DESCRIPTION AND PERFORMANCE RESULTS FOR THE ADVANCED RANGE TELEMETRY (ARTM) TIER II WAVEFORM

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ABSTRACT

The Advanced Range Telemetry (ARTM) program is a tri-service telemetry modernization project whose goal is to assure that all Department of Defense (DoD) test and training ranges are able to use telemetry as necessary to carry out their respective missions. Multi-h Continuous Phase Modulation (CPM) has been selected by the ARTM JPO as the Tier II ARTM waveform, because it offers significant improvements over both legacy telemetry waveforms (PCM/FM) and the newly-introduced Tier I waveform (Feher-patented FQPSK) in terms of spectral containment and detection efficiency, while retaining a constant envelope characteristic. The paper describes the theoretical and measured performance of the ARTM Tier II multi-h CPM waveform, and the implementation of the trellis demodulator being developed for it.

KEY WORDS

Continuous Phase Modulation, Spectral Efficiency, and Trellis Demodulator.

INTRODUCTION

Recently developed airborne data systems can generate and/or collect instrumentation data at rates that far exceed the data transmission capabilities of current telemetry equipment. With increasing data demands and limited frequency allocations, it is imperative that more spectrally-efficient techniques be employed.

This paper describes the multi-h Continuous Phase Modulation (CPM) waveform that is being developed for the ARTM Tier II program. The waveform parameters presented here yield a signal that can effectively triple the data capacity of present binary FM techniques with no loss in Eb/No performance. Furthermore, the constant envelope nature of the waveform allows it to be used with the efficient Class C amplifiers on the airborne platforms. Tradeoffs in bandwidth and detection efficiency can be easily made by changing the modulation index and frequency pulse characteristics.

SIGNAL DESCRIPTION

The constant-envelope signal of interest can be represented as

$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)d\tau \quad -\infty < t < +\infty$$

where the information bearing phase $\phi(t,\alpha)$ is determined by the M-ary data sequence ($\boldsymbol{\alpha} = [\alpha_{-\infty}\ldots\alpha_{+\infty}]$ where $\alpha_i = \pm 1, \pm 3, \cdots, \pm M-1$ for M even), the frequency function g(t), and the modulation index h. An equivalent description can be obtained using the phase function q(t).

$$q(t) = \int_{-\infty}^{t} g(\tau)d\tau$$

$$\phi(t,\overline{\alpha}) = 2\pi h \sum_{i=-\infty}^{+\infty} \alpha_i q(\tau - iT)$$

A great variety of CPM schemes can be obtained by varying the parameters h and M and choosing different frequency pulse shapes. A convenient method of comparing the performance of schemes with different parameters is to plot their location on the Bandwidth-Efficiency plane. Using results from [1] and [2] provided insight into which set of parameters were likely to achieve the combination of data throughput and detection performance required for the ARTM Tier II program. It was found that a quaternary scheme (M=4) was the best candidate in terms of bandwidth utilization, detection performance, and implementation.

To simultaneously achieve the desired detection and spectral efficiency, a multi-h CPM scheme was selected. Instead of using a fixed modulation index, a set of values (**h** = h_1,h_2) are cycled through periodically. The instantaneous phase is now represented as

$$\phi(t,I) = 2\pi \sum_{i=-\infty}^{+\infty} h_i \alpha_i q(\tau - iT)$$

The basic idea is to change the modulation index each symbol to delay the point at which phase trajectories with different starting symbols remerge. This increases the minimum distance and thereby reduces the asymptotic probability of symbol error. The cost for obtaining better detection efficiency through the use of a multi-h scheme is an increase in receiver complexity as compared to the single-h case.

In order to achieve the desired spectral performance, the CPM signal bandwidth must be significantly less than the existing binary FM spectrum. This is accomplished by smoothing the phase function, spreading the phase change over more symbol intervals, and by reducing the modulation index. A Raised Cosine frequency pulse g(t) with a duration of three symbol intervals (L=3) was selected and its frequency pulse g(t) is shown in Figure 1. The corresponding phase tree for the Tier II waveform is shown in Figure 2.

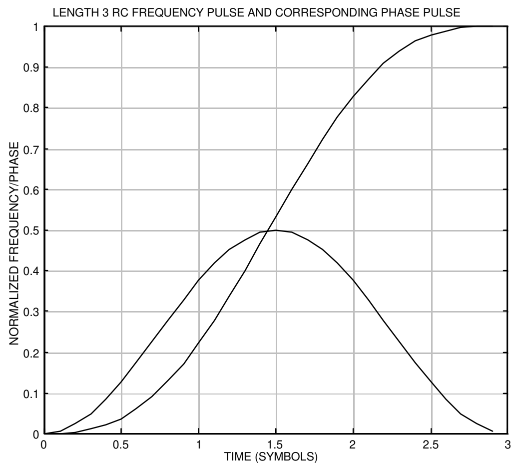

Figure 1. Frequency and Phase Pulse L=3RC

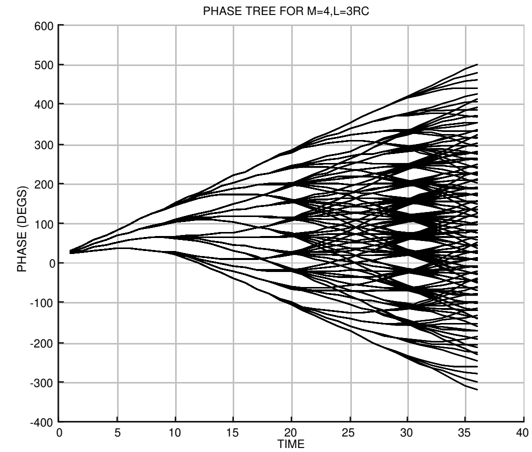

Figure 2. Phase Tree for M=4, h1=4/16, h2=5/16, L=3RC

Using results from [3], Figure 3 compares the power spectra of a typical binary PCM/FM signal (h=0.7, Pre-modulation filter with -3 dB point at 0.7 times the data rate), Feher patented FQPSK-B (revision 1), GMSK BT=0.3, and the ARTM Tier II M=4, h1=4/16, h2=5/16,L=3RC CPM waveform. The CPM signal requires significantly less bandwidth than the binary FM approach and is the most spectrally efficient of the group. Consequently, the new scheme allows more channels to be packed into a fixed bandwidth allocation.

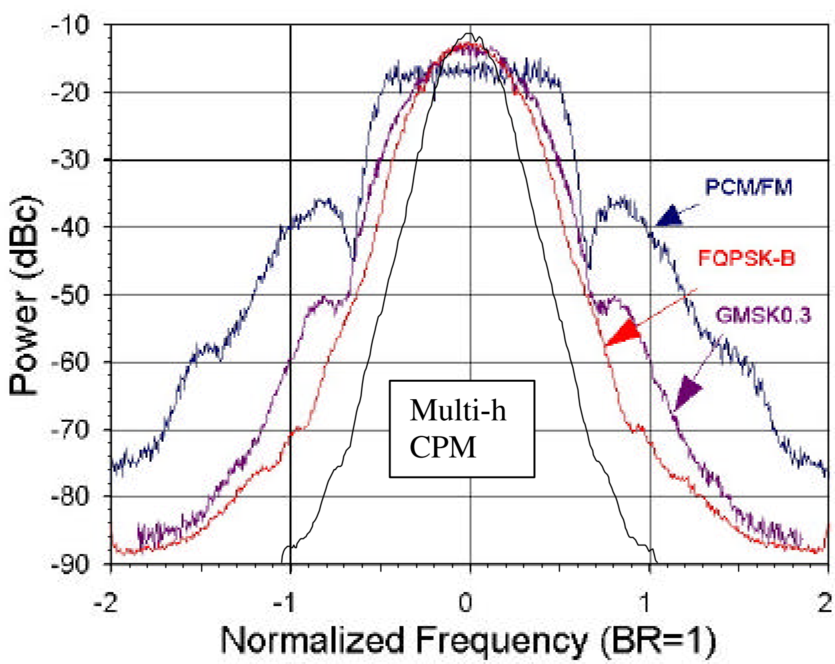

Figure 3. PSD Comparison of Multi-h CPM with other Telemetry Waveforms

TRELLIS REPRESENTATION

Given that g(t) is of finite length (L= 3T) and **h** is rational, the phase tree can be reduced to a phase trellis. The information-bearing part of the phase can be described by

$$\phi(t,\overline{\alpha}) = 2\pi \sum_{i=-\infty}^{n} h_i \alpha_i q(\tau - iT) = 2\pi \sum_{i=n-L+1}^{n} h_i \alpha_i q(\tau - iT) + \pi \sum_{i=-\infty}^{n-L} h_i \alpha_i$$

$$= \theta_n(t,\overline{\alpha}_n) + \theta_n \qquad nT \le t \le (n+1)T$$

For any given symbol interval, the phase $\phi(t,\alpha)$ is completely specified by the correlative state vector $\alpha_n = (\alpha_n, \alpha_{n-1}, \ldots, \alpha_{n-L+1})$ and the phase state θ_n, where

$$\theta_n = \pi \sum_{i=-\infty}^{n-L} h_i \alpha_i \mod 2\pi$$

The number of phase states is equal to $M^{(L-1)}$. For h=2k/p (k,p are integers) there are p different phase states equally spaced around the unit circle. The total state is defined by the L-tuple $\sigma_n = (\theta_n, \alpha_{n-1}, \ldots, \alpha_{n-L+1})$ and the number of such states is

$$S = pM^{L-1}$$

which is a critical parameter in determining the overall receiver complexity since the Viterbi algorithm will be used to recover the data symbols.

For the multi-h Tier II waveform, the selected parameters (M=4, L=3, h1=4/16=2*4/32 and h2=5/16=2*5/32) yield p=32 phase states and $S=32(4^{(3-1)})= 512$ total states. The trellis connections are periodic over two symbols due to the alternating modulation index.

MODULATOR DESCRIPTION

Conceptually, the multi-h CPM waveform can be generated by filtering the data symbols (α_i's) with a pre-modulation filter, scaling the output by $2\pi h_i$ to achieve the proper frequency deviation, and applying the result to an FM modulator. In practice, it is easier to use a memory device that contains the pulse shape necessary to create the instantaneous frequency or phase signal that is applied to the corresponding modulator. Figure 4 illustrates the frequency and phase modulator configurations.

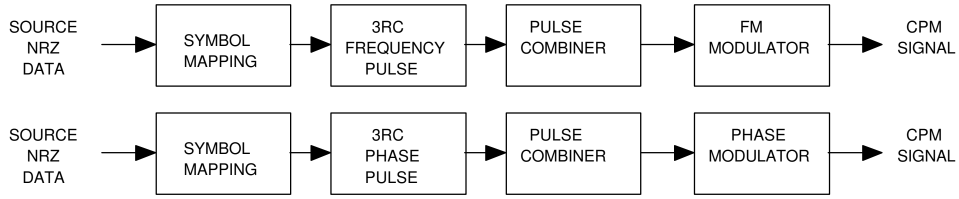

Figure 4. Frequency and Phase Modulator Configurations

DEMODULATOR DESCRIPTION

Because the signal can be represented in a finite state trellis, the Viterbi algorithm can be used for recovering the modulated data. Key functions in the demodulator include IF filtering, sampling and coherent downconversion, metric calculation, survivor path update, traceback, data recovery, and synchronization. A block diagram of the receiver is shown in Figure 5.

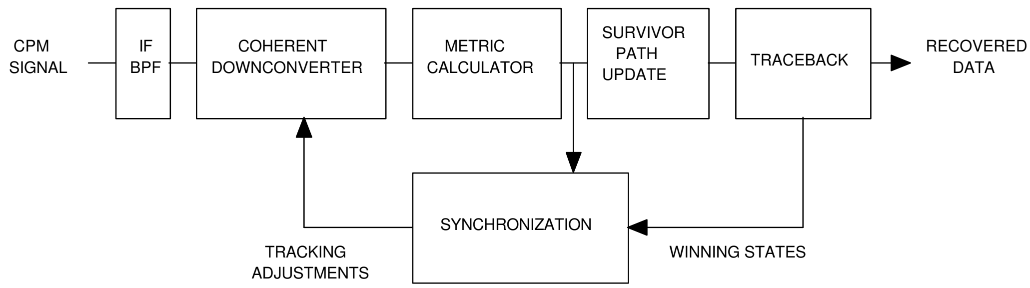

Figure 5. Multi-h CPM Demodulation Process

Although the computational requirements for demodulating the Tier II waveform seem quite high, the current implementation is a hardware based design with data throughput exceeding 20 MBps.

DETECTION PERFORMANCE

The minimum distance for this waveform is given in [2] as 1.39, which is 1.57 dB asymptotically inferior to MSK. Therefore, the probability of error can be approximated at large SNR's by

$$Pe \approx Q\left(\sqrt{d_{\min}^2 \frac{E_b}{N_o}}\right)$$

Although the PSD of the Tier II waveform is significantly narrower than a binary FM system, the detection efficiency is similar. To determine the realizable increase in data capacity requires investigating the detection performance when adjacent channels are present. One quantitative measure of ACI performance is to define the minimum channel spacing as the frequency separation at which two adjacent channels, at a level of 18 dB higher than the desired, cause one dB of BEP degradation as compared to the case without adjacent channels.

Figure 6 illustrates the effect of reducing the channel spacing for a scenario with two relatively large adjacent channels. As the spacing is reduced, more energy from the interfering signals overlaps into the desired channel. Simulations with various IF filters and channel spacings were performed and the results are presented in Figure 7. The conclusion is that the Tier II waveform, with a channel spacing of approximately 0.7 bit rates, has a packing density of nearly three times that of binary PCM/FM with similar detection efficiency.

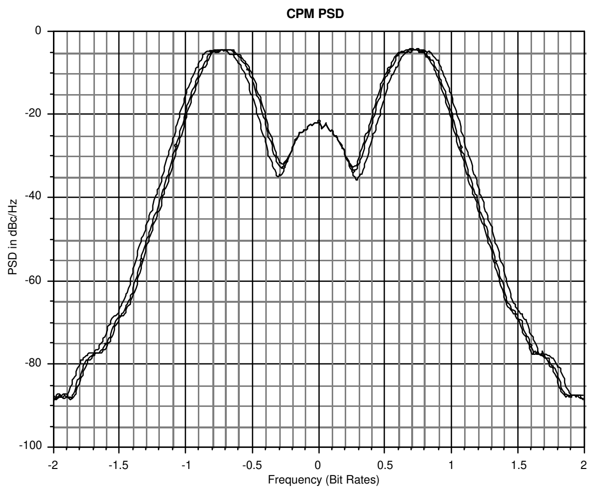

Figure 6. Effect of Reducing Channel Spacing

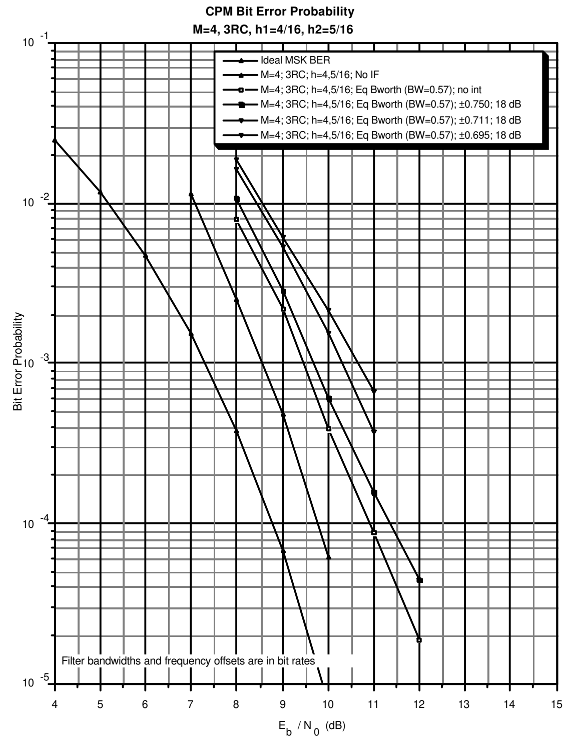

Figure 7. Simulation Results with Different IF filters and Channel Spacings

CONCLUSIONS

This paper has presented the implementation and performance of the ARTM Tier II multi-h CPM waveform that provides nearly three times the data capacity of the current binary FM systems. The superior spectral efficiency was achieved by increasing the modulation order to a quaternary scheme, reducing the modulation index, and using a relatively smooth frequency pulse.

The detection efficiency goal was met by incorporating a multi-h scheme that increased the minimum distance thereby reducing the probability of symbol error. Although this increased the receiver complexity a prototype system with data throughput exceeding 20 MBps is currently undergoing field testing. Moreover, the modulator and demodulator architecture is ideally suited for other types of CPM signaling as well.

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