IS THERE A SHAPED OFFSET 8-PSK?

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ABSTRACT

Motivated by the success of the ARTM Tier-1 modulation known as Shaped Offset QPSK, this paper examines whether improved spectral efficiency can be achieved using an a Shaped Offset 8PSK. Three possible interpretations of this question are examined and it is shown that there does not appear to be a shaped offset 8-PSK in the context of aeronautical telemetry.

INTRODUCTION

Improved spectral efficiency has been an important issue in aeronautical telemetry over the past decade. This effort began in earnest in 1997 with the Advanced Range Telemetry (ARTM) program [1]. The goal was to triple the bandwidth efficiency of the modulated carrier relative to PCM/FM without sacrificing detection efficiency (the signal-to-noise ratio required to achieve a target bit error rate). This goal was accomplished in two phases. In the first phase, two interoperable modulations were adopted as options in the IRIG 106 standard: Feher-patented QPSK [2], version B or FQPSK-B (2000) and Shaped Offset-QPSK [3] version TG or SOQPSK-TG (2004). An "open source" version of FQPSK, called FQPSK-JR, was adopted as an interoperable alternative in 2004 [4]. These modulations, known collectively as "ARTM Tier-1 modulations," achieved a two-fold improvement in spectral efficiency over PCM/FM [5]. The second stage, completed in 2004, defined a multi-index partial response CPM (continuous phase modulation) [6][7], termed ARTM CPM, as an option in the IRIG-106 standard. ARTM CPM offered an additional 50% improvement in spectral efficiency without sacrificing detection efficiency.

The ARTM Tier-1 modulations are interoperable in the sense that each occupies the same bandwidth (for the same bit rate) and each produces the same bit sequence with essentially the same bit error rate when demodulated using a conventional (unshaped) offset-QPSK demodulator. While improvements in the bit error rate are possible using more advanced demodulators [8]—[16], detection using the simple, symbol-by-symbol OQPSK demodulator is attractive since 1) it is a relatively simple demodulator capable of operating at high data rates; 2) it does not have to "know" which of the ARTM Tier-1 modulations is being used since it is not optimized for any one of them, and 3) it met the stated objectives of the ARTM program.

The demodulator for the ARTM Tier-2 modulation is, by comparison, very complex [6] and symbol-by-symbol detection is not an effective demodulation method [17]. While some substantial complexity reducing techniques have proven useful when applied to ARTM CPM

[18]—[20], none of these achieve the performance and simple elegance of the linear offset QPSK demodulator and its application to the ARTM Tier-1 modulations.

This observation has led some to ask, "Is there a shaped-offset 8-PSK?" In context, this question expresses the desire to find a modulation, suitable for demodulation with a relatively simple demodulator, that offers the same bandwidth efficiency improvements over the Tier-1 modulations that unshaped 8-PSK offers over unshaped QPSK (i.e. a 50% improvement in spectral efficiency). The search, however, is not completely unconstrained. Like the ARTM Tier-1 and Tier-2 modulations, the shaped-offset 8-PSK must be compatible with non-linear power amplifiers.

Two conditions are necessary for a modulation to be compatible with a non-linear power amplifier. These conditions are best described using a phase trajectory plot. The phase trajectory plot is obtained by writing the modulated carrier in the general form

$$s(t) = I(t)\cos(\omega_c t) - Q(t)\sin(\omega_c t) \quad (1)$$

where $I(t)$ is the "in-phase" component of the modulated carrier and $Q(t)$ is the "quadrature" component and ω_c is the carrier frequency in radians/second. The phase trajectory is a plot of $Q(t)$ vs. $I(t)$. It can be thought of as a "rectangular" or "Cartesian" representation of the waveform. The magnitude of a point on the plot is the instantaneous envelope of the modulated carrier while the angle between the point and the positive $I(t)$ axis is the instantaneous phase of the modulated carrier; hence the name. To be compatible with a non-linear power amplifier, the phase trajectory must satisfy two important conditions:

- The phase trajectory should not pass through the origin of the $Q(t)$ vs. $I(t)$ plot. When the phase trajectory does pass through the origin, the power amplifier output is reduced to zero for an instant and returns to full scale (or close to full scale) an instant later. This is equivalent to quickly turning off then turning on the power amplifier. This action exercises all of the transients associated with the device nonlinearities and produces a signal whose spectral occupancy is much greater than it would be otherwise. For linear modulations (such as QPSK), a phase trajectory through the origin occurs when the signs of the both $I(t)$ and $Q(t)$ change at the same time. Usually, this is prohibited from occurring when $Q(t)$ is delayed relative to $I(t)$ by half of the symbol time. The delay offsets the data transitions occurring in $I(t)$ and $Q(t)$ so that simultaneous transitions are not allowed.
- The phase trajectory should follow a circle in the $Q(t)$ vs. $I(t)$ plot. The magnitude of the phase trajectory is the amplitude modulation (AM) component of the carrier. Any AM present in the modulated carrier is compressed by the non-linear characteristic of the power amplifier. This distorts the signal as it passes through the amplifier. One of the consequences of this distortion is an increase in the occupied bandwidth of the modulated carrier. For many power amplifiers a quasi-constant envelope (or amplitude) is sufficient to ensure acceptable performance.

Putting this all together, to answer the question with "yes," a modulation should meet the following requirements:

- A generic demodulator designed to operate with unshaped 8-PSK or unshaped offset 8-PSK should be able to recover the data from the modulated carrier with no (or very little) loss in detection efficiency relative to PCM/FM with limiter-discriminator detection.
- The bandwidth efficiency should be 50% better than the bandwidth efficiency of the ARTM Tier 1 modulations. This is equivalent to requiring the bandwidth efficiency to be 3 times better than that of PCM/FM.
- The modulation should be compatible with non-linear RF power amplifiers: namely the phase trajectory should not have transitions through the origin and the phase trajectory should approximately follow a circle.

In the next three sections, modulations that satisfy these conditions are examined. First 8-PSK with an offset inphase and quadrature component is examined. Such a modulation is the most obvious way to meet the first condition. However, it is shown that the third condition cannot be met with this approach. Next, the first condition is relaxed somewhat in that a demodulator using symbol-by-symbol detection with 8 phase states is allowed in place of an unshaped 8-PSK demodulator. Several representative examples are summarized. It is shown that it is difficult (maybe impossible) to achieve improved spectral efficiency without decreased detection efficiency. Finally, the first condition is dropped altogether. The remaining two constraints define the conditions under which the ARTM Tier-2 modulation was developed. Hence ARTM CPM is the "answer" in this case.

8-PSK WITH AN OFFSET INPHASE AND QUADRATURE COMPONENT

The phase trajectory and I/Q eye-diagrams of a band-limited version of 8-PSK is illustrated in Figure 1. Observe that the phase trajectory is concentrated around the 8 phase states and that the eye diagrams each have 5 valid levels at the optimum sampling instants. Applying a half-symbol-time offset to the quadrature component of the 8-PSK signal produces the phase trajectory and eye diagrams illustrated in Figure 2. Observe that the eye diagrams are shifted relative to each other just as expected. However the phase trajectory displays transitions through the origin.

The reason for the undesired transitions through the origin of the phase trajectory is the placement of 8-PSK constellation points directly on the inphase and quadrature axes. This is the most evident by the phase trajectory plot of Figure 1. The most straight forward way to overcome this characteristic is to rotate the constellation points by any angle that is not a multiple of $2\pi/8 = \pi/4$. Rotating the points by $\pi/8$ produces the phase trajectory and eye diagrams of Figure 3 for the non-offset case and the phase trajectory and eye diagrams of Figure 4 for the offset case. The $\pi/8$ phase shift is able to produce a phase trajectory without transitions through the origin. However, the phase trajectory exhibits concentrations at 12 points that are not on a circle. Thus, it is hard to see how selecting a different pulse will result in constant envelope behavior.

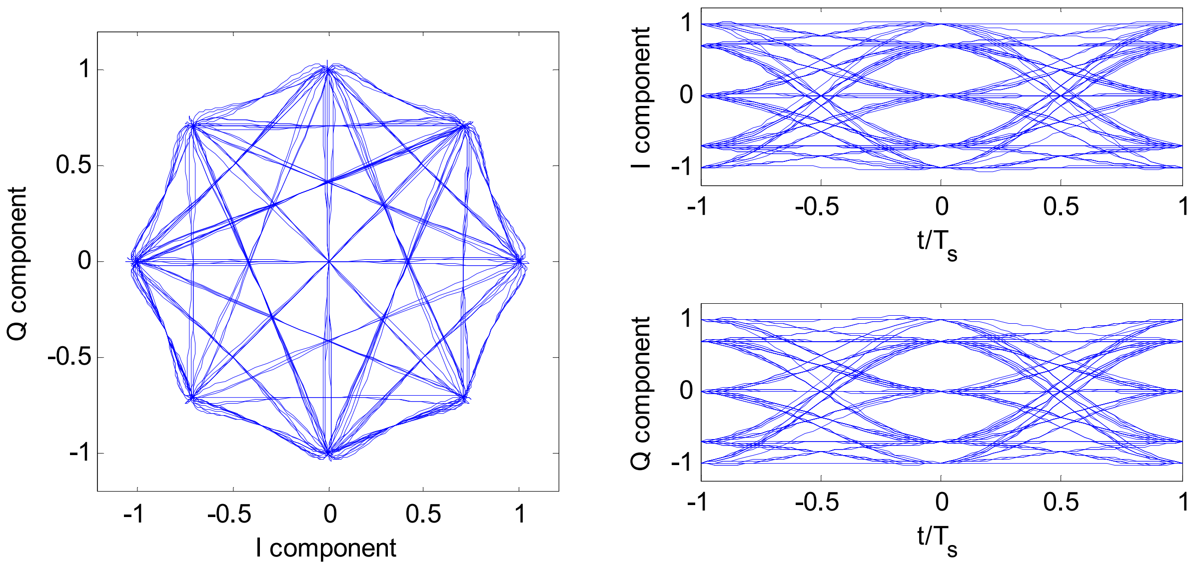

Figure 1: Phase trajectory (left) and eye diagrams (right) for non-offset 8-PSK using the raised cosine pulse shape with 100% excess bandwidth.

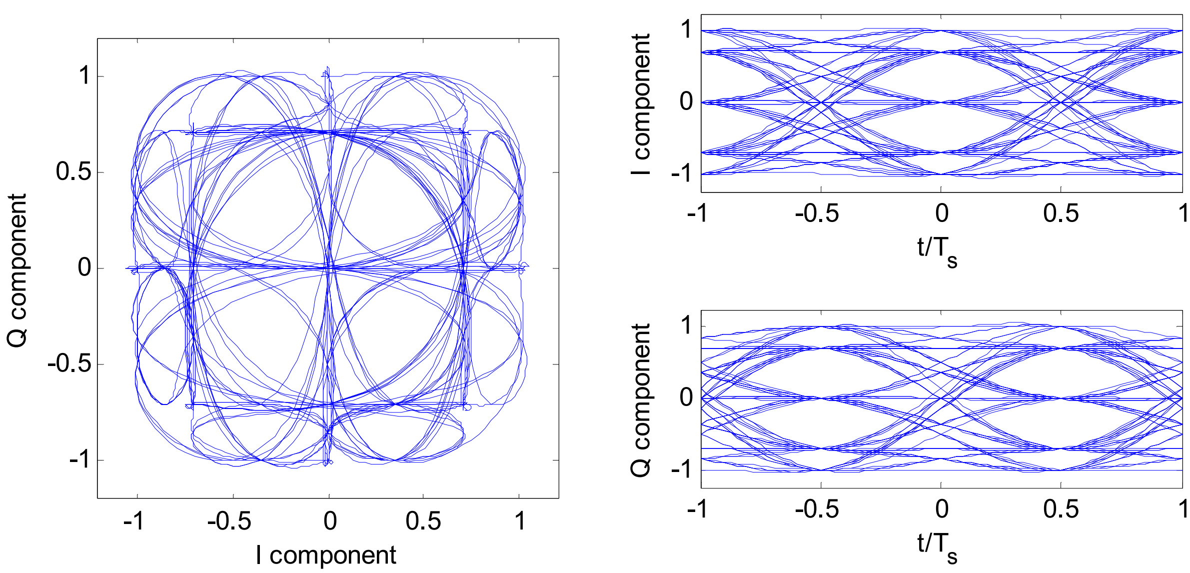

Figure 2: Phase trajectory (left) and eye diagrams (right) for offset 8-PSK using the raised cosine pulse shape with 100% excess bandwidth.

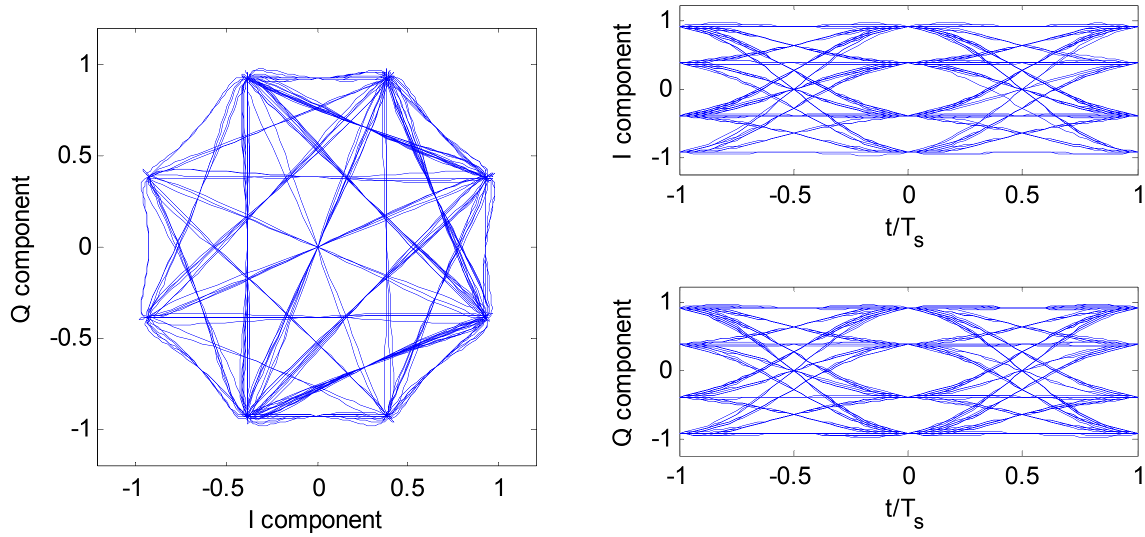

Figure 3: Phase trajectory (left) and eye diagrams (right) for non-offset 8-PSK using the raised cosine pulse shape with 100% excess bandwidth. The constellation points have been rotated by $\pi/8$.

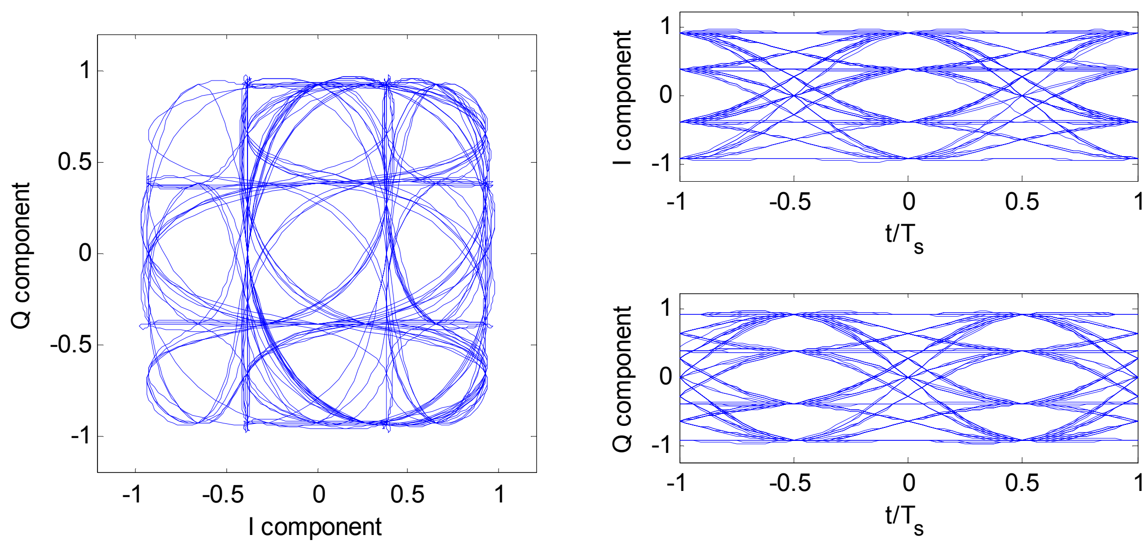

Figure 4: Phase trajectory (left) and eye diagrams (right) for offset 8-PSK using the raised cosine pulse shape with 100% excess bandwidth. The constellation points have been rotated by $\pi/8$.

CONSTANT ENVELOPE MODULATIONS WITH 8 PHASE STATES

The results of the last section demonstrate that it is difficult (impossible?) to produce an offset 8-PSK that has constant envelope or quasi-constant and phase transitions that do not pass through the origin. This observation motivates an alternative interpretation of the question: Is there a shaped offset 8-PSK? In this interpretation, we relax the constraint that the data be recoverable from an unshaped offset 8-PSK demodulator and replace it with the following constraints:

- the modulation must have 8 phase states, and
- a symbol-by-symbol demodulator operating on 8 phase states must be able to recover the data.

The second notion constrains the demodulator to "look like" an 8-PSK demodulator in the sense that is has approximately the complexity as the 8-PSK demodulator. Whether it has the same detection efficiency depends on the properties of the waveforms generated by the modulator.

To meet the constant envelope requirement, we consider continuous-phase modulations (CPMs) that consist of 8 phase states. A CPM signal is of the form

$$s(t) = \cos(\omega_c t + \phi(t;\boldsymbol{\alpha})) \tag{2}$$

where ω_c is the carrier frequency in radians/sec and where the phase is

$$\phi(t;\boldsymbol{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{k=-\infty}^{n} \alpha(k) f(x - kT_s) dx \tag{3}$$

for $nT_s \le t < (n+1)T_s$ and $\boldsymbol{\alpha} = \ldots, \alpha(0), \alpha(1), \ldots, \alpha(n), \ldots$ is the data symbol sequence. The CPM signal is defined by three parameters: the modulation index *h*, the frequency pulse $f(t)$ which spans LT_s seconds (i.e., it spans *L* symbol times), and the alphabet from which $\alpha(k)$ is drawn. For example, SOQPSK-TG is defined as a CPM with a modulation index h = 1/2, a length-$8T_b$ frequency pulse, and a ternary alphabet. The number of phase states is a function of *h*, *L*, and *M* (the size of the symbol alphabet) as described in [21], [22]. Using the definition, SOQPSK-TG has 8 phase states as expected with an offset QPSK.

There are a variety of pulse shapes, alphabets, and modulation indexes that produce a modulated carrier with 8 phase states. A representative sampling is the following:

- S8PSK, 9: CPM using the 1 REC pulse shape, h = 1/4, with a 9-ary alphabet. The next symbol is determined by the most recent 3 bits and is designed to produce a phase shift, along the unit circle, that is a multiple of $\pi/4$.
- S8PSK-TG, 9: this is the same as S8PSK,9 described above, except the TG pulse is used.
- S8PSK, 7: CPM using the 1 REC pulse shape, h = 1/4, with a 7-ary alphabet. The next symbol is determined by the four most recent bits and is designed to produce a phase shift, along the unit circle, that is a multiple of $\pi/4$.
- S8PSK-TG, 7: this is the same as S8PSK, 7 described above except the TG pulse shape is used.
- SOQPSK-MIL, h=1/4: CPM using the 1REC pulse shape with h = 1/4 and the constrained ternary alphabet.
- SOQPSK-MIL, 2REC: CPM using the 2REC pulse shape with h = 1/2 and the constrained ternary alphabet.
- CPM QPSK: CPM using 1 REC pulse shape with h = 1/2 and a true 4-ary symbol alphabet.

- CPM QPSK-TG: this is the same as CPM QPSK above except the TG pulse shape is used.
- 2 alphabet: this is a variant of π/4-shifted QPSK alternating between two 4-ary symbol alphabets to produce 8 phase states. The 1 REC pulse shape is used.
- 2 alphabet, TG: this is the same as the 2 alphabet modulation above, except the TG pulse shape is used.

The last two are not CPMs but rather variations of π/4-shifted QPSK, which is widely used in mobile cellular telephony [23] for the same reasons it is of interest here.

For each case, the modulated signal was generated using random data and the power spectral density was estimated using the windowed periodogram method. In addition the minimum Euclidean distance for each modulation was also determined. This was used to estimate the probability of error using

$$P_e \sim Q\left(\sqrt{\frac{E_b}{N_0} d_{\min}^2}\right) \tag{4}$$

where $Q(x)$ is the area under the tail of the standard Gaussian probability density function.

A summary of the results is plotted in Figure 5. The bandwidth is reported as a normalized bandwidth: the −60 dB bandwidth divided by the bit rate. Thus, the smaller this number is, the more bandwidth efficient it is. The detection efficiency is measured by the value of E_b/N_0 required to achieve a probability of error 10^{-6}. The smaller this number is, the better the detection efficiency. Thus, the most desirable location in the plot of Figure 5 is the lower left-hand corner: the modulated carrier requires zero bandwidth and zero power to achieve an error rate of 10^{-6}.

It should be pointed out that the detection efficiency is based on minimum Euclidean distance formulations which assume fully coherent sequence detection. A symbol-by-symbol detector for each modulation would require a higher value of E_b/N_0 than that reported in Figure 5 to achieve a probability of error 10^{-6}. The authors' experience with SOQPSK-TG is that there is a 2 dB difference between the optimal detector (whose performance follows the minimum Euclidean distance approximation) and the simpler symbol-by-symbol detector.

Several observations are in order:

- First, the plot is not well populated in the most desirable location in the lower left corner.
- Second, the use of the TG pulse over the 1REC pulse shape reduces the bandwidth (and improves the spectral efficiency) in all cases, but the cost in probability of error performance is different. This effect is the most dramatic with the two CPM QPSK modulations.
- Third, of the modulations with the best detection efficiency, the ARTM Tier 1 modulation has the best spectral efficiency.
- Fourth, of the modulations with the best spectral efficiency, CPM QPSK has the best detection efficiency, but is still worse than the Tier 1 modulations.

This by no mean a formal proof that there is no CPM with 8 phase states that meets the performance specifications set forth in the introduction. Improvements in detection efficiency are achieved at the expense of bandwidth efficiency and vice versa. It appears that SOQPSK-TG occupies a special place in this space.

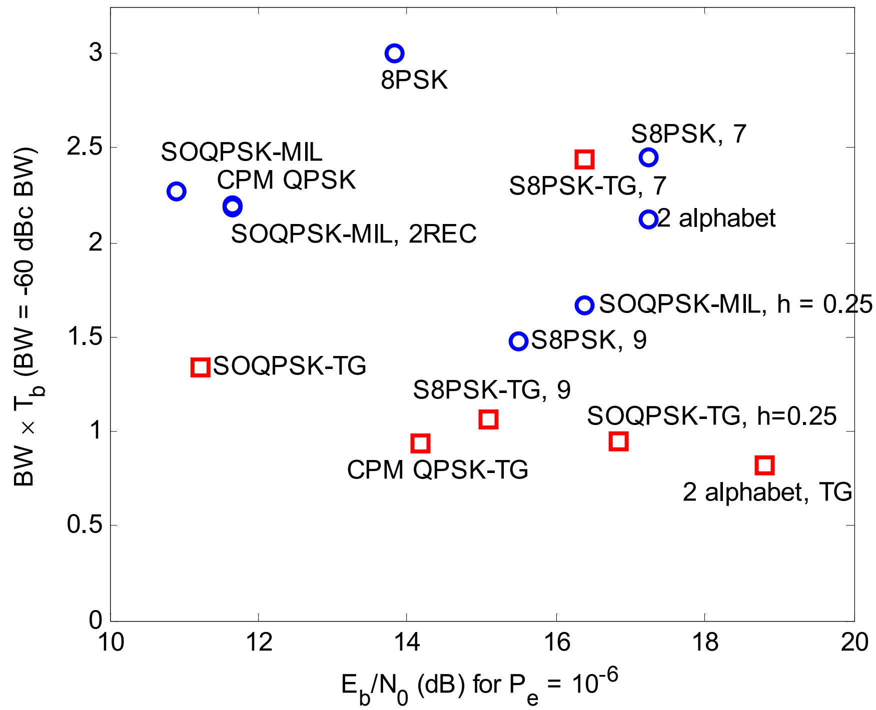

Figure 5: Normalized Bandwidth vs. Power Efficiency for the modulations described above.

A MODULATION THAT OFFERS A 50% IMPROVEMENT IN BANDWIDTH EFFICIENCY OVER THE TIER-1 MODULATIONS

The results of the previous section seem to indicate that there is no 8-state CPM that simultaneously possesses better spectral efficiency and the same detection efficiency as SOQPSK-TG. The constraint that the modulated carrier have 8 phase states (and thus a symbol-by-symbol detector whose complexity is commensurate with that of an 8PSK demodulator) seems to be the limiting factor. If this constraint is removed, then the question "is there a shaped-offset 8-PSK" is answered "yes" if there is a modulation that meets the second and third constraints set forth in the introduction.

A constant envelope modulation that has approximately the same detection efficiency as the Tier-1 modulations and a 50% improvement in bandwidth efficiency has already been identified: ARTM CPM, defined in the 2004 version of IRIG 106. This answer might have been anticipated by the removal of the complexity constraint on the demodulator.

CONCLUSIONS

This paper has examined the question "Is there a shaped-offset 8-PSK?" In its context, the question asks if there is modulation, suitable for use with a nonlinear power amplifier, with the same detection efficiency as the ARTM Tier-1 modulations, 50% better spectral efficiency than the ARTM Tier-1 modulations, and compatible with a relatively simple 8-PSK demodulator using symbol-by-symbol detection. It was shown that these requirements cannot all be met simultaneously, even when the complexity constraint is loosened somewhat. When the complexity constraint is completely eliminated (i.e., the requirement of being compatible with an 8-PSK demodulator is removed), the ARTM Tier-2 modulation is the answer.

While an almost infinite number of CPMs with 8 states can be conceived, it is hard to see how any of them will offer simultaneous improvements in spectral and detection efficiency. We conclude that, given the constraints of aeronautical telemetry, the ARTM Tier-1 and ARTM Tier-2 modulations provide an excellent compromise between spectral efficiency and detection efficiency (bandwidth and power) that is hard to beat.

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