Meteor scatter communication with very short pings

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Abstract

A simple statistical model is presented to compare the FSK441 and MSK144 high-speed digital communication protocols using meteor scatter pings in the range 20–120 ms. FSK441 has the ability to make partial decodes with pings shorter than the minimum ~ 70 ms needed for an MSK144 message frame. Because many sequences may be required to assemble a complete message with FSK441 partial decodes, in most situations it is preferable to use MSK144 and wait for a single, sufficiently long (> 70 ms) ping.

Keywords: meteor scatter, FSK441, MSK144, WSJT

Introduction. The fast modes of the WSJT and WSJT-X software suites have been instrumental in facilitating digital communication on the VHF and UHF amateur bands using meteor scatter. Since the introduction of FSK441 nearly two decades ago, there have been significant advances in the performance of computer hardware. The MSK144 protocol was developed in 2017 to exploit this enhanced processor capability. The baud rate is 4.53 times higher and decodes can take place in nearly real-time. Messages are augmented with forward error correction, a cyclical redundancy check, and frame averaging for pings longer than 100 ms. This results in dramatically improved sensitivity and decode reliability [1].

MSK144 sends data repetitively in 72 ms frames. A 128-bit codeword that includes the message payload, forward error correction, and cyclical redundancy check is separated into 48- and 80-bit sections that are interleaved with two 8-bit, 4 ms synchronization words. Pings ~ 70 ms or longer are needed to produce reliable, all-or-nothing decodes [1]. No partial decodes are possible. Stations must have their VFOs aligned to within 200 Hz or better, which is a tighter tolerance requirement than FSK441.

FSK441 does not have fixed frames; the message length depends on the character count [2]. A message with two callsigns and a grid report will exceed 100 ms. Partial decodes are possible, however, using portions of a message as short as 20 ms [3].

The frequency-dependence of radio reflections from meteors (i.e. pings) was discussed by Bain in the May 1974 issue of QST [4]. Pings become shorter and less frequent as frequency increases. Recent research has led to a more complicated physical picture of sporadic meteor scattering at UHF. The volume immediately surrounding the meteor is overdense plasma with a characteristic size much smaller than a wavelength, resulting in a frequency-dependent Rayleigh scattering cross-section [5]. "Overdense" means the RF is below the critical frequency, which is proportional to the square-root of the ionization density. The meteor appears as a point-like reflector to the incident wave. Ionization in the elongated trail, on the other hand, may be too low to contribute [6]. Efficient reflection occurs when the fast moving meteor head is within the antenna field-of-view, leading to very short pings [7]. In these conditions, many operators prefer FSK441 over MSK144.

Pings having duration > 70 ms do occur on 222 MHz, as evidenced by the successful MSK144 QSOs that take place on that band. The question being addressed in this paper is whether it is more efficient to wait for a single MSK144 ping to decode or to exploit the partial decodes afforded by FSK441 with more abundant, short duration (< 70 ms) pings.

It is difficult to compare the two modes directly in on-air testing because conditions are variable and cannot be controlled. Partial decodes observed with FSK441 may cause operators to favor it over MSK144 in marginal conditions with few and short pings. This assumption can be tested through simulations, in which ping duration is the parameter of interest. All other variables – including sensitivity – are held constant. It should be noted that prodigious use of simulations has been crucial in the development of the various WSJT modes [8].

This analysis does not consider shorthand messages that are available in both protocols. These messages are optionally sent after the initial callsign exchanges. They are primarily used on 144 MHz and higher frequencies to convey information with pings as short as 20 ms. FSK441 implements shorthand messages with single tones whereas MSK144 has 40-bit, 20 ms frames that incorporate forward error correction.

Synchronization in FSK441. The FSK441 protocol was described by Joe Taylor in the December 2001 issue of QST [2]. It uses four tones labeled 0, 1, 2, 3 to generate an alpha-numeric character set, each character formed by a unique sequence of three of the four tones or "dits". This defines 4 x 4 x 4 = 64 character combinations. Four shorthand messages (R26, R27, RRR, 73) are rendered by a sequence of three identical tones. To implement time synchronization in multi-tone messages, Tone 3 is absent from the first dit position of any character. The number of unique three dit combinations then becomes 3 x 4 x 4, less the single-tone sequences for R27, RRR, and 73. This leads to a reduced 45 character set.

The four tones are harmonic multiples of 441 Hz at 882, 1323, 1764, and 2205 Hz, sampled at 11025 samples/sec. Each tone or dit is generated with 25 sample points; 3 dits define a character duration of approximately 6.8 ms.

To reliably decode a ping, the software must locate at least one time synchronization point in the multi-tone data string. The synchronization process can be understood by examining the *FORTRAN* source code. The multi-tone decoder mtdecode.f90 calls the subroutine longx.f90 when a potential ping is located in the captured audio stream. If FSK441 modulation is encountered, any frequency offset is corrected and tones are assigned to sequential dit positions by the subroutine sync.f90. A systematic sorting of the data is then performed to look for the presence of Tone 3. Because there are three tones (dits) per character, there are three possible synchronization sequences. No character starts with Tone 3, so the data sequence that is *missing* Tone 3 at every third position identifies the correct synchronization.

Some example data strings can illustrate the critical role of Tone 3 in the decoding algorithm. The message WO7R K5QE is rendered in FSK441 as:

213133013202**033**123011201230**033**

This message contains 10 characters including two space characters (033) and has duration 68 ms. At least one space is present in every multi-tone message and assures synchronization in the event that other characters are not present to perform this task. In the above example message, the two callsigns WO7R and K5QE can individually provide synchronization without a space. The combination of characters K (123) and E (230) accomplish this for the four characters K5QE. The single character O (133) does the same for the string WO7R.

To obtain synchronization without a space, the sequence of decoded characters must place at least one Tone 3 in the positions of the second and third dits. Six characters have Tone 3 at dit position 2: L, M, N, O, E, and Z. Nine characters have Tone 3 at dit position 3: 0, 3, 7, C, G, K, O, S, and W [9]. Characters from both sets must be in a ping for it to properly decode *unless* the letter O or the space is also present.

An example of a message without any of the first set of characters is KG5CCI WA7HQD. It is generated as a 14 character sequence of duration 95 ms:

1231130111031031210**033**2131010131202011100**033**

This longer message will not synchronize without the space character. This has implications for partial decodes with short pings.

In the message WO7R K5QE, the 21 ms, 9-dit sequence 301120123 produces the partial decode 5Q. The 21 ms sequence 213133013 gives a three character partial decode WO7 because it contains the letter O. Both of these partial decodes do not use the space. Partial decodes are possible with the second example message, but the space character 033 must be part of the sequence. Consider this 46 ms portion of the second message:

32131010131202011100

Even though this ping is more than twice as long, it may not decode due to the synchronization ambiguity introduced by Tone 3 being absent in dit position 2.

Statistical analysis of FSK441 with short pings. When pings are too short to convey a complete message, partial decodes in FSK441 can be used to collect the missing characters over multiple transmit-receive sequences. To make the following statistical simulations general, the presence of the space character is required for all partial decodes. Messages that draw from both the special 6- and 9-character sets and/or having the single character O in particular will have an advantage for partial decoding. This message-specific advantage is ignored here to illustrate trends.

Partial decodes often provide enough information for an operator to realize where in the QSO message sequence the transmitting station is, without decoding the complete message. The accepted procedure for meteor scatter work is that *all* characters in the message must be received before proceeding to the next message. Construction of a complete message is required for the following simulations.

A 1x2 callsign station calling a 1x2 callsign requires a 10 character message of duration 68 ms. A 20 ms ping will have as many as three characters, but may not always include a space. Pings without a space are discarded for decoding but included in the count. The position in the message where the ping occurs cannot be anticipated and is entirely random. Considering *only* 20 ms pings, the task is to determine how many pings will occur – both decoded and not decoded – until the complete message is recovered [3].

The simulation randomly selects a three-character sequence and counts how many of these short pings are required to piece together a complete 1x2 1x2 message (Message 1). To generate a statistically significant data set, the simulation is run 1000 times representing essentially 1000 message communication attempts. Many thousands of pings are analyzed. Results are depicted in the top-left histogram of Figure 1. The probability of receiving the minimum four decodes that contain the entire message is small. The average ping count to receive the complete message is 21.3.

In VHF contests, a 4-digit grid square accompanies the callsigns. This lengthens the message to 15 characters and 102 ms (Message 2). The bottom-left histogram in Figure 1 shows that the needed 20 ms ping count increases to 35.8, as expected for a larger message payload. For both messages, 59% of the pings decode.

In general, a 2x3 callsign cannot be conveyed using exclusively 20 ms partial decodes. The reason is that the interior characters are too far time-separated from the space character, rendering synchronization ambiguous.

The situation improves when the ping duration increases to 30 ms, allowing partial decodes of four characters in the sequence. Simulation data is shown in the histograms in Figure 1, right. Message 1 with 1x2 callsigns requires an average of 7.7 pings. Adding the grid square to the message (Message 2) shifts the peak of the distribution. The corresponding average is 13.4 pings, a significant reduction compared to the

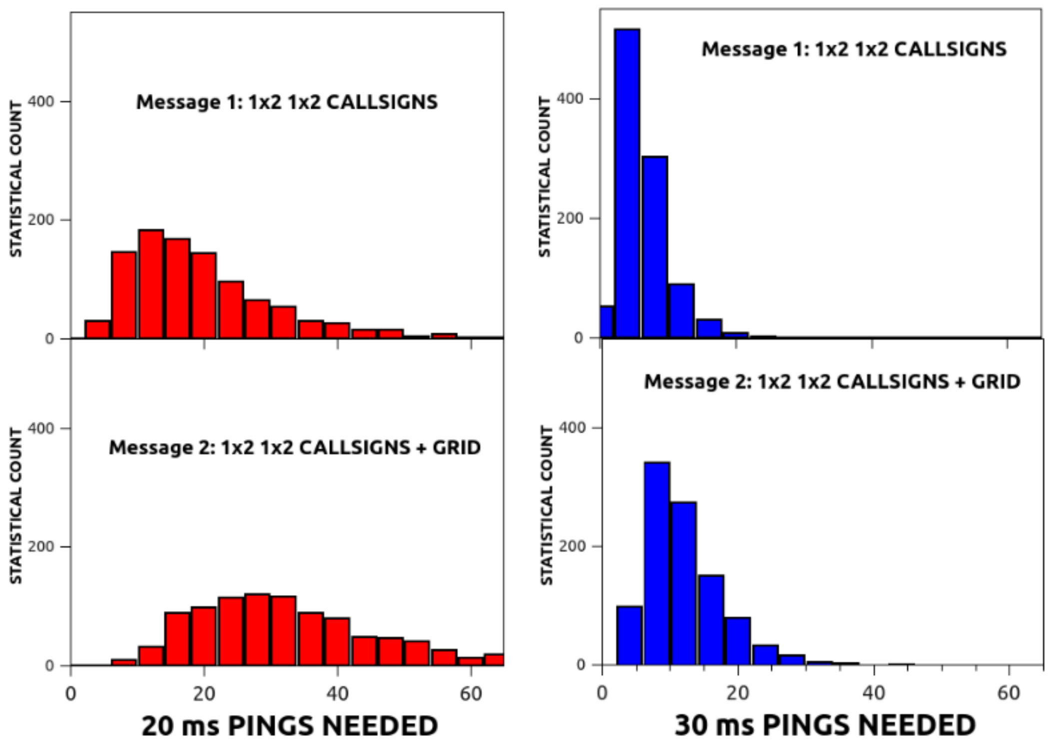

Figure 1: Simulations to construct FSK441 messages with 1x2 callsigns. Top, left: Number of 20 ms pings to assemble a 68 ms message. Bottom, left: Number of 20 ms pings to assemble a 102 ms message that includes 4-digit grid square. Non-decoding pings are included in the counts. Right: Everything the same except simulations are with 30 ms pings.

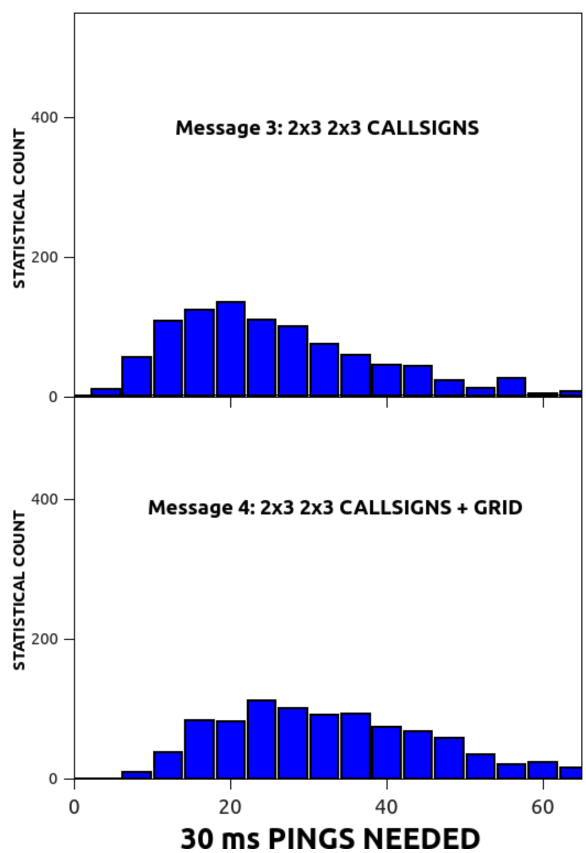

Figure 2: Simulations with 30 ms pings to build FSK441 messages with 2x3 callsigns. Top: Number of 30 ms pings to assemble a 95 ms message. 56% of the pings decode. Bottom: Number of 30 ms pings to assemble a 129 ms message that includes 4-digit grid square. 63% of the pings decode.

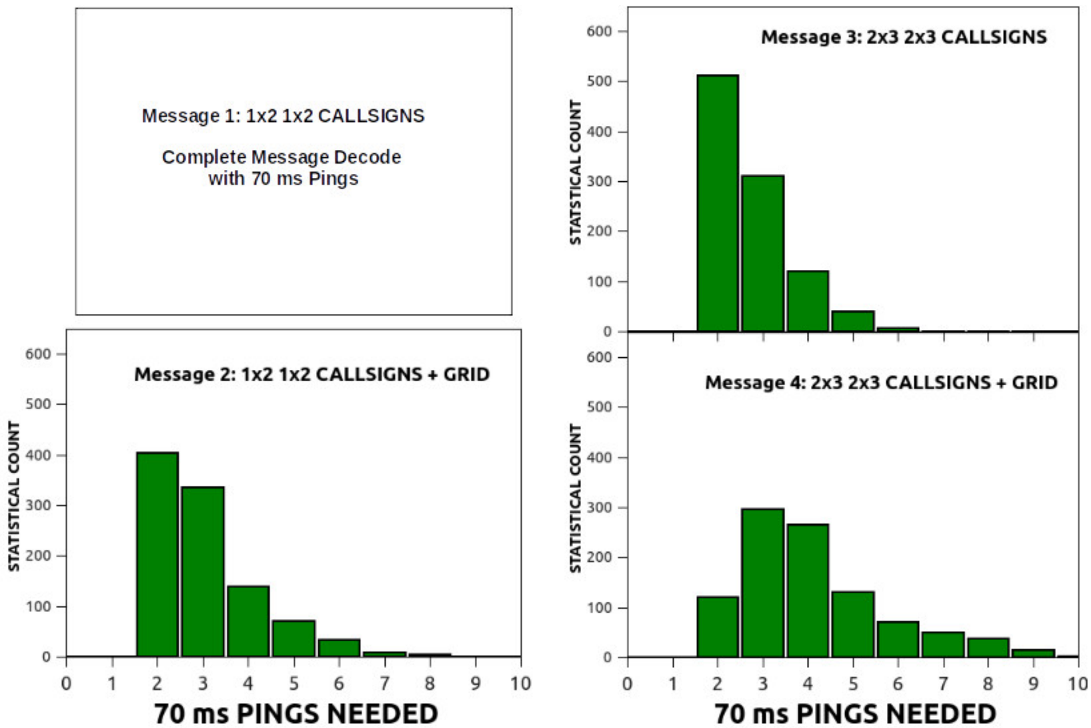

Figure 3: Simulations of FSK441 decodes with 70 ms pings. Top, left: The 1x2 1x2 message always decodes with a single ping. Bottom, left: A 70 ms ping is too short to convey both callsigns and the grid square data. Multiple partial decodes are needed, with an average count of 3.1. Right: Only partial decodes are possible with longer messages, but the decode rate is 100%. The average number of pings needed is 2.7 (top) and 4.2 (bottom).

same message using only 20 ms decodes. The longer 30 ms pings result in an 80% decode probability.

Now consider longer operating messages. A 2x3 callsign calling a 2x3 callsign is rendered with 14 characters including two spaces in a message that spans 95 ms (Message 3). A ping duration of 30 ms places all characters within reach of the space characters, making partial decodes of the complete message possible with enough sequences. Simulation results for a message with only the 2x3 callsigns are shown in Figure 2, top. The average decode count in this case is 20. Adding the 4-digit grid square produces a 129 ms message (Message 4) and a statistical increase in the needed 30 ms ping count to 38. The decode probabilities are 56% and 63%, respectively. The slight increase for the second message reflects a grid string that is two characters shorter than the callsigns. This puts the interior of the string closer to the spaces.

A 70 ms ping is approximately the same length as an MSK144 frame, so that is the clear mode of choice on this timescale. All messages payloads – subject to the MSK144 protocol limits – are accessible at this duration with the signal-to-noise benefit provided by forward error correction. It is worth noting that 3 of the 4 example messages still require multiple partial decodes using FSK441 with 70 ms pings. These pings are long enough that the space character is always present. Simulation results are shown in Figure 3.

Realistic Simulations. The duration of meteor scatter pings spans a wide range, depending on the operating frequency, time of day, time of year, whether a shower is occurring, the atmospheric conditions, transmitter power, antenna gain, and many other factors. The preceding simulations use very short, fixed-duration pings to illustrate the effectiveness of FSK441 in re-constructing messages with random partial decodes. A more realistic model should account for the statistical variation of ping duration.

Fewer and shorter pings occur on the 144 and 222 MHz amateur bands compared to 50 MHz. Data on the variability of their duration does not appear to be available in the published literature. A heuristic approach is taken here. It is assumed that pings having duration 20–30 ms are most probable. A 75 ms ping is taken to be 6 times less likely. A probability distribution function with these boundary conditions is constructed as a quasi-exponential and is depicted in Figure 4. This function is believed to be a conservative representation of conditions on 222 MHz [10]. The horizontal axis is delineated by the number of FSK441 characters composing a ping, ranging from a minimum of 3 to a maximum of 18. This corresponds to approximately 20–122 ms, since each character is 6.8 ms.

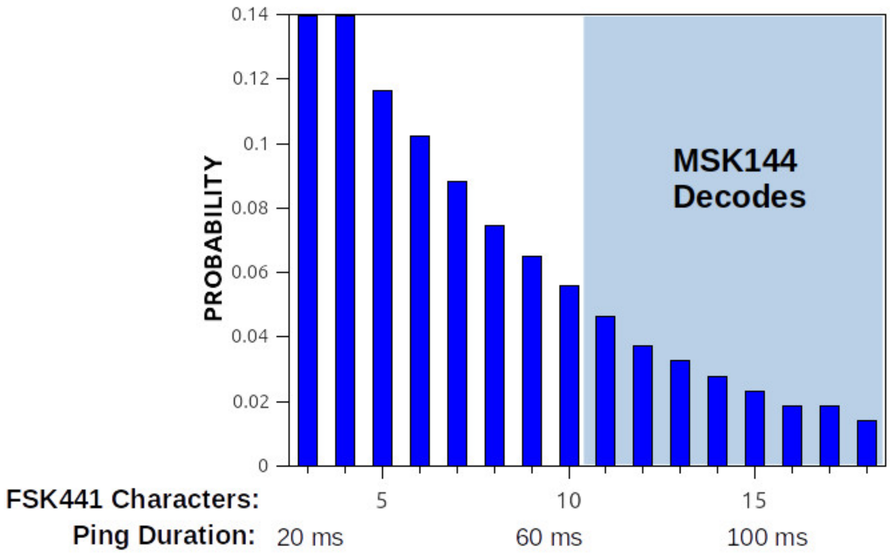

Figure 4: Heuristic ping probability distribution used in the simulations. The x-axis is labeled in units of FSK441 characters and also ping duration. The shaded region denotes pings longer than 70 ms that decode with MSK144. These represent 22% of the pings in the model, or about 1 in 5.

Pings longer than 11 characters or 75 ms will always produce a complete message decode with MSK144. This is shown by the shaded region in Figure 4. Only a minimum 1x2 1x2 callsign message will completely decode with 11 characters in FSK441. Larger message payloads require longer pings or multiple partial decodes. Only 22% of the pings in the distribution of Figure 4 are long enough to decode a 72 ms MSK144 message frame.

The simulation is modified to include variable duration pings as described by the probability distribution in Figure 4. If the ping duration exceeds 10 FSK441 characters, a complete MSK144 decode occurs. The same pings are also evaluated as the source of random FSK441 message characters, with the requirement that the space character must be present to ensure synchronization. A message is then constructed by accumulating partial or full decodes. In this way, the efficiency of the FSK441 and MSK144 protocols can be compared. As above, 1000 simulations are performed for each message.

A comparison of the two modes can also be done with Gaussian white noise present on the pings. This can demonstrate the advantage of forward error correction afforded by MSK144, but requires implementation of both decoder algorithms. To isolate the role of ping duration, the simulations here assume that both modes are equally sensitive in all conditions. In practice, MSK144 will work much better than FSK441 when the pings are weak.

Results for example messages using 1x2 callsigns are shown in Figure 5. For the shortest 1x2 1x2 callsign

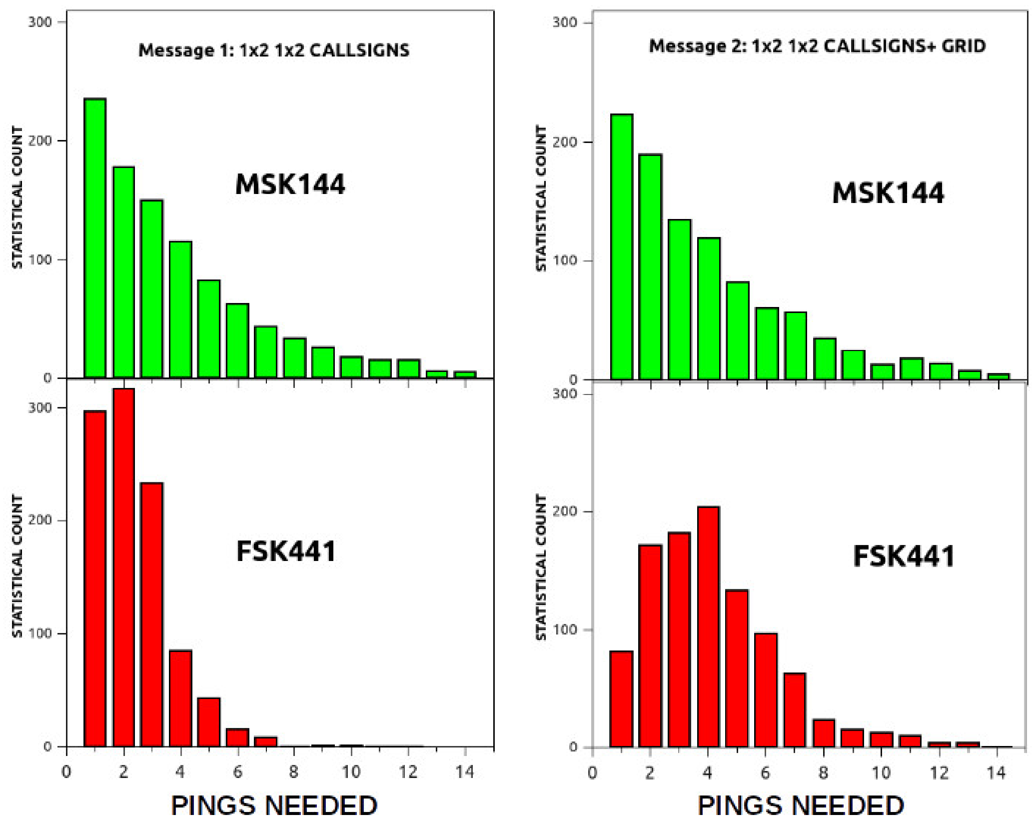

Figure 5: Simulations comparing MSK144 and FSK441 with 1x2 callsign messages using the distribution of ping durations shown in Figure 4. The two modes perform the same within the statistical uncertainty [11].

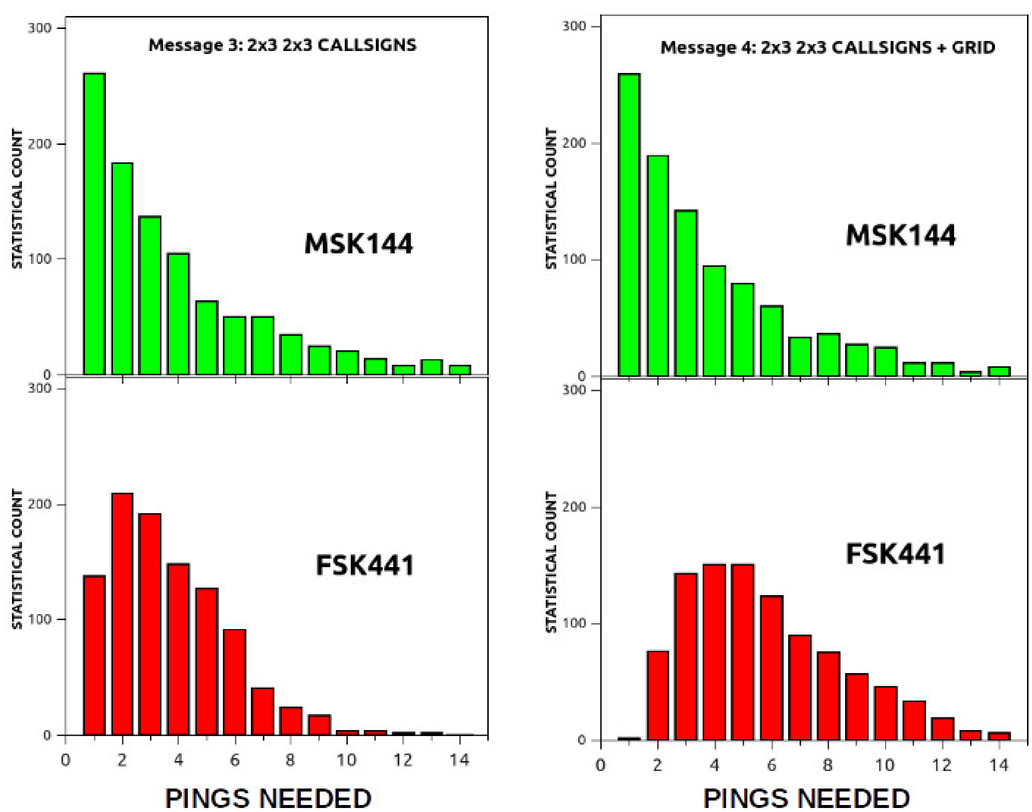

Figure 6: Same as Fig. 5 except 2x3 callsign messages. MSK144 is more efficient as the message payload lengthens.

message (Message 1), FSK441 requires on average 2.4 ± 1.6 pings while MSK144 averages to 4.0 ± 2.0 pings. Adding the 4-digit grid square (Message 2) lengthens the FSK441 message and shifts the peak of the decoded distribution (Figure 5, right). The average number of pings for a full messsage decode increases to 4.1 ± 2.0. Statistics for the MSK144 mode should not change as compared to the shorter payload; the simulation confirms this at 4.3 ± 2.1 pings. The two modes have equivalent efficiency within the uncertainty of the model [11].

Simulations with the longer 2x3 callsign messages are shown in Figure 6. Message 3 with just a pair of 2x3 callsigns requires 3.7 ± 1.9 pings with the FSK441 protocol compared to 4.1 ± 2.0 pings using MSK144. When the grid square is added to generate Message 4, the ping count for FSK441 increases to 6.0 ± 2.4 and remains at 4.0 ± 2.0 for MSK144. Message 4 rarely decodes with a single FSK441 ping in this statistical model. MSK144 is clearly a superior choice with these longer messages, even with an abundance of partial decodes available with FSK441. Results of the simulations in this section are summarized in Table 1.

Mode	Message 1: 1x2 callsigns	Message 2: 1x2 callsigns + grid	Message 3: 2x3 callsigns	Message 4: 2x3 callsigns + grid
FSK441	2.4 ± 1.6	4.1 ± 2.0	3.7 ± 1.9	6.0 ± 2.4
MSK144	4.0 ± 2.0	4.3 ± 2.1	4.1 ± 2.0	4.0 ± 2.0

Table 1: Number of pings needed to convey a complete message using FSK441 and MSK144. Pings are assumed to be strong enough that decode sensitivity is the same for both modes.

The statistical distribution is modified so that approximately 1 of every 3 pings has duration long enough to decode with MSK144. This is modeled as a quasi-exponential shown in Figure 7. The simulations are repeated and results are summarized in Table 2.

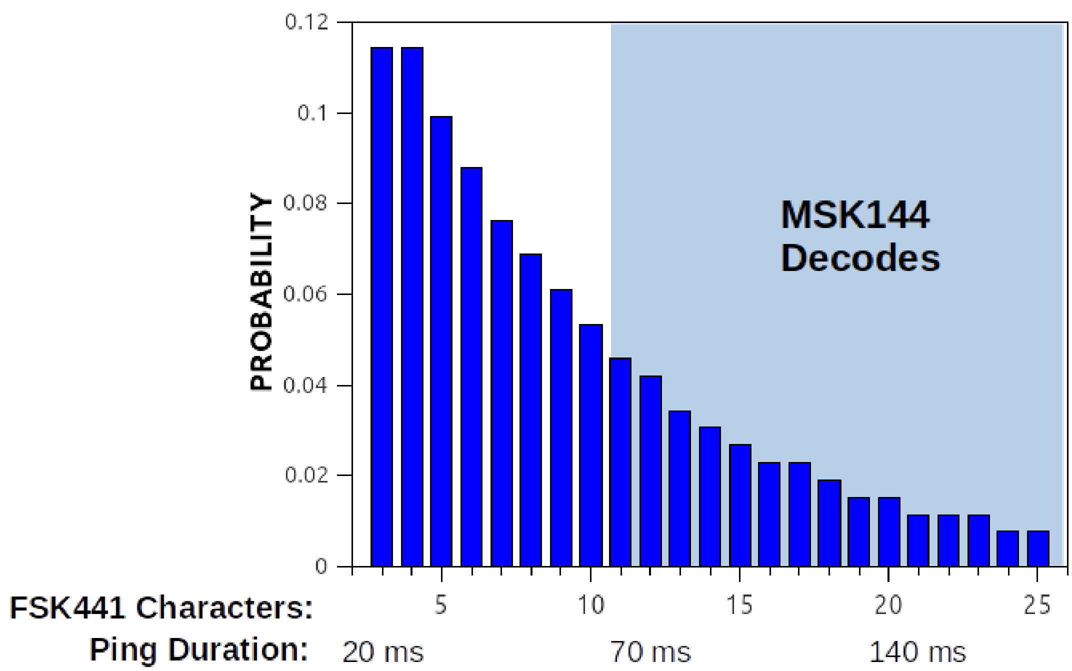

Figure 7: Modified probability distribution in which 33% of the pings (about 1 in 3) completely decode with MSK144.

Mode	Message 1: 1x2 callsigns	Message 2: 1x2 callsigns + grid	Message 3: 2x3 callsigns	Message 4: 2x3 callsigns + grid
FSK441	2.0 ± 1.0	3.0 ± 1.7	3.0 ± 1.7	4.3 ± 2.1
MSK144	2.9 ± 1.7	2.8 ± 1.7	2.9 ± 1.7	2.8 ± 1.7

Table 2: Number of pings needed to convey a complete message using FSK441 and MSK144 with the statistical distribution in Figure 7.

In this revised model slightly longer pings are statistically more likely. Both modes require fewer pings to get complete decodes, but MSK144 again exhibits superior performance with longer messages.

Conclusion. Simulations were performed to compare the efficiency of FSK441 and MSK144 in conditions dominated by short, strong meteor scatter pings. FSK441 can obtain partial decodes of multi-tone pings in the range 20–70 ms, which are too short to convey general messages with MSK144. An accumulation of partial decodes can be used to reconstruct a message depending on its length and the presence of synchronization data. The statistical model presented here shows that – on average – it can take the same or less time to complete a QSO with MSK144. This was demonstrated with the conservative assumption that only 22% of the simulated pings are long enough to support an MSK144 message frame. Essentially the same result is obtained when the model is modified for a higher occurrence of slightly longer pings. The MSK144 protocol produces a complete message decode with single pings > 70 ms, which may not always happen with FSK441. Very important is that MSK144 may provide as much as 8 dB or more sensitivity due to forward error correction. FSK441 can, however, make decodes with a looser frequency tolerance between the communicating stations. Unless pings longer than 70 ms are anticipated to be very unlikely, MSK144 should be the preferred mode for VHF-UHF meteor scatter work.

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[8] J. Taylor, "The JT65 Communication Protocol", *Proc. of the 39th CSVHF Conf.* (2005).

[9] The four characters / # , ? can also perform this function. The latter three are unlikely to be used in meteor scatter messages.

[10] Operations during the 2020 ARRL UHF distance contest suggest that the *majority* of pings on 222 MHz were long enough to support the 72 ms duration MSK144 frames.

[11] The statistical uncertainty associated with a normal (Gaussian) distribution cannot be applied to these asymmetric histograms. The FSK441 data is reasonably described by a Poisson distribution and the MSK144 data aligns with an exponential probability distribution with no fitting parameters. The stated deviation is the square-root of the mean.

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