TECHNIQUES FOR IMPROVING POWER AND BANDWIDTH EFFICIENCY OF UHF MILSATCOM WAVEFORMS

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ABSTRACT
Multi-h continuous phase modulation (CPM) employing a constant envelope modulation technique is being used over UHF military satellite communication (MILSATCOM) channels. It was implemented as a result of the Advanced Digital Waveform (ADW) program. The goal of this program was to increase throughput on UHF SATCOM channels. The resulting waveform, described in MIL-STD-188-181B, is a 4-ary, 2-h, linear shaped, full response CPM. The purpose of this paper is to describe techniques for further improving the power and bandwidth performance of multi-h CPM. Improving power efficiency will benefit disadvantaged platforms by allowing link closure at lower C/N0 levels. Improving bandwidth efficiency will allow higher data rates to be used. Three methods for accomplishing these goals are explored. The first is to increase the symbol alphabet size from 4 to 8 symbols by encoding 3 bits per symbol instead of 2, thus increasing bandwidth efficiency by 50 percent. The second area of interest is to implement a partial response waveform, meaning that each symbol is shaped over multiple symbol periods. This second method will add more memory to the trellis structure and should also cause the spectrum to become more compact. The third method investigated is to increase the number of modulation indices. The idea is that using three or more indices will spread the trellis more, increasing the minimum Euclidean distance. The first two areas of research, 8-ary CPM and partial response CPM, show promising results, in some cases improving both power and bandwidth efficiency. Of these two, 8-ary CPM seems the more practical path for immediate further development. Partial Response is actually more promising in theory, but is much more complex and requires further research. Early results of three-h CPM show that adding another h-value does not improve performance and does not appear to be a promising avenue for further research.

BACKGROUND
The UHF MILSATCOM band is divided into 42 5-kHz channels and 36 25-kHz channels. UHF has many desirable characteristics that are unavailable in other frequency bands. Most notably, UHF systems can use relatively small, inexpensive terminals with non-directional antennas and operate through weather and foliage. The downside of UHF is that the assets are very limited and demand far exceeds available resources. In addition, the limited assets, UHF satellites use a nonlinear, hard limiting transponder that prohibits the use of bandwidth efficient modulations such as quadrature amplitude modulation (QAM).

The ADW program produced the multi-h Continuous Phase Modulation (CPM) waveform now specified in MIL-STD-188-181B. This waveform greatly improves the throughput on UHF SATCOM, making rates of 9600 bps available on 5-kHz channels and 48-56 kbps available on 25-kHz channels. While these data rates are about three times the data rates previously available, the program fell short of the original target data rates of 12 kbps and 64 kbps on 5-kHz and 25-kHz channels, respectively.

The goal of the project described in this paper is to build on the accomplishments of ADW and develop the technology necessary to push the throughput on UHF channels to or beyond the original target rates. Another goal is to improve the power efficiency of existing data rates so that disadvantaged users may have access to them. Therefore it is desirable to improve both the power performance and the bandwidth efficiency of this waveform.

Power efficiency of a waveform is a measurement of the bit error rate (BER) in relation to the signal to noise ratio. The idea is to maintain a particular signal quality, measured by the BER, using as little signal power as possible. An improved BER corresponds to a lower probability of error, \( P_e \). The value of \( P_e \) can be approximated, for reasonably high signal to noise ratios, as

\[
P_e \equiv Q(\sqrt{d_{\text{min}}^2 (E_b / N_0)})
\]  

(1)

where

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-z^2/2} dz.
\]  

(2)

The quantity \( d_{\text{min}}^2 \) is the minimum squared Euclidean distance of a waveform. Power efficiency then is improved by achieving a lower \( P_e \) without increasing the signal power. Equation (1) shows that this can be done by
increasing the value of $d_{min}^2$. Better power efficiency allows power limited platforms to close links at higher data rates than would otherwise be possible.

The bandwidth efficiency of a waveform is the ratio of a particular data rate to the amount of bandwidth required by that data rate, sometimes expressed as bps/Hz. The advantage of greater bandwidth efficiency is the ability to transmit higher data rates in the same amount of spectrum. The most straightforward way to increase bandwidth efficiency is to transmit a greater number of bits per symbol. Often power efficiency must be sacrificed to achieve better bandwidth efficiency.

CONTINUOUS PHASE MODULATION

The general CPM waveform is defined by

$$s(t, \alpha) = \sqrt{\frac{2E_s}{T_s}} \cos(2\pi f_0 t + \phi(t, \alpha)).$$

(3)

where $E_s$ is the symbol energy, $T_s$ is the symbol period and $f_0$ is the carrier frequency. The $\phi(t, \alpha)$ term is the information carrying phase and is defined as

$$\phi(t, \alpha) = 2\pi \sum_i h_i \alpha_i q(t - iT_s).$$

(4)

where $h_i$ is the modulation index, $\alpha_i$ is the data symbol and $q(t)$ is the phase response. The data symbols are simply a mapping of bits to decimal values where

$$\alpha_i \in \{\pm 1, \pm 3, \ldots, \pm (M-1)\}$$

(5)

and $M$ is the symbol alphabet size. The phase response is related to the instantaneous frequency pulse, $g(t)$, as

$$q(t) = \int g(\tau) d\tau.$$  

(6)

The length, $L$, of $g(t)$ is the number of symbol periods over which each symbol is shaped. If $L < 1$, the waveform is said to be full response. If $L > 1$, the waveform is partial response. Typical types of instantaneous frequency pulses are rectangular (LREC) and raised-cosine (LRC). Others may be used but these are the most common.

The MIL-STD-188-181B version of CPM has the following characteristics. It varies the value of $h_i$ from symbol to symbol by alternating between two values of $h_i$ ($H = 2$). This is referred to as multi-h and its purpose is to increase the minimum Euclidean distance of the waveform. It is a 4-ary waveform, meaning there are two bits transmitted per symbol, yielding four possible values of $\alpha$. The number of bits, $m$, mapped to each symbol is related to the size of the symbol alphabet size, $M$, as $M = 2^m$. Finally, this is a full response waveform ($L = 1$) and uses a rectangular instantaneous frequency pulse, thus it is a 1REC waveform.

Decoding of CPM is accomplished using a Viterbi decoder with a phase trellis structure. If $h_i$ is a ratio of two integers as

$$h_i = \frac{2k_i}{p},$$

(7)

then there are $p$ states in the phase trellis. The value $k_i$ is simply an integer chosen to set the value of $h_i$. In an index pair at least one of the values of $k_i$ will be an odd integer. The phase trellis has phase states with values

$$\theta_n \in \left\{\frac{2\pi}{p}, \frac{4\pi}{p}, \ldots, \frac{(p-1)2\pi}{p}\right\}$$

(8)

In the MIL-STD waveform the value of $p$ is 32 so there are 32 phases in the phase trellis. Typical values used are $\left\{\frac{5}{16}, \frac{6}{16}\right\}$. The factor of 2 in the numerator of equation (7) results in the values of $h_i$ having a denominator of 16.

RESEARCH AREAS

The characteristics described above are the basis of the three main areas of research explored in this paper. The first of the ideas discussed is to transmit one more bit per symbol, increasing the symbol alphabet size of the waveform from 4-ary to 8-ary. An 8-ary waveform would increase data throughput, but normally at the expense of power efficiency. The next research area is to move from a full response to a partial response system so that each symbol is shaped over multiple symbol periods. The final area discussed is to increase the number of modulation indices, $h_i$.

8-ary CPM

In a traditional PSK system, increasing the symbol constellation size by a factor of 2 necessitates, as a matter of course, a 3 dB increase in $E_b/N_0$ in order to maintain a particular BER. This is not necessarily the case with CPM because data symbols are not fixed points in a constellation but rather continuous phase transitions, so $d_{min}^2$ is more a function of $h_i$ than strictly a function of the signal constellation size.
In 4-ary CPM, several pairs of modulation indices are used and a general correlation exists between the value of the larger index and the coding gain and spectral occupancy associated with that index pair. Waveforms that use the smaller modulation index pairs occupy less bandwidth but also have lower coding gains. The larger index pairs have larger power spectra at a given data rate but offer better BER performance. A classical power vs. bandwidth tradeoff exists here wherein bandwidth can be spent to buy power. Table 1 shows this relationship between index values used within MIL-STD-188-181B and coding gain.

Table 1. Modulation index values for CPM as defined by MIL-STD-188-181B along with corresponding gains.

<table>
<thead>
<tr>
<th>Modulation Indices</th>
<th>Gain Ref. To MSK (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>{4/16, 13/16}</td>
<td>2.3</td>
</tr>
<tr>
<td>{5/16, 6/16}</td>
<td>2.8</td>
</tr>
<tr>
<td>{6/16, 7/16}</td>
<td>3.2</td>
</tr>
<tr>
<td>{7/16, 10/16}</td>
<td>3.8</td>
</tr>
<tr>
<td>{12/16, 13/16}</td>
<td>4.5</td>
</tr>
</tbody>
</table>

It turns out that the same correlation between modulation index size and coding gain is not present to the same degree when using 8-ary CPM as it is with 4-ary CPM. Most of the higher minimum distance values result from index values less than 13/32. Using higher indices than this consumes more bandwidth but does not buy the BER performance as in the 4-ary case. Table 2 suggests a set of \( h \) values to be used for 8-ary CPM along with the gain relative to MSK of each pair of indices. The range of index pairs in this table covers the usable index values. No pair of indices higher than \{10/32, 13/32\} provides any more coding gain and to use values below \{5/32, 6/32\} would not be practical unless an external forward error correcting code (FEC) were used in conjunction to raise the coding gain of the system.

The upside here is that good coding gain can be achieved at lower bandwidth than is possible using 4-ary CPM. For example, if the indices \{9/32, 12/32\} are used, 4.4 dB of gain can be achieved relative to MSK. The same gain can be had in 4-ary CPM using \{12/16, 13/16\}, but the 8-ary system uses slightly less bandwidth than the 4-ary system and it provides for higher throughput. The only cost is added complexity.

Results from a simulated 8-ary system using these indices aren't quite this good. 8-ary CPM underperforms the 4-ary system with the same theoretical gain by about 0.5 dB using these indices and in general underperforms somewhat using any index pair. This may simply be a matter of optimizing the software used in the simulations because simulations of 4-ary systems do achieve the expected coding gain. Figure 1 compares the measured power and bandwidth properties of these waveforms derived from a Matlab simulation. Note that the power spectra are shown for a given symbol rate, whereas the BER curves are expressed in energy per bit.
more $E_b/N_0$ to achieve the same BER using an 8-ary constellation. Still, these losses are not unreasonable considering the corresponding increase in data throughput.

Implementing 8-ary CPM is relatively straightforward once it has been determined which index values will be used. The algorithm is the same as that used for smaller signal constellations, i.e. 4-ary. The decoder uses a trellis structure with twice the number of states. There are also twice the number of $\alpha_i$ values. This means the decoder complexity can be expected to be 4 times that of 4-ary CPM.

<table>
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<tr>
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<tbody>
<tr>
<td>${5, 6}$</td>
<td>0.6</td>
</tr>
<tr>
<td>${32, 32}$</td>
<td></td>
</tr>
<tr>
<td>${6, 7}$</td>
<td>1.1</td>
</tr>
<tr>
<td>${32, 32}$</td>
<td></td>
</tr>
<tr>
<td>${7, 10}$</td>
<td>3.1</td>
</tr>
<tr>
<td>${32, 32}$</td>
<td></td>
</tr>
<tr>
<td>${9, 12}$</td>
<td>4.4</td>
</tr>
<tr>
<td>${32, 32}$</td>
<td></td>
</tr>
<tr>
<td>${10, 13}$</td>
<td>4.8</td>
</tr>
<tr>
<td>${32, 32}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Modulation index values for 8-ary CPM along with corresponding gain.

**Partial Response CPM**

The second topic of research is partial response CPM. Partial response means that each symbol is shaped over more than one symbol period. The technique chosen here is 3REC, meaning a rectangular instantaneous frequency pulse 3 symbols in length is used. The shape of the $n$th symbol being encoded depends not only on $\alpha_n$, but also on $\alpha_{n-1}$ and $\alpha_{n-2}$. This introduces more memory into the phase trellis, which translates into coding gain. It also greatly increases the decoder complexity.

An analysis of the minimum distances of various combinations of $h_i$ values was performed on the 3REC CPM waveform. The phenomenon observed is that the lower indices of the partial response waveform perform poorly as compared to the full response version, but partial response exhibited higher theoretical gains at higher values of $h_i$. For example, the gain using the $\{4/16, 5/16\}$ index set is 1.5 dB lower for partial response than for full response, but at the high end, partial response outperforms full response by 1.3 dB using indices $\{12/16, 13/16\}$. Table 3 details a set of partial response indices.

These results are theoretical because a 2-h partial response decoder has not yet been simulated, but they are consistent with simulation results of simpler, single-$h$ partial response schemes. Figure 2 shows a comparison between full response and partial response CPM.

![Figure 2. Comparison of (a) the theoretical $P_e$ performance and (b) the power spectra of 3REC (Partial Response) and 1REC (Full Response) CPM using indices $\{12/16, 13/16\}$.](image)

In terms of spectral efficiency, the bandwidth used by partial response is much less than a full response waveform with the same indices. This effect is seen across the full range of $h_i$ values. Looking at it another way, the spectral occupancy of partial response using $\{12/16, 13/16\}$ is approximately the same as a full response scheme with indices $\{6/16, 7/16\}$. The gains relative to MSK for these schemes are 5.8 dB and 3.2 dB for the partial and full response schemes, respectively. This means 2.6 dB of gain can be achieved with no increase in bandwidth by switching to partial response.
The caveat here is that it is difficult to know how much of this will be given back in implementation loss. There is a tendency for a Viterbi decoder with a very large number of states to become "lost" in the trellis in the presence of a noisy signal. The other side of the implementation issue is that synchronization is more difficult with a partial response system. More work is needed in this area.

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<td>[4, 5] [16, 16]</td>
<td>0.8</td>
</tr>
<tr>
<td>[5, 7] [16, 16]</td>
<td>2.6</td>
</tr>
<tr>
<td>[7, 9] [16, 16]</td>
<td>4.5</td>
</tr>
<tr>
<td>[10, 11] [16, 16]</td>
<td>5.4</td>
</tr>
<tr>
<td>[12, 13] [16, 16]</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Table 3. Modulation index values for 4-ary 3REC CPM along with corresponding gains.

3-h CPM

As has been discussed already, MIL-STD CPM is a 2-h system, meaning two different modulation indices are used in an alternating fashion. This technique adds memory to the trellis and results in added coding gain when compared to an equivalent single-h system. Intuitively, it would seem that adding a third index and cycling them would increase the minimum distance of the system by spreading the trellis that much more.

An exhaustive analysis of the minimum distance of 3-h CPM was done which compares all combinations of indices. The results of this analysis indicate that there is nothing to be gained by adding a third index. In almost every case the third index hurts the performance of a 2-h scheme with similar spectral properties. Simulation of a 3-h system showed degradation compared to a 2-h counterpart in every case tried.

CONCLUSION AND FUTURE WORK

Three techniques for improving the power and bandwidth efficiency of UHF SATCOM have been studied in the course of this project. Of the three, the most promising appears to be 8-ary CPM. Increasing the alphabet size of CPM allows better spectral efficiency and in many cases the power efficiency is comparable to 4-ary. A substantial advantage to 8-ary CPM is that it has been shown here to work in simulation and the complexity is not a grave issue. It follows that hardware implementation would be relatively straightforward.

It would be more useful if the lower indices, which provide better bandwidth efficiency, provided the same high gains realized for 4-ary modulation. As it is, the higher index values cannot be exploited to achieve higher data rates than those already specified in MIL-STD-188-181B. However, these higher indices can be used to lower the link requirements for some existing data rates. This will allow disadvantaged platforms, such as submarines and manpacks, to use higher data rates than their link capabilities now allow. Additionally, data rates beyond 64 kbps can still be achieved using smaller modulation indices. Adding FEC will make these higher data rates possible using existing link budgets. One idea being considered is to use turbo product codes (TPC) as an outer FEC. These codes are very powerful and can be implemented in hardware or software. TPCs exhibit better coding gain than Reed-Solomon codes and are available at very high code rates. They also do not have the same error floor problems as traditional turbo codes.

Like 8-ary CPM, partial response CPM offers both power and bandwidth improvement. While also promising, partial response involves a greater degree of receiver complexity than 8-ary CPM. 3-h CPM is the only topic researched here which does not appear to hold promise.

The first recommendation for future work is to implement 8-ary CPM on a real platform to verify the promising results shown here. Assuming that is successful, the 8-ary CPM waveform then could be used in conjunction with FEC to try and gain high throughputs at reasonable power levels. Another worthwhile approach is to continue investigating partial response techniques. If partial response could be successfully implemented, it would be a very powerful tool for improving UHF SATCOM performance. One very reasonable path to pursue would be a less complex 2REC waveform or a 3REC, single-h waveform.

REFERENCES
