Energy Efficient CPM Waveforms for Satellite Mesh Networks

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***Abstract*—This papers addresses the design of new energy-efficient Continuous Phase Modulation (CPM) waveforms suitable for being adopted in satellite mesh networks that are characterized by the absence of the Hub, and by small antennas and power amplifiers with moderate to low output saturated power at the user terminal. In particular, a CPM modulation format concatenated with a proper convolutional code for low spectral efficiency values has been selected to implement an efficient waveform for power-limited scenarios. Performance results show the gain obtained with respect to the DVB-RCS2 CPM waveforms at higher spectral efficiency also when transmission techniques, such as Burst Repetition, are considered, and confirm the suitability of the new designed CPM waveforms for satellite hub-less scenarios.**

I. Introduction

CPM waveforms specified in the DVB-RCS2 standard [1], have been analyzed in [2], in view of a potential application to satellite mesh networks [3]. The results there provided represent a benchmark for the selection of new waveforms and the optimal configuration for such kind of networks. Results in [2] show how CPM can be considered as an efficient solution for satellite mesh networks with single or multi beams coverage for low to medium spectral efficiencies, due to its constant envelope and its resilience to impairments that affect transmissions, such as Adjacent Channel Interference (ACI), phase noise, uncompensated frequency offset, and transmitter non-linearities. Satellite mesh networks in hub-less configurations are in fact characterized by terminals with a small and low-cost antenna as well as a transmit amplifier with moderate to low output saturated power, which impose several constraints on the link budget. Taking into account such power-limited scenarios, we have investigated the possibility to design new CPM waveforms having lower spectral efficiency but being very efficient in power.

The most straightforward way to implement a waveform at lower spectral efficiency is to adopt the Burst Repetition (BR) technique, which consists in transmitting each burst twice over the channel, at least to increase the capabilities of the receiver to successfully detect the signal. This, for example, is particularly true for fading channels, due to beneficial time diversity. Since the burst is transmitted twice, a 3dB gain in C/N can be observed with respect to the sheer single burst transmission, assuming that C is the received power of each received replica. In other words, burst repetition would yield a 3dB power gain and a 3dB spectral efficiency loss. In fact, the gain cannot be observed in E_b/N_0, since E_b represents the average energy per information bit, and even if the burst is transmitted twice, the conveyed information content does not increase. In addition, it is worthwhile highlighting that such a C/N gain is achieved under the assumption of perfect combining, which involves an ideal channel and timing estimation. This approach, although attractive, is not the optimal one as it does not exploit the introduced redundancy.

These considerations have motivated the design of a new waveform, as a whole, which, thanks to an increased robustness, can be more suitable to match the more challenging requirements imposed by power-limited scenarios. This paper

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therefore focuses on the investigation of new energy-efficient CPM waveforms for lower spectral efficiencies and describes the approach followed for the selection of convolutional codes to be concatenated with the considered CPM modulation formats.

The paper is organized as follows. Section II describes the steps followed for the selection of the best CPM format while Section III reports the approach considered for the selection of the convolutional code to be concatenated with the CPM modulation. Section IV presents the performance analysis results, comparing the new CPM waveforms with the DVB-RCS2 benchmark considering also the adoption of Burst Repetition. Finally, conclusions are drawn in Section V.

II. CPM Scheme Selection

We have carried out a study on the selection of the most suitable modulation and coding parameters for CPM waveforms to be employed in power-limited scenarios, which typically translates into lower spectral efficiency values with respect to usual operating conditions. In particular, we have focused on the spectral efficiency $\eta = 0.25$ b/s/Hz. The investigation has started with the selection of the most effective CPM modulation parameters to cope with the mentioned scenario. Mainly, the parameters taken into account in the selection process have been the modulation index h, the cardinality of the modulation M, the modulation memory length in symbols L, the phase pulse type, and the bandwidth normalized to the symbol rate (FT, where F is the frequency spacing between two adjacent users and T is the symbol time). The most effective modulation formats have been first selected by using the information-theoretic analysis described in [4]. In particular, we have considered a set of binary modulation formats with rectangular (REC) and raised-cosine (RC) frequency pulse, with at most $L = 2$, to guarantee that the receiver can be designed by considering the principal component of the Laurent decomposition [5] only, as proved in [6]. At the beginning of our analysis, we have considered also other CPM formats such as Gaussian minimum shift keying (GMSK) but the achieved performance results have not shown a remarkable gain with respect to above mentioned binary CPM modulation formats so as to take the decision to focus only on these latter. For each of those considered, we have computed the spectral efficiency versus E_b/N_0. It is worthwhile pointing out that, when computing the spectral efficiency for a given value E_b/N_0, we have assumed that adjacent users were present with the same power and the same modulation formats of the useful signal. Also, we have considered, as in [4], the spacing between two adjacent signals as a measure of the bandwidth, optimized for each CPM modulation format and each E_b/N_0 value. In Fig. 1, we report the maximum achievable Spectral Efficiency (SE) as a function of E_b/N_0 for the selected CPM schemes with REC and RC pulses. From these curves, we can observe that for low E_b/N_0 values, where the systems are thermal-noise limited, the selected modulation formats have a similar performance in terms of max achievable spectral efficiency. The same conclusion can be drawn from Fig. 2, where we plot the achievable spectral efficiency of the considered schemes as a function of C/N.

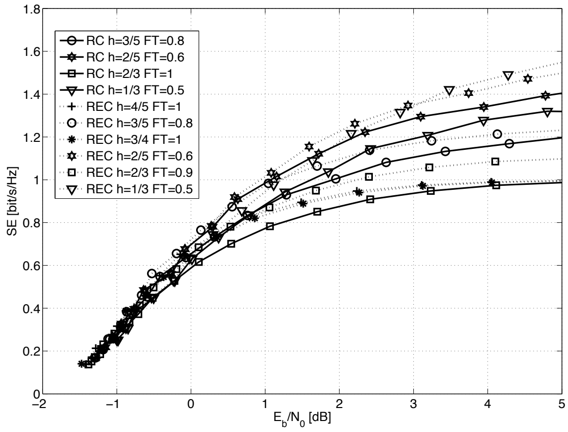

Fig. 1. Maximum achievable spectral efficiency as a function of E_b/N_0 for different CPM formats.

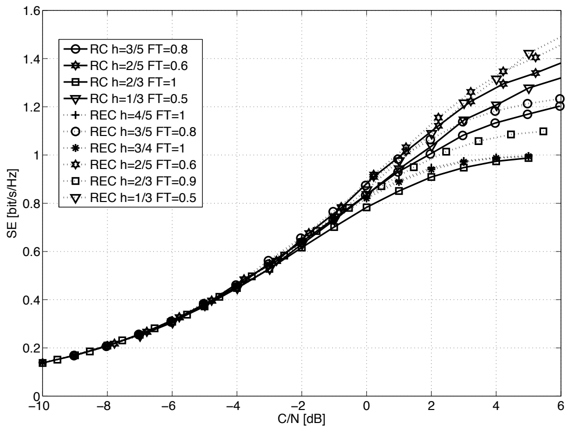

Fig. 2. Spectral efficiency as a function of C/N for different CPM formats.

Since the selected CPM schemes perform similarly for low achievable spectral efficiency values. For this reason, we have also carried out a further selection through EXIT charts in order to identify the most suitable modulation formats. After these two steps, the modulation formats in Table I have been selected. Notice that the code rate is uniquely determined by the spectral efficiency and the (optimal) channel spacing.

Once the CPM modulation parameters have been determined, the second step has been to seek for the convolutional codes to be concatenated with the selected modulation formats.

Pulse	h	Spacing	Code rate
2REC	4/5	1	1/4
2RC	2/3	1	1/4

TABLE I
Selected CPM modulation formats

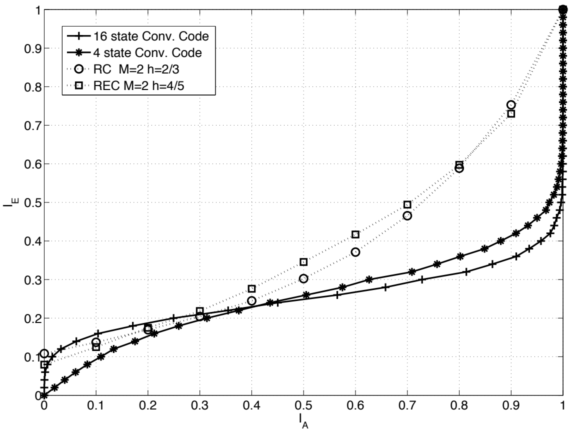

Fig. 3. EXIT Chart for the two selected CC-CPM schemes with code rate $1/4$.

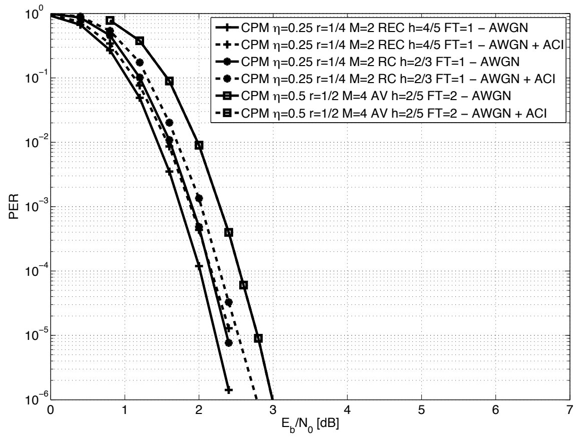

Fig. 4. Performance comparison between CPM waveforms at $\eta = 0.5$ b/s/Hz and $\eta = 0.25$ b/s/Hz in AWGN Channel and AWGN+ACI (PER vs. E_b/N_0), Short Traffic Burst (k=400 bits).

An investigation based on EXIT charts has been performed first. In Fig. 3, we consider the two schemes in Table I and the two rate-1/4 convolutional codes with 16 (generators $[21, 23, 27, 31]$) and 4 (generators $[5, 5, 7, 7]$) states, respectively. The EXIT curves for the CPM detector have been computed at E_b/N_0 =1 dB, which corresponds to a PER of around 10^{-3}, for the better performing waveforms, thus is a proper observation point for comparison.

This analysis suggested that we should consider 4-state convolutional codes with rate $1/4$, since 16-state code would yield, as shown, to a closed tunnel in the EXIT chart (see Fig. 3), which means a crossing between the inner and outer code mutual information characteristics. When this is the case, it is always prevented the possibility of reaching the top-right corner of the EXIT chart throughout the iterative process, which means that some information will always be lost, regardless of the number of iterations allowed. On the contrary, the 4-state code is more powerful in the start of the iterative process, thanks to a wider open tunnel in the EXIT chart. However, this code can have worse performance in the error floor region with respect to its 16-state counterpart, although this investigation is able to predict the waterfall and not a possible error floor. Therefore, to cope with this partial unpredictability, we have resorted to PER computer simulations, as reported in Fig. 4.

Fig. 4 shows a comparison between the performance of the CPM waveforms at $\eta = 0.5$ b/s/Hz spectral efficiency specified in the DVB-RCS2 standard and the new waveforms, at $\eta = 0.25$ b/s/Hz. It can be seen that among the considered waveforms, the best performance is given by the one with the REC pulse and $h = 4/5$, by around 0.2 dB both in AWGN and AWGN with ACI. In particular, 6 Adjacent Channel Interferers are considered, with power perfectly balanced with that of the user carrier, i.e., no ACI power unbalance is taken into account. This test has been carried out by considering the code identified by generator polynomials $[5, 7, 7, 7]$, that is reported as the optimal code in terms of minimum Hamming distance for that constraint length ([7], [8]). On the basis of such results, a further analysis on the selection of the optimal code has been carried out and discussed in detail in the next section.

III. Code Selection

CPM waveforms in the DVB-RCS2 standard are designed with a rate-$1/2$ convolutional code, possibly punctured to achieve a desired code rate, identified by generator polynomials [5, 7] in the case of constraint length $K = 3$ and [15, 17] in the case of constraint length $K = 4$, which are reported in [7] and [8] as the optimal codes in the sense of the minimum Hamming distance (d_{min}). When designing the new binary ($M = 2$) CPM waveforms in power-limited environments, thus for lower operating spectral efficiencies ($\eta = 0.25$ bit/s/Hz) the same criterion, based on the minimum Hamming distance, has been originally followed in order to select the most suitable rate-$1/4$ code. However, there are multiple suggestions in the literature for this case. For $K = 3$ both generators [5, 5, 7, 7] and [5, 7, 7, 7] were found to be the best choice (respectively [7], [8]). Preliminary tests have shown that between such two generators, the latter performs better in the considered system and scenario, but the next step has been to evaluate the best convolutional code to be concatenated with the selected CPM formats. More precisely, in a "turbo-like" system, as the Convolutional Code-CPM (CC-CPM) scheme, the d_{min} optimality criterion plays no more a fundamental role. In fact, the minimum distance between signal trajectories (in the trellis) in the signal space determines the asymptotic behavior for high E_b/N_0 value (in the so called floor region) whereas the waterfall behavior is determined by the distance spectrum. The minimum Euclidean distance between signal trajectories is also considered in [8]. It must be noted, however, that [8] does not consider bit interleaving nor iterative demodulation and decoding, and that the authors do not deliver a mathematical technique for finding the best codes (in the sense of the minimum Euclidean distance), but rather a series of considerations that can help in dramatically reduce the number of codes (i.e., generators polynomials) to be considered in the optimal code search, which is being still carried out by means of a brute force approach. In [8] it is also shown that optimal codes often share recurring characteristics, regarding the trellis branches labeling. In our analysis, due to the relative few codes to be generated using the specified parameters, we have performed a code search by means of a brute force approach, building on some simplificative assumptions, to reduce the codes set cardinality: for instance, the "all-zero" code [0, 0, 0, 0] is not considered, as well as the generators with all polynomials set to the same value. Also, generator polynomials which are merely time-reversal of one another have been considered only once.

IV. Performance Analysis

The results of the mentioned brute-force approach are reported in Fig. 5 where the dotted lines represent our available benchmarks, i.e. the DVB-RCS2 CPM waveform at $\eta = 0.5$ b/s/Hz and the same waveform considering the adoption of the Burst Repetition technique, which achieves spectral efficiency $\eta = 0.25$ b/s/Hz but has performance which is indistinguishable in the PER vs. E_b/N_0 plane. Three sets of closely spaced lines summarize the outcome of the brute-force approach over the considered set of code generator polynomials, after having removed equivalent polynomials, and other codes of no use, as mentioned in the previous section. It can be seen that there are subsets of codes that perform very close to each other and each of these families shows different performance. Note that, in order to ease the reading of the performance chart, only some representative curves have been reported here from the comprehensive analysis, precisely two for each subset of codes. The gain achieved with the best codes with respect to the worst codes and the BR technique is significant: at a PER of 10^{-4}, up to more than 1 dB of gain in E_b/N_0 is observed between the waveform adopting the best code and the DVB-RCS2 waveform with Burst Repetition.

Moreover, for the codes represented by the solid lines, the waterfall region seems to start before than for the codes represented by dashed lines. However, at higher values of E_b/N_0, the performance of the two families of codes crosses, also because several other codes of the solid lines subset show an error floor.

Finally, Fig. 6 shows the same comparison in the PER vs. C/N, in which is further appreciated the benefit brought by the design of the new waveforms. Indeed, as said, BR yields a gain of exactly 3 dB, due to the fact that each burst is transmitted twice, but the new binary CPM waveforms, along with the selection of the most suitable code, can bring another gain of more than 1dB with respect to the BR solution, up to a total of more than 4 dB with respect to the existing DVB-RCS2 waveform at $\eta = 0.5$ b/s/Hz.

The above reported results, which show a significant gain of the new waveforms, motivated us to investigate the behavior of power-efficient CPM waveforms in presence of other impairments. For this reason we added to the analysis a phase

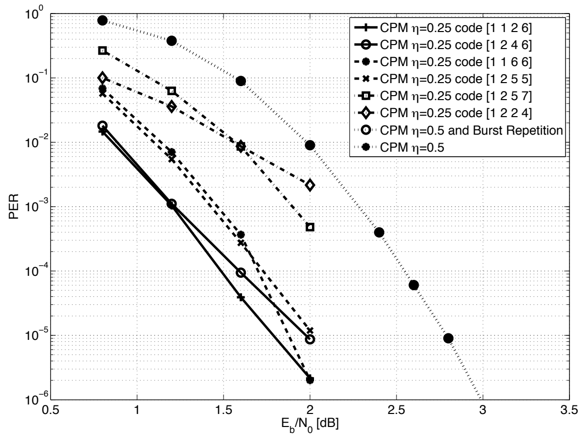

Fig. 5. Performance comparison between CPM waveforms at $\eta = 0.5$ b/s/Hz with and without Burst Repetition and $\eta = 0.25$ b/s/Hz with different convolutional codes (PER vs. E_b/N_0).

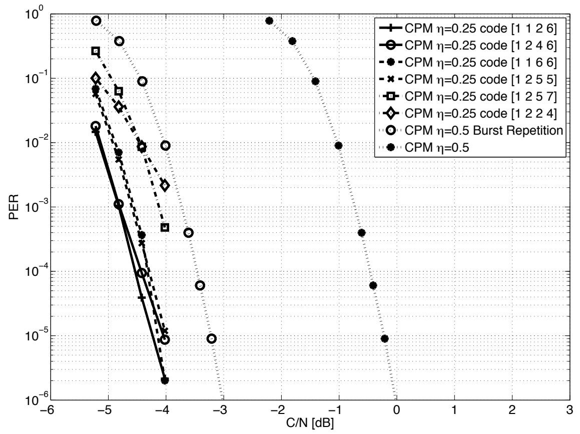

Fig. 6. Performance comparison between CPM waveforms at $\eta = 0.5$ b/s/Hz with and without Burst Repetition and $\eta = 0.25$ b/s/Hz with different convolutional codes (PER vs. C/N).

noise process (described by the spectral mask in [16]). This led us to move to a noncoherent detector [6], that is based on a phase synchronization technique embedded in the BCJR algorithm of the MAP CPM detector, in which a statistical model is assumed for the phase noise process.

The achieved results are reported in Fig. 7, in which we analyzed the behavior of one of the most promising waveforms, the one having generator polynomials for the convolutional code equal to $[1, 1, 6, 6]$. The performance of this waveform in presence of AWGN, ACI and phase noise is compared with the performance of the existing CPM DVB-RCS2 waveform at $\eta = 0.5$ b/s/Hz with burst repetition in AWGN only, i.e. without ACI and phase noise. As it clearly appears, the new waveform impaired by phase noise and ACI outperforms the BR solution with coherent detection and no impairments, thus proving further the robustness of the proposed solution.

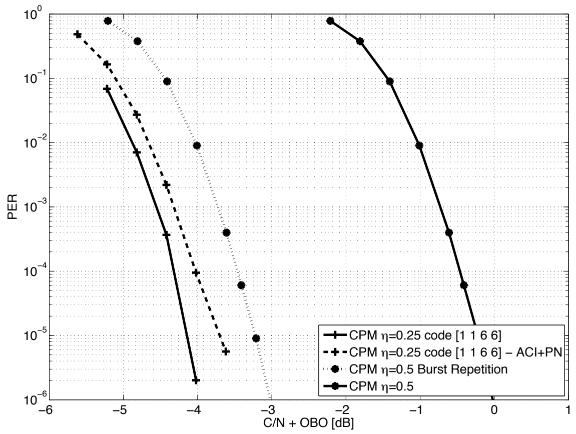

Fig. 7. Performance comparison between CPM waveforms at $\eta = 0.5$ b/s/Hz with and without Burst Repetition and $\eta = 0.25$ b/s/Hz in presence of impairments (PER vs. C/N).

V. CONCLUSION

The challenges of satellite mesh networks motivated the choice to design new energy-efficient CPM waveforms potentially suitable for power-limited scenarios. To do this, we first investigated the CPM modulation formats, based either on REC or RC pulses, to be employed for spectral efficiency $\eta = 0.25$ b/s/Hz. Then, we considered the convolutional code to be concatenated with such CPM modulation formats, starting from information theoretical considerations about the best constraint length of the code. We first examined the codes which are known to be the optimal according to the minimum Hamming distance property, and we realized that such criterion could not yield to the best design. For this reason, we moved toward an exhaustive search for the optimal convolutional code generators. This search provided several codes having interesting performance either in the waterfall region or in the floor region.

The results show the good performance achieved by the new energy-efficient CPM waveforms which confirm the suitability of CPM for low spectral efficiencies in challenging scenarios. The performance gain can be further improved by designing an ad-hoc interleaver and by deepening the investigation on the best code to be concatenated with the CPM modulation.

ACKNOWLEDGMENT

This work has been in part supported by the ESA Project n. 4000102296/11 “Cost Effective Satellite Terminals for MESH Overlay Networking”.

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