CONTINUOUS PHASE MODULATIONS FOR FUTURE SATELLITE COMMUNICATION SYSTEMS

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ABSTRACT

Continuous Phase Modulations (CPM) are a wide class of constant envelope modulations. Iterative decoding of serially coded CPM yields high performances when reasonable interleaver sizes (less than 1024) are considered. Performances of some binary and quaternary coded CPM schemes are assessed, then the effect of the modulation index on waveform performance is emphasized. Simulation results will represent a guideline to select the best fitted CPM for future satellite communications systems in Ka band. The choice takes into account power and spectral performances, complexity as well as adaptive aspects. The latter criterion is justified by the significant channel fluctuations in Ka band. In such circumstances, non adaptive waveform leads automatically either to a non efficient channel exploitation or weak system availability.

1. INTRODUCTION

Future satellite communications systems face several handicaps which may affect their performances and capacity. Difficulties are mainly related to the propagation channel characteristics in Ka band, adjacent channel interferences and the required high QoS (Quality of Service). High data rate and QEF (Quasi Error Free) transmission are required to support multimedia applications.

The adaptive waveform is a key factor for the success of such systems. To achieve this, CPM based waveforms represent a promising path to explore. In fact, CPM signals show high resistance to channel non-linearity thanks to their constant envelope. Moreover, iterative decoding of serially coded CPM yields high power performances [4, 5]. Finally, the multiplicity of modulation schemes offer more flexibility than "classic" waveform to cope with propagation conditions.

The paper starts with a brief review of CPM and its major properties, then the iterative decoding of serially coded CPM is tackled. Simulation results for coded binary and quaternary schemes are given, then the effect of modulation index variation is emphasized. Finally, and given simulation results and receiver complexity, a general guideline for selection of CPM parameters is proposed.

2. A CPM OVERVIEW

2.1 CPM Signals

Let us consider a single user communication over AWGN channel. A sequence of statically independent m-ary symbols denoted $\underline{a} = (a_0, a_1, \cdots a_{N-1}, a_N)$ is transmitted, $a_i \in (\pm 1, \pm 3 \cdots \pm (M-3), \pm (M-1))$. The frequency-modulated carrier is given as following:

$$s(\underline{a}, t) = \sqrt{\frac{2E}{T}} \cos\left(2\pi f_0 t + \varphi\left(\underline{a}, t\right)\right) \tag{1}$$

where f_0 is the carrier frequency, T and E denote respectively symbol duration and energy. φ denotes the signal phase and is given by the following:

$$\varphi(\underline{a}, t) = 2\pi h \sum_{i=0}^{N} a_i \, q(t - iT) \tag{2}$$

Where the parameter h is called the modulation index. In practical cases, h is a fraction $h = \frac{u}{p}$, u and p have no commun factor and usually $u < p$. $q(t)$is a non decreasing time function which verifies:

$$\begin{aligned} q(t) &= \int_0^t g(\tau)\, d\tau \\ q(\infty) &= q(LT) = \frac{1}{2} \\ q(t) &= 0 \text{ for } t < 0 \end{aligned}$$

$g(t)$ is called the pulse shape with time support $I = [0 \; LT]$, L is called pulse length, the most known shapes are the *Raised Cosine* (RC), the *Rectangle* (REC) and the *Gaussian*(GMSK).

To justify the trellis representation of CPM signals the equation 2 may be rewritten as:

$$\begin{aligned} \varphi(\underline{a}, t) &= 2\pi h a_N \, q(t - NT) + 2\pi h \sum_{i=N-L+1}^{N-1} a_i q(t - iT) \\ &+ \pi h \sum_{i=0}^{N-L} a_i \end{aligned} \tag{3}$$

As we can see the third term in (3) namely $\theta = \pi h \sum_{i=0}^{N-L} a_i$ can take only p (or $2p$) values modulo 2π. It represents the phase state of the modulator. In our studies the decomposition proposed by Rimoldi [6] is adopted, so the modulator phase state takes only p values and the CPM trellis is time independent. The second term could be represented by the $L-1$ dimension vector $(a_{N-L+1} \, a_{N-L+2} \ldots a_{N-1})$. It represents the state of the register of the modulator, the CPM modulator state is then defined by:

$$\sigma = (a_{N-L+1}, \, a_{N-L+2}, \cdots a_{N-1}, \, \theta)$$

The next state of the trellis is entirely defined by the present state and the N^{th} transmitted symbol. At the modulator output, a pulse which characterizes the transition is transmitted during one symbol period. In [6], Rimoldi demonstrates that a CPM modulator can be decomposed into a serial concatenation of a CPM phase encoder and a Mapper. A CPM phase encoder with 5 states is illustrated in figure 1.As we can see, the trellis consists of pM^{L-1} states and pM^L transitions.

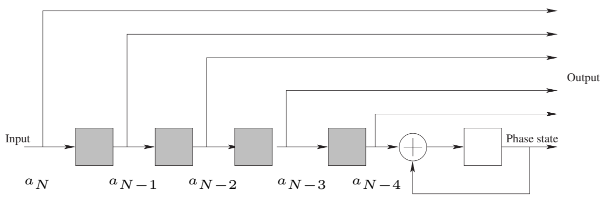

Figure 1: CPM Phase Encoder

2.2 CPM Receiver

The received analog noisy signal is baseband converted, sampled then fed into a digital filter bank which consists of pM^L matched filters. Generally, time responses of those filters are highly correlated and the CPM signal space could be spanned by a set of only 3 to 6 orthogonal filters with non significant degradation [5]. A receiver diagram is shown in figure 2. At

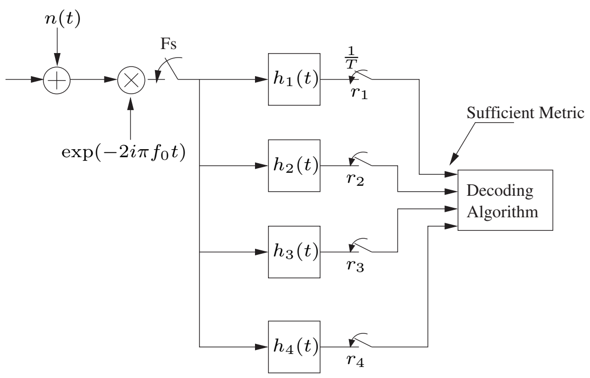

Figure 2: CPM Receiver Diagram

time kT the output vector r represents a sufficient statistic that permits an optimal decoding of the received signal. Thanks to trellis representation of CPM signals, a Viterbi or MAP algorithm could be performed to decode such signals, both algorithms have almost the same performance. The metric of a transition between states s_1 and s_2 denoted $\lambda(s_1, s_2)$ is given by the conditional probability $P(r/s)$ of the noisy received vector r given a transmitted pulse s. When AWGN channel is assumed, this metric could be written as following:

$$\lambda(s1, s2) \sim \exp\left(Re(r\Lambda^{-1}m^*)\right) \tag{4}$$

Where m is the filter bank perfect output when the received pulse is s. The hermitian matrix Λ is the noise correlation matrix at the output of the filtrer bank, it is a diagonal matrix if the reduced orthogonal filter bank is used. In addition to Viterbi and MAP decoding, the major application of CPM trellis modelling is iterative decoding of serially coded CPM, in this case the MAP algorithm is used since it provides soft output. This topic is tackled in the next section.

3. SERIALLY CODED CPM :PRINCIPLES AND PERFORMANCES

3.1 Principles

The advent of *turbo codes* [3] widens the range of iterative process in the area of communication. In [2] Benedetto demonstrates that iterative decoding of serially concatenated convolutional codes (CC) could also be performed and leads to high power performances. Since it behaves like a systematic recursive convolutional code, CPM could be decoded iteratively when concatenated with a convolutional code. In this paper non-recursive non-systematic codes are considered. The encoding/decoding process is illustrated in figure 3. The decoding process is mainly made up of two SISO (Soft

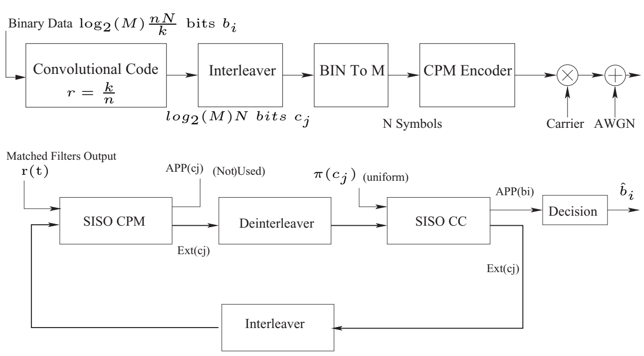

Figure 3: Iterative Coding/Decoding of Serially Coded CPM

Input Soft Output) units namely the CPM SISO and the CC SISO. Both SISO are based on the BCJR algorithm [1], they provide two kinds of information: a-posteriori information and extrinsic information. Unlike parallel turbo codes, the delivered extrinsic information is relative to coded bits. Extrinsic information delivered by the CPM SISO is interleaved and used as a priori information by the CC SISO and vice-versa as shown in figure 3. The delivered a-posteriori information by both units is not exploited by the iterative process. At the CC SISO output the a-posteriori information is relative to information bits, it serves to make the decision about transmitted information bits after the specified iteration number.

3.2 Simulation Results And Analysis

Final performance of serially coded CPM depends on many parameters, such as the interleaver[1], the code minimum distance and, of course, CPM parameters given by the modulation order M, the modulation index h, the pulse shape and its length L. To keep reasonable receiver complexity, only quaternary and binary CPM are considered. In the binary case the 1REC[2] and the 3RC are considered. To select the CC constraint length and the interleaver size, simulation of coded 1REC with h=1/2 [3] with many codes with different constraint length and the same rate are performed. Results are illustrated in figure 4. Codes with low constraint length have higher performances at low SNR. For higher SNR the (2,3) have the worst performances while the (7,5) code keeps its good behaviour. It gives then the best trade-off between performances and complexity.
Iterative decoding leads to better results when longer interleaver are considered. Meanwhile, long interleaver requires more resources and processing time which is not compliant

[1]Random interleavers are considered in this paper
[2]L=1 pulse shape=Rectangle
[3]Known as MSK

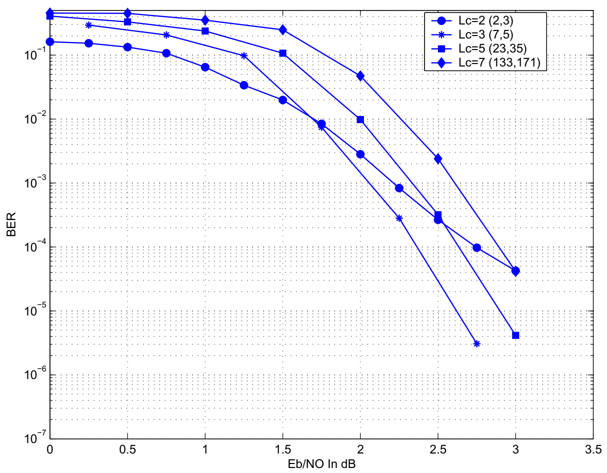

Figure 4: BER Performances of serially coded 1REC with different CC, $h = 1/2$, Interleaver Size=1024, Iteration Number=12

with some applications such as VOIP (Voice Over IP) or real time applications. The figure 5 shows results of coded MSK with different interleaver sizes. Interleaver size of 1024 seems

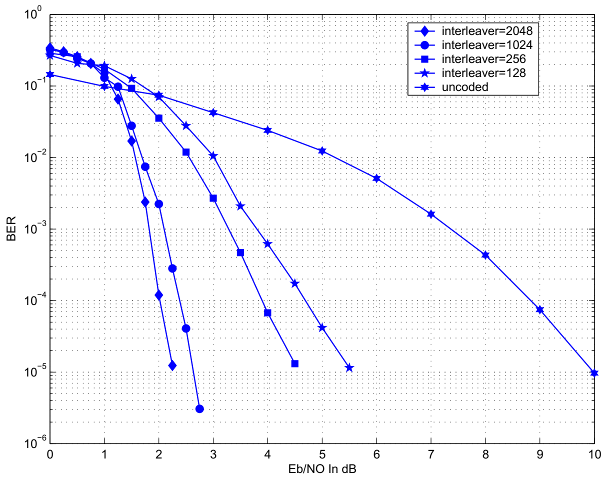

Figure 5: BER Performances of serially coded 1REC with different interleaver sizes, $h = 1/2$, CC=(7,5), Iteration Number=12

to be the most suitable since it has good performances with reasonable complexity. Henceforth the adopted code is the (7,5) and the interleaver size is equal to 1024.
Even if the Rectangle pulse has better spectral efficiency [4] than the Raised Cosine, the latter one have better spectral properties. In fact, the signal spectrum is attenuated faster when Raised Cosine pulse is used, this property is very important to reduce ACI (Adjacent Channel Interference) in multi-user communication with MF-TDMA access. To improve the waveform spectral performance when the Raised Cosine pulse is adopted, partial response CPM ($L > 1$) are required. The figure 6 shows the out-of-band power for binary CPM with both pluses, the modulation index is equal to 1/2. The out-of-band signal level is more than 20dB lower

[4]By default, bandwidth is the 99% power-in-band definition

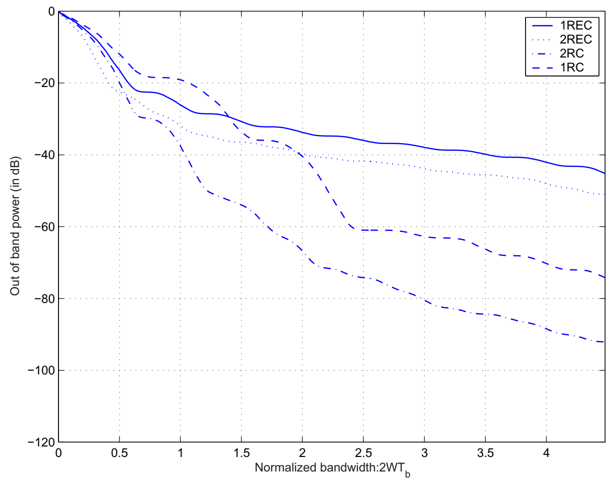

Figure 6: Out-of-band power versus normalized bandwidth

($2WT_b > 2.5$) when Raised Cosine pulse is used rather than the Rectangle one.
As we have mentioned in the beginning, propagation conditions in Ka band are very stringent, for instance degradation could exceed 12 dB during 0.1% of an average year in a typical Europe climate. In such conditions, adaptive waveform is required to guarantee good system availability and capacity. To achieve this, CPM represent a promising path to explore. Variation of one CPM parameter results in a change of the waveform power and spectral performances. To keep the same receiver complexity we vary only the pulse shape and the modulation index while keeping constant its denominator p. This technique requires only variation of the receiver filter bank when switching from one mode to another. Figure 7 shows waveform performances for binary 3RC with different modulation index. More than 5 dB power margin could be

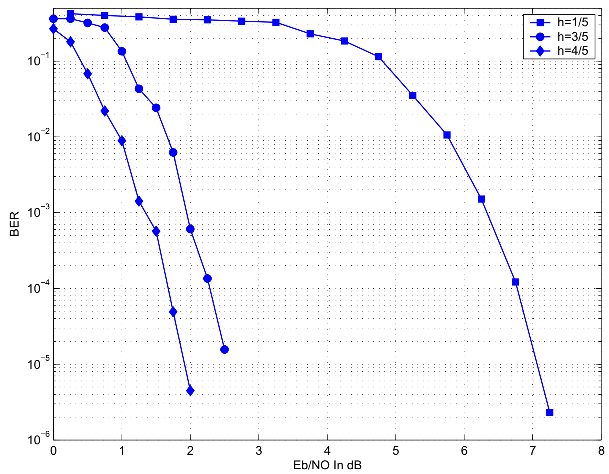

Figure 7: BER Performances of serially coded 3RC with different different modulation index, Interleaver size=1024, code=(7,5)

obtained for a BER= 10^{-5} when the modulation index vary from 0.2 to 0.8, consequently waveform spectral efficiency is varied (0.93 bit/sec/hz for h=0.2 versus 0.45 bit/sec/hz for h=0.8). The power margin is expected to be larger for lower BER because the slope is steeper in the power efficient scheme.

Quaternary CPM schemes have generally lower spectral performances than binary ones, meanwhile, we could mitigate this fact by adopting partial response CPM ($L > 1$). For the sake of acceptable receiver complexity only the case L=2 is considered. Simulation results relative to some quaternary schemes with Gray mapping are illustrated in figure 8. The figure 9 summarizes power and spectral performances

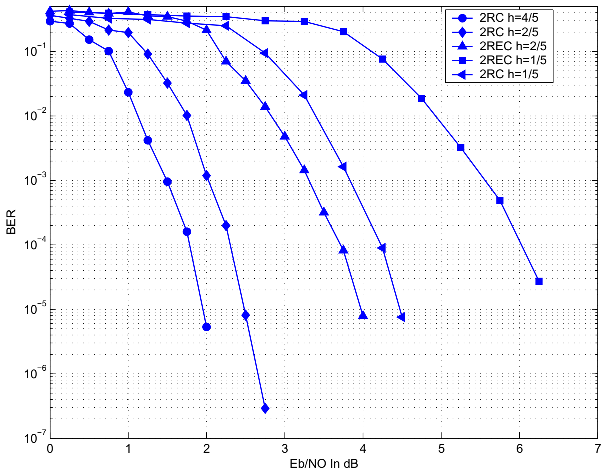

Figure 8: Performances of some quaternary CPM with Gray mapping, CC =(7,5) interleaver size=1024

of simulated binary and quaternary CPM. The $\frac{E_b}{N_0}$ is given for a BER=10^{-5} and the signal bandwidth is defined by the 99% (and 95%) power-in-band definition. Quaternary

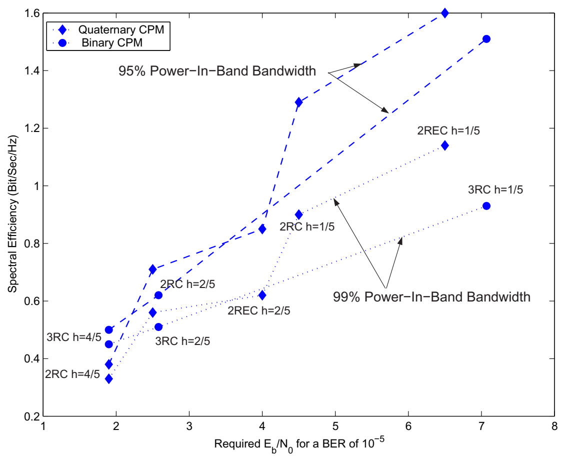

Figure 9: Power and spectral performances of some binary and quaternary CPM, CC =(7,5), interleaver size=1024

schemes seems to be more attractive than binary ones. For instance, the quaternary 2RC with $h = 1/5$ have the same spectral efficiency than the binary 3RC with $h = 1/5$. Meanwhile, it requires 3dB less power to achieve the same BER of 10^{-5}. Furthermore, quaternary schemes could provide more power margin than binary CPM if extreme modulation index ($h < 1/5$ and $h > 4/5$) are considered.

CPM based waveform provides an efficient technique to mitigate channel degradation by varying its modulation index. Moreover, the power margin obtained by varying the modulation index could be increased when associated with a variation of the code rate. To be fair, the comparaison between quaternary and binary schemes have to take into account the complexity aspects. The proposed binary CPM have 40 transitions and 20 states, while the quaternary one have 80 transitions and 20 states. We have also to take into account waveform performance in a multi-user communication with MF-TDMA access.

4. CONCLUSION

In this paper, performance of several CPM based waveforms have been assessed. Simulation results show the good performances of such coded waveform. The effect of the modulation index variation have been assessed and emphasized. For instance, a power margin of more than 5 dB could be obtained when varying the modulation index when the binary 3RC is adopted. Here, we have to keep in mind that the denominator of the modulation index is kept constant to reduce the switch process complexity. To reduce ACI a Raised Cosine pulse is preferred because its good spectral performances.

In addition to its good performance, CPM signals have a constant envelope so they show high resistance toward nonlinearity. All those properties make CPM a promising solution for the design of adaptive waveform for future satellite communication systems. Meanwhile, CPM encounter some difficulties as regards synchronization and complexity especially for non-trivial schemes. Those problems are not yet sufficiently explored and represent a promising sector for future work.

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