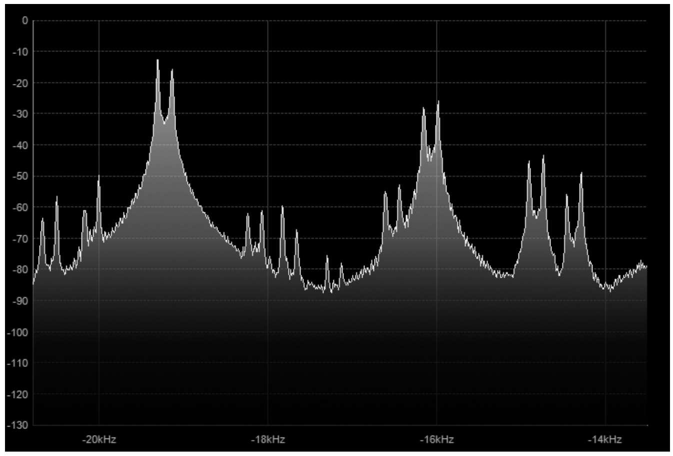

Figure 11 — Signal with 75 dB SNR showing keying sidebands. Sidebands from other strong stations are clearly visible.

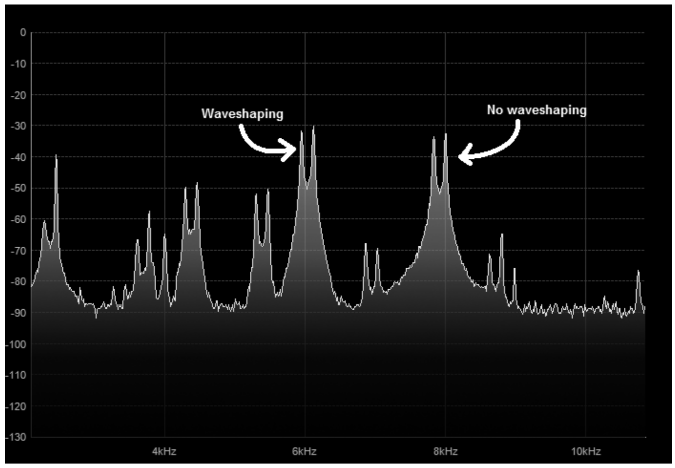

Figure 12 — Two signals of the same strength, with and without wave shaping. The weak signal at about 7 kHz has interference from the signal at about 8 kHz, but not from the wave-shaped signal at 6 kHz.

also running amplifiers (we have the contest results). Because their signals are strong, the keying sidebands interfere with stations on adjacent frequencies. You can see the signal flaring out below the –40 dBc point. This will sound like key clicks that dissipate as you tune away from the signal. These sidebands cannot be filtered out at the receiver; the transmitters really are putting out energy on these frequencies.

Figure 12 shows two signals of the same strength — about 60 dB SNR, or roughly S-9+ on a quiet band. The signal at 6 kHz has some moderate wave shaping applied. This results in steeper skirts on the transmitted signal (judging by the shape, this is most likely *MMTTY*'s default AFSK filter). The signal at 8 kHz is using internally generated FSK, probably with *EXTFSK* (there is a small amount of timing jitter on the signal, which could be explained by the *Windows* timer). The signals are separated by about 2 kHz. Note the weaker signal that is approximately halfway between the two large signals. If I tune my receiver to copy this weaker signal I will hear keying clicks from the strong signal above but not from the signal below. The wave shaping allows me to hear the noise floor of the band 500 Hz away, while the unshaped FSK signal does not.

General Conclusions

1. **Keying sidebands have real consequences.** Given the signal strengths and signal spacing in contest situations, it would appear that the phase-continuous FSK generators in most amateur transceivers have the potential to create quite a bit of unnecessary interference well outside the receiver bandwidths most ops use.

2. **Keying sideband energy cannot be cleaned up by better receiver filters.** DSP and roofing filters cannot eliminate this kind of interference. The energy is really there, and the best receiver selectivity in the world cannot make it go away.

3. **The wide keying sidebands of RTTY communication are not unavoidable.** Empirical evidence shows that they can be greatly reduced through wave shaping in a real transmitter.

4. **Transmitter IMD is *not* a reason to avoid wave shaping FSK.** Unless you have truly horrible IMD in your PA chain, your IMD products and keying sidebands will be well below those of the phase-continuous FSK keying sidebands. The K3 used in this analysis will not win any awards for third-order transmit IMD, but it is clearly much narrower than phase-continuous FSK after about –35 dBc, where the filtering starts to take effect. Some of the high-end radios that employ class A amplifiers may well be much narrower.

5. **An unwanted sideband image is a secondary problem.** An image at the –60 dB level that results from AFSK keying in a conventional SSB transmitter is a secondary problem relative to the energy produced in phase-continuous FSK sidebands. A phase-continuous FSK signal will be greater than –60 dBc across 2 kHz of spectrum! Many modern radios have *far* better sideband suppression than this with just the stock SSB filter in the IF. (Many manufacturers only specify what the FCC requires, which is a pretty low bar; actual sideband suppression is often much better). In this test the K3's sideband suppression was greater than 90 dB. Narrower transmit filters would likely help in some radios, because the filter "blowby" 4 kHz away is probably less with a 1 kHz filter than with a 3 kHz SSB filter. Using high tones might also help for the same reason. This would ultimately depend on what the stop band of the IF filter really looks like at the image frequency.

Improving Things

Many operators may just assume that RTTY "key clicks" on strong signals are part of the game, because so many people are generating signals this way. Phase-continuous FSK's sidebands roll off at a rate of 6 dB per *octave*, which is why loud RTTY signals sound disproportionately "wide" in the receiver. It doesn't need to be this way. Here are some possible ways to clean things up, in no particular order:

1. **Implement wave shaping in the radio's internal FSK generator.** FSK in many transceivers is done in DSP, so it is entirely possible that this change could be done in some radios' firmware. Those using FSK keying would not have to change a single piece of hardware, and their signals would become more neighbor friendly. It would retain all the hardware simplicity of FSK keying without the extra bandwidth. This would be a very elegant solution for everyone.

2. **Make FSK keying bandwidth part of the standard product review test suite.** FSK keying bandwidth is not captured by any test in any publication that I'm aware of. Adjacent-channel interference is the primary reason for conducting CW keying bandwidth and two-tone IMD tests for transmitters. This is really no different, and the popularity of RTTY contesting may give manufacturers an incentive to change things.

3. **Consider transmitting through a narrower IF filter, if your radio allows it.** Even radios that generate FSK by switching or slewing mark and space tones directly in the DDS (as the Yaesu FT-1000MP does) may still have the ability to transmit through narrower IF filters. Using a 1000 Hz or 600 Hz filter in line for RTTY transmission would be a significant help, provided the tones could be equalized in the filter passband and group delay is not excessive. If and how this might be done is specific to each radio.

4. **Consider using AFSK with wave shaping, rather than the internal FSK generator, provided you can ensure a clean signal free of noise and distortion.** This may be easier said than done in some environments. Switching from logical "FSK" keying to "AFSK" modulation with a sound card involves many more variables that have to be controlled. A filter ahead of the RF modulator (eg, the K3's AFSK-TX filter) can mitigate many of the common AFSK issues, but it does not solve all of them. That said, several big guns do use AFSK modulation successfully, and you can identify their signals easily with a spectral display.

5. **Make sure you understand what your radio and software can do to help you transmit a clean signal.** There may be options available to you that are not enabled by default. I didn't know about the optional AFSK filter menu in the K3 until G3YYD pointed it out to me. Other radios may have similar features (eg, transmit audio filters) that can be employed for the same purpose.