How Much “Punch” Can You Get from Different Modes?

The mode you choose can make a big difference in how far you can communicate.

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In chasing DXCC entities, we do everything that we can to improve the chances of logging a new one. Our chances of improving the DX score depend on how flexibly we use frequency bands and operating modes. During a recent quest for the WAS Triple Play Award, one of us (KE4PT) noticed that working the same station on CW was easier than on RTTY, and that RTTY was easier than SSB. We will compare CW, phone, RTTY, and various digital modes — and determine how far each can “talk.”

Not all Modes Transmit Equally

We account for a complete transmission path that uses a pair of transceivers and antennas shown in Figure 1. Each receiver has a typical noise figure of about 10 dB, while the transmitters emit up to, but no more than, 100 W peak envelope power (PEP). Two factors affect the maximum range: *average transmitter power* and *receiver sensitivity*. For example, PSK31 (upper curve in Figure 2) emits an average of half PEP transmitting “0” bits, and full PEP during “1” bits, so the average power with an equal number of “1” and “0” bits is 75% of PEP.

A Morse code CW signal (lower curve of Figure 2) operates at full PEP during key down dits and dahs, but zero power during key up. Transmitting the standard word “PARIS_” including the inter-word space results in 44% of PEP or 44 W average power. FM voice, on the other hand, generates the full 100 W PEP for the duration of the voice transmission. When our equipment limits us to a certain PEP, typically 100 W for many ham transceivers, the *average transmitted power differs for different ham radio modes* according to Table 1, and this affects the performance in the radio transmission link of Figure 1.

Our own measurements for FM, CW, RTTY, PSK31, and JT65 transmitter power levels closely correspond with the Table 1 average power values. Clearly, FM voice, RTTY, PSK31, and JT65 can generate more average power than can CW, AM, or SSB voice. Signals like SSB voice can be processed to increase the average power by a few decibels — however we consider unprocessed voice here. But that is not the full story; the receiver sensitivity for each mode also plays a role, as we can see in Table 2.

Different Modes Vary in Receiver Sensitivity

Table 2 shows receiver sensitivity both in traditional microvolts and in decibels relative to a milliwatt (dBm). The last column shows decibels compared to CW sensitivity. We gleaned the receiver sensitivities shown in Table 2 from an average performance of 30 popular ham transceivers that were measured in the ARRL Lab and reported in product reviews.[1] We relied on the ARRL measurements for AM and FM sensitivities, as well as minimum discernable signal (MDS) in a 500 Hz bandwidth from which we derived SSB and CW sensitivities. Although this is lab-measured data and not theory, keep in mind that “white noise” is the only impair-

[1]Notes appear on page 3.

Table 1
Average Power for 100 W PEP Transmitter

Mode	Average Power (W)	Compared to CW (dB)
AM	25	–2.5
SSB	25	–2.5
FM	100	+3.6
RTTY	95	+3.3
CW	44	ref: 0
PSK31	75	+2.3
JT65	100	+3.5

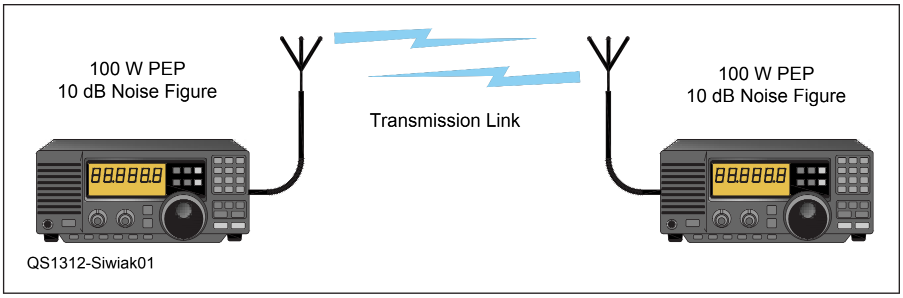

Figure 1 — A pair of transceivers and antennas form the basic radio transmission path link.

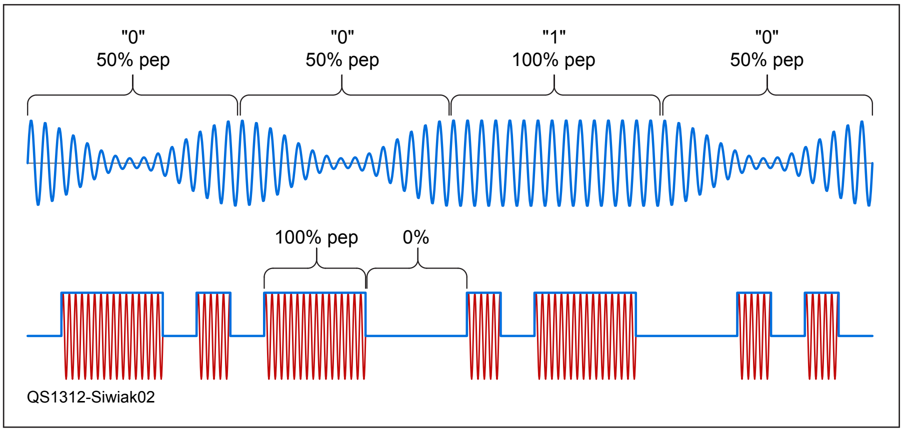

Figure 2 — PSK31 (upper curve) emits half PEP during “0” and full PEP during “1” bits, so average power with an equal number of “1” and “0” bits is 75% of PEP; CW (lower curve) emits 44% of PEP.

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Table 2
Average Receiver Sensitivities

Mode	Receiver Sensitivity (microvolts)	Receiver Sensitivity (dBm)	Compared to CW (dB)
AM	0.72	–109.9	–25.1
SSB	0.22	–120.3	–14.7
FM	0.29	–117.7	–17.3
RTTY	0.096	–127.3	–7.7
CW	0.040	–135.0	ref: 0
PSK31	0.023	–139.8	+4.8
JT65	0.0035	–156.2	+21.2

What We Mean by "Receiver Sensitivity"

Consistent comparisons of receivers and modulation modes require us to apply a consistent standard definition of sensitivity. For voice modes we chose 12 dB SINAD for FM and 10 dB (S+N)/N for AM, straight out of the ARRL product reviews. For SSB we adopted 10 dB above the minimum detectable signal (MDS) measured in the SSB bandwidth, adjusted from the ARRL Lab measured MDS in a 500 Hz bandwidth. Thus, all of the measurements can be traced to ARRL Lab product review tests and test procedures.[A]

For CW and conversational digital modes like RTTY, and PSK31, we defined sensitivity as the signal level needed to decode a random five-character group ("PARIS_") with a 95% reliability. For CW that level is 9.2 dB above MDS in a 100 Hz bandwidth using theory for on-off keying. A 100 Hz bandwidth corresponds to the ERB (effective rectangular bandwidth) of the ear for a 700 Hz CW side tone frequency.[B] Yes, the human ear can act as the final bandwidth filter for aurally decoded CW. CW at 20-25 words per minute occupies nearly 100 Hz of spectrum.

We calculated the PSK31 sensitivity using theory for Differential PSK as 9.4 dB above the MDS in an ideal 31.25 Hz receiving bandwidth, but the necessary or occupied bandwidth is 62.5 Hz. That signal level includes an additional 2 dB for decoder implementation loss. Using 2-FSK theory we calculated that 170 Hz shift two-tone 45.45 baud Baudot RTTY modulation requires 11.9 dB signal to noise ratio to decode the 990 ms string "PARIS_" with 95% reliability. We stated the RTTY sensitivity in a 250 Hz occupied RTTY bandwidth and then allowed 2 dB for decoder implementation loss. JT65 data are encoded with a Reed Solomon (63,12) code and use limited vocabulary messages as well as synchronized transmissions, so we relied on published measurements.[C] We normalized sensitivity to the 2.7 Hz effective noise bandwidth of JT65 tones.[D]

Other sensitivity standards are possible including "20 dB Quieting" level for FM. Different standards result in different audio quality. Short CW exchanges such as with a DXpedition station are not "random groups." They use a very limited vocabulary that often may be copied at much weaker signal to noise ratios than our 9.2 dB standard. Our measurements are in "Additive White Gaussian Noise" (AWGN). Measurements in different noise conditions can alter the results dramatically and differently for each modulation.

[A] *ARRL Lab Test Procedures Manual*, **www.arrl.org/how-equipment-is-tested.**

[B] The effective rectangular bandwidth (ERB) of the ear is $(0.108F + 24.7)$ Hz, F is the center frequency in Hz: B. C. J. Moore and B. R. Glasberg, "A revision of Zwicker's loudness model," *Acta Acustica*, vol. 82, pp 335-345, 1996.

[C] J. Taylor, K1JT, and B. Walker, W1BW, "WSPRing Around the World," *QST*, Nov 2010 pp 30-32.

[D] S. Ford, WB8IMY, "JT65 – The 'Musical' Mode," *QST*, Apr 2011, p 45.

ment in these lab measurements. We explain what we mean by receiver sensitivity in the sidebar. Good operators might copy signals at weaker signal to noise ratios than we defined for our almost-perfect-copy measurement standard, especially when using the very limited vocabulary of DXpedition exchanges. "Arm chair copy" of SSB, on the other hand, may require stronger signals than our measurement standard. The sensitivities measured in the ARRL Lab are of course for the complete receiver with the correct IF filters appropriate to each mode. Our own measurements of PSK31 and RTTY sensitivities for the entire transmitter to receiver path link of Figure 1 are shown by the **X** symbols in Figure 3.

The Full Transmission Link Tells the Story

We might be tempted to compare modes using just the receiver sensitivities in Table 2 and conclude, for example, that JT65 outperforms CW by 21.2 dB. The full transmission link, however, includes the PEP limitation of the transmitter as well as the receiver sensitivity. With a 100 PEP transmitter JT65 generates 3.5 dB more average transmitter power than does CW. So, the full advantage of JT65 over CW is 21.2 + 3.5, or 24.7 dB. Adding up the relative advantages of the modes in both Tables 1 and 2, we arrive at the Figure 3 comparison of modes. The error bars signify estimates of implementation loss variations, and the performance variations across the 30 ARRL Lab measured ham transceivers that we used for the comparisons.

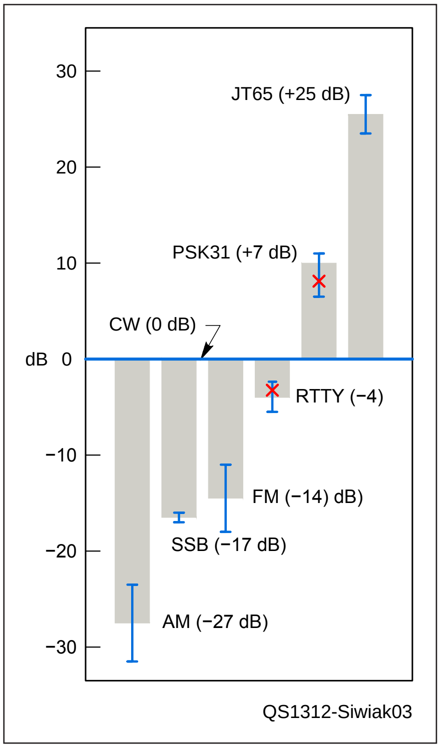

Figure 3 – Comparison of ham radio modes relative to CW.

Comparing Modes in the Full Radio Path

FM compared to SSB emerges as a surprise. Although the typical SSB receiver is more sensitive than the FM receiver by 2.5 dB, the FM radio link performance benefits from FM's 6 dB average transmitter power advantage over SSB, netting a 2.5 dB advantage. Remember that FM was measured using a 12 dB SINAD standard and with an FM detector, while SSB sensitivity was measured at the 10 dB SNR standard using a linear detector, so audio qualities are very different at the threshold signal levels even though their pre-detection SNRs are about the same. One of us (N0ADL) measured and verified the FM versus SSB performance, but also noted a strong preference for the SSB audio quality

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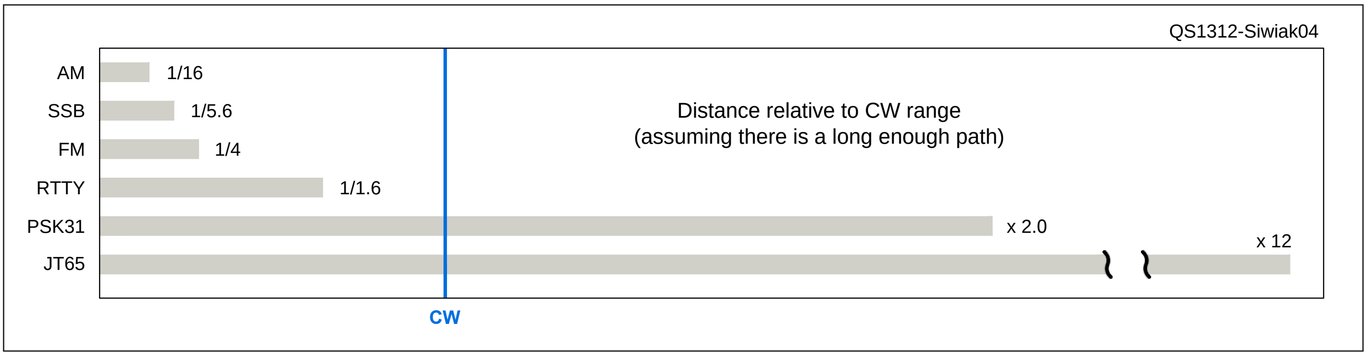

Figure 4 – Relative range of different modes for a radio path link.

Table 3
Occupied Bandwidth and Noise Bandwidth

Mode	Noise Bandwidth, Hz	Occupied Bandwidth, Hz	Emission Designator
AM	6000	6000	6K00 A3E
SSB	2456	2500	2K50 J3E
FM	12,500	12,500	12K5 F3E
RTTY	180	250	250H F1B
CW	100	100	100H A1A
PSK31	31.25	62.5	62H5 G1B
JT65	2.692	175	175H F7B

over FM audio at marginal signal strengths, especially at levels below our measurement standard.

The full spread of performance from AM to JT65 (remember, this is in a white noise environment) is more than 52 dB, a power ratio of 160,000. That's a "big knob" that we can crank to choose the radio path link performance. The receiver effective noise bandwidth per mode accounts for much of the huge spread in receiver sensitivity. The receiver audio pass band is treated simply as the "last IF" for digital modes. Digital mode software and its implementation losses further processes the digital signal, applies digital bandwidth filtering and decodes the message. Table 3 shows how noise bandwidths and occupied bandwidths compare for the various modes. The listed SSB noise bandwidth corresponds to an average value for the 30 measured radios. We quote the pre-detection FM noise bandwidth in Table 3, which does not relate linearly to post detection noise bandwidth. The FCC and ITU-R show us how to calculate the occupied bandwidths, and how to assign the emission designators.[2] Although JT65 occupies a bandwidth of about 175 Hz, clever signal design keeps the effective receiver noise bandwidth at a far smaller 2.7 Hz. Couple that with its powerful error correcting code plus the high average transmit power, and JT65 can place spectacular distance performance at our DX-hungry fingertips. It's easy to see why hams use a version of JT65 for EME (Earth-Moon-Earth) contacts.

So which mode is best? That depends on what you want to send, and how fast you want to send it. A JT65 contact comprises a limited vocabulary of just call signs, signal strengths, and locations, and operates at roughly three words per minute. The voice modes, on the other hand, support real-time conversations, but require vastly more power for a given distance. It's all about the noise bandwidth in Table 3 and average power in Table 2. The "best mode" lets you pass the information you want at the rate and distance that you want.

How Far Does it Talk?

How much further can one mode "talk" compared to another? For a fair comparison of *distance*, a long enough path must actually exist (we're ignoring skip zones in an ionospheric path). But if a good path does exist for a JT65 contact at the threshold of performance, Figure 4 reveals the range would be 12 times the range of a threshold CW contact.[3] CW range would extend to nearly 6 times that of SSB and AM talks only 1/16 as far as CW. DX operators commonly use CW, RTTY, and SSB, which can have a performance spread of about 17 dB. Those popular DX modes may have a range spread of up to 6 to 1 among them. Individual DX stations on the other hand use all modes. One of us (KE4PT) recently snagged a new one (Reunion Island) on two bands using JT65. If you need that rare one in your logbook, concentrate on CW, then on RTTY, and finally SSB *in that order*. Using this strategy the authors have increased their DXCC totals using every mode except AM or FM.

In Conclusion

In this simple comparison we considered "Additive White Gaussian Noise" (AWGN) as the only impairment in the radio link. While we did take transmitter PEP and receiver bandwidth filters into consideration, we didn't account for the Sun, Moon, radio settings, QSB (fading), QRN (natural noise), QRM (man-made noise), or QLF, so your experience may vary.[4] You can target the DX station's operating mode more confidently when you know that CW can outperform unprocessed SSB by 17 dB, and that RTTY can outperform SSB by 11 dB. If you can't get them on phone, try RTTY or better still, try CW.

Notes

[1] **www.arrl.org/product-review**

[2] Modes and occupied bandwidths for emissions are defined in US Title 47 Code of Federal Regulations: 2.201 – 2.202, and ITU-R Recommendation SM.1138, 1995.

[3] Range estimates, assuming that a long enough ionospheric path exists, use a 23log (distance) propagation model based on: K. Siwiak, KE4PT, "Optimum Height for an Elevated HF Antenna," *QEX*, May 2011, pp 32-38.

[4] QLF means, in fun, "I'm sending with my left foot," and here refers to operator skill.

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