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Journal of the European Microwave Association

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The Proceedings of the European Microwave Association is an archival, peer-reviewed publication appearing 4 times per year. Its mission is to enhance the communication among microwave engineers and researchers in Europe, neighbouring areas, as well as world-wide. It will be interdisciplinary and application oriented, also providing a platform for the European microwave industry. *The Proceedings* solicit original and review articles in the following areas:
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Foreword: the Proceedings of the Eu*M*A

In April 2003 the General Assembly of the European Microwave Association approved a document entitled "Towards a renewed Eu*M*A" a kind of roadmap for the development of the Association over the following years. The European Microwave Association (Eu*M*A), founded in 1998 as a non-profit association with the aim of revitalizing the European Microwave Conference as well as providing improved services to the European Microwave community had fully met its original goals. After five years, the European Microwave Week (EuMW) was recognized as the most important microwave event in Europe and the second in the world. Nevertheless, the European Microwave Association felt that there was much more to do in order to better serve the microwave community in accordance with its Statutes which state: ... *promoting European microwaves, networking and uniting microwave scientists and engineers in Europe, providing a single voice for European microwave scientists and engineers in Europe, promoting public awareness and appreciation of microwaves, attaining full recognition of microwaves by the European Union, ... and circulating information among European microwave scientists and engineers ...* While the European Union has been significantly enlarged and its presence in the world is assuming increasing importance, the role of the Eu*M*A should go beyond the original scope in order to strengthen the links among European countries and beyond, in the spirit of a peaceful cooperation among all peoples. According to the roadmap approved in 2003, a number of initiatives have since then been undertaken:

1. Eu*M*A membership, originally restricted to a small number of representatives constituting the General Assembly, has been open to all qualified microwave experts, including students, not only from Europe but from all over the world. This is a fundamental change that will affect not only the Association but also the whole European microwave community. This step is instrumental in order for the Eu*M*A to qualify as the representative of the microwave community in Europe. Eu*M*A members receive a number of benefits, in addition to reduced fees to attend Eu*M*A conferences.
2. The governing body of the Eu*M*A, i.e. the General Assembly, has been enlarged to 35 members, in order to include more representatives of European countries or groups of countries.
3. An electronic Newsletter is now distributed to all Eu*M*A members, containing information about Eu*M*A activities.
4. The EuMC Proceedings Archive, a DVD collecting all papers which appeared in the EuMC Proceedings from 1969 to 2003 has been produced and made available at a discounted price to the Eu*M*A members.

This new journal, the Proceedings of the European Microwave Association (in short: The Eu*M*A Proceedings), represents a further significant step aimed at fulfilling the scopes of the Association. The Journal is intended to provide information on scientific and technical innovation in the area of interest of the Eu*M*A, namely in microwave technology, including antenna and device technologies for microwave and millimetre-wave up to optical frequencies applications. In addition, the Journal will provide information about microwave activities in Europe, namely: conferences, educational programs in European institutions (Universities, High Schools, Colleges ...), industrial activities, news from research laboratories, etc. Attention will also be paid to microwave activities in the non-European Mediterranean area.

We are fully aware that there are already several outstanding technical journals in the area of microwave and radio frequency techniques. Nevertheless, we feel that a European Microwave journal is needed as the official voice of the European Microwave Association, a communication link among microwave engineers in Europe, between academy and industry, western and eastern countries, students and scientists. The Eu*M*A Proceedings will increase the visibility of the Association in order for it to become an official reference for microwave technical activities in Europe.

I am convinced that the Eu*M*A Proceedings will constitute a precious service to Eu*M*A Members: a journal covering all aspects of microwave activities with specific emphasis on European activities and European interests would be appreciated both in Europe and by the many countries looking to Europe as their reference for developing their own microwave activities in scientific, industrial and educational areas. The Eu*M*A is deeply indebted to the Editor-in-Chief, Professor Robert Weigel who has kindly accepted, in spite of his many commitments, to undertake such a complex and difficult job. Our sincere thanks go to the members of the Editorial Board, a group of internationally renowned experts representing both academia and industry in Europe and all over the world: the success of the Journal is strongly relying to their expertise and dedication. I could not conclude these introductory remarks without thanking the members of the Board of Directors and particularly Professor André VanderVorst who have supported this endeavour with enthusiasm and offered substantial help for the birth of the Journal.

Roberto Sorrentino
President of the EuMA

EuMA starts its proceedings

With this inaugural issue of the EuMA Proceedings the European Microwave Association starts its new journal for the purpose of creating a focus for the European microwave community, and for providing a high quality, affordable microwave journal. Microwave researchers and users are invited to submit papers and help make the EuMA Proceedings a leading microwave publication in the world. Papers dealing with microwave engineering and applications are of special interest in addition to those dealing with microwave theory and techniques.

This Inaugural Issue consists of a collection of review papers, original articles, and six papers which received one of the prizes of the European Microwave Week 2004, held in Amsterdam, The Netherlands, during 11 to 15 October, 2004. This issue offers a comprehensive view of the current state-of-the-art and future trends in the development of microwave technologies both in theory and practice covering different microwave fields, aspects and applications.

The EuMA Proceedings will have four issues per year. The next issue will include a Special Issue on Flexible Front-end Solutions for Cellular Communication Terminals, guest-edited by Georg Fischer, Lucent Technologies, Nuremberg, Germany and Clemens Ruppel, EPCOS, Munich, Germany; the scheduled publication date is June 2005. Further special issues are planned. Actual call for papers will be printed in the EuMA Proceedings, and can also be obtained at EuMA's URL http://eumwa.org.

We would like to thank all the authors for their contribution to this Inaugural Issue. Special thanks are also due to the expert reviewers of all the papers submitted and for their critical assessment of the reported work. Their guidance to us and to the authors was instrumental in the compilation of an outstanding set of papers.

Finally, let me thank Roberto Sorrentino, Andre Vander Vorst, Piet van Genderen, and all the members of our Editorial Board for the many fruitful discussions and their efficient help. I would wish to thank the staff members of the publisher Edizioni Plus, Pisa, Italy, especially Claudia Napolitano and Stefano Fabbri, for their ideas and work to set-up this first issue. The help of Henning Ehm and Sebastian Winter of the University of Erlangen-Nuremberg, Germany, who will form the Editorial Office of this journal, is greatly acknowledged, too.

Robert Weigel
Editor

Robert Weigel was born in Ebermannstadt, Germany, in 1956. He received the Dr.-Ing. and the Dr.-Ing. habil. degrees, both in electrical engineering and computer science, from the Munich University of Technology in Germany, in 1989 and 1992, respectively. From 1982 to 1988, he was a Research Engineer, from 1988 to 1994 a Senior Research Engineer, and from 1994 to 1996 a Professor for RF Circuits and Systems at the Munich University of Technology. In winter 1994-95 he was a Guest Professor for SAW Technology at Vienna University of Technology in Austria. From 1996 to 2002, he has been Director of the Institute for Communications and Information Engineering at the University of Linz, Austria. In August 1999, he co-founded DICE – Danube Integrated Circuit Engineering, Linz, meanwhile an Infineon Technologies Development Center which is devoted to the design of mobile radio circuits and systems. In 2000, he has been appointed a Professor for RF Engineering at the Tongji University in Shanghai, China. In 2002, he has moved to Erlangen, Germany, to overtake the Directorship of the Institute for Electronics Engineering at the University of Erlangen-Nuremberg.

He has been engaged in research and development on microwave theory and techniques, integrated optics, high-temperature superconductivity, SAW technology, and digital and microwave communication systems. In these fields, he has published more than 400 papers and given more than 200 international presentations. In 2002, he received the German ITG award. His review work includes European and Asian research projects and international journals.

Dr. Weigel is a Fellow of IEEE, a member of the Institute for Components and Systems of The Electromagnetics Academy, and a member of the German ITG and the Austrian ÖVE. Within IEEE MTT-S, he is a member of AdCOM, Chair of the Austrian COM/MTT Joint Chapter, Region 8 Coordinator, Distinguished Microwave Lecturer, and Vice-Chair of MTT-2 Microwave Acoustics.

Limits for CPM signals representation by Walsh functions

Francisco A. Monteiro[1], António J. Rodrigues[1 2]

Abstract – This paper explores the feasible limits for complexity reduction of a very simple front-end block for the calculus of phase transition metrics on a continuous phase modulation (CPM) receiver. A quasi-optimum receiver of very low complexity is attained by splitting the function of the optimum receiver bank filters in two blocks: calculus of projections coefficients on a low dimensional space of Walsh functions followed by simple matrix calculus. A sequence detection algorithm follows this block. The presented approach enables the reduction of the matched filters or correlators to just two integrators, regardless of the CPM scheme. Research on the reduction limits of the space dimension is conducted using catastrophic *M*-ary CPM schemes, taking advantage of their very low number of phase states. Performance of 1REC $h = 1/2$ 16-ary scheme is for the fist time presented. A rule is defined concerning the number of Walsh functions that must be used. That outcome proves to be valid for two CPM schemes of high power gain. The receiver is tested under additive white gaussian noise (AWGN).
Index terms – Continuous phase modulation (CPM), metrics calculus, Walsh functions

I. Introduction

Continuous phase modulation (CPM) signals have constant amplitude and so they are a good solution for systems requiring insensitivity to non-linear amplitude amplification. Their phase continuity allows good spectral performance and implies a code gain due to the inherent memory effect. These properties have motivated the common use of GMSK (gaussian minimum shift keying), which is a simple member of the CPM family, in widespread use systems such as GSM/DCS, PCS, DECT, CT2 and Bluetooth. The use of other CPM schemes more spectrally efficient and better power efficient was restrained owing to excessive detection complexity [1]. The number of analogue matched filters (or correlators) needed is often unbearable for practical implementation. The number of phase states to be detected can very large as well. Conception of simple receivers is nowadays a main concern within CPM research. This paper shows that Walsh functions can generate a space where it is possible to find signals close to the original CPM signals. Digital signal processing (DSP) allows fast matrix calculus using both received and stored signals.

II. CPM formatting and performance

Every CPM signals can be expressed in the form:

$$s(t, \tilde{\mathbf{a}}) = \sqrt{2E_s/T_s}\cos(\omega_c t + \varphi(t, \tilde{\mathbf{a}}) + \varphi_0) \quad (1)$$

The carrier frequency is f_c, where $\omega_c = 2\pi f_c$, φ_0 is the arbitrary initial phase and E_s is the energy per symbol, related with the bit energy by $E_s = \log_2(M)\cdot E_b$. Channel symbols are $\gamma_i \in \{\pm1, \pm3, \cdots, \pm(M-1)\}$, forming the *M*-ary sequence $\boldsymbol{\gamma}$. Each symbol γ_i carries $\log_2(M)$ bits as a result of a natural mapping of the information bits stream $\boldsymbol{\alpha}$. The information carried by N_S channel symbols is keyed in signal's phase:

$$\varphi(t, \tilde{\mathbf{a}}) = 2\pi\, h \sum_{i=0}^{N_s} \gamma_i q(t - iT_s) \quad (2)$$

A constant modulation index, $h = p/q$, is considered, where p and q are integers with no common factors. (h is rational in order to have a finite number of phase states.) Phase transition pulse shape, $q(t)$, affects phase transitions shape during L symbols. However, its effect remains until the end of the transmitted sequence. $q(t)$ is defined by the frequency pulse $g(t) = \int_{-\infty}^{t} g(\tau)d\tau$. The normalisation $q(t) = \int_0^{\infty} g(\tau)d\tau = 1/2$ is applied so that the maximum phase transition during a symbol time, T_s, is $h\cdot(M-1)\cdot p$. Different frequency pulses define different CPM families. The most common are: LREC, LRC (L is the variable mentioned above) and GMSK [1,2]. LREC is defined by $g(t) = \mathrm{rect}[t/(LT_s)]/2$, where $\mathrm{rect}(t) = 1$ for $-1/2<|t|<1/2$ and zero elsewhere. Schemes with 1REC pulses are also known as CPFSK (continuous phase frequency shift keying). A smother $g(t)$ such the named LRC (raised cosine pulse shaping) usually conducts to narrower bandwidth than the ones given by LREC pulses.

In order to evaluate CPM power performance one uses the *minimum normalised squared euclidean distance* (MNSED) between two signals transporting sequences $\boldsymbol{\gamma}$ and $\boldsymbol{\gamma}'$:

[1] Instituto de Telecomunicações and ISCTE; [2] Instituto de Telecomunicações and Instituto Superior Técnico, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal. Tel: +351 218418484; Fax: +351 218418472; E-mail: frmo@lx.it.pt

(3) $$d^2_{\min}(\tilde{a},\tilde{a}') = 1/(2E_s)\min_{\tilde{a},\tilde{a}':\tilde{a}\neq\tilde{a}'}\int_0^{\infty}\left[s(t,\tilde{a})-s(t,\tilde{a}')\right]^2 dt$$

Bit error rate (BER) is given by (e.g. [1])

(4) $$P_b \approx C\cdot Q\left(\sqrt{d^2_{\min}\frac{E_b}{N_0}}\right)\approx Q\left(\sqrt{d^2_{\min}\frac{E_b}{N_0}}\right)$$

C is a constant ≈1 for most schemes (and 2 for MSK). $Q(x)$ is the area under the unit variance gaussian distribution in $[x, \infty]$. Power efficiency comparisons can be made from (4) merely by $d^2_{\min}$ knowledge or converting it to a gain relative to MSK, being $G = 10\cdot\log_{10}(d^2_{\min}/2)$ [dB].

Bandwidth is usually given in terms of $B_\varepsilon T_b$ where B_e is the bandwidth that enclosures ε% of all transmitted power. $T_b = T_s/\log(M)$ is the bit interval; bit rate is $R_b = 1/T_b$. For MSK $B_{99.0}T_b = 1.2$. Spectrum efficiency is thereby $\zeta = 1/(B_\varepsilon T_b) = R_b/B_\varepsilon$. By reducing h, phase transitions get smother, tightening bandwidth, but that also forces MNSED to decrease due to the greater similitude among transitions during each T_s interval. A greater M enhances simultaneously spectrum and power behaviour at a cost of boost in complexity.

III. Optimum detection

To obtain metrics for each one of the Ξ phase transitions the optimum CPM receiver requires 2Ξ matched filters (or equivalent correlators), one for each branch I and Q. Metrics have to be calculated for all transitions $\tau_{I,b}\in\{\tau_{I,1}, \tau_{I,2}, \cdots, \tau_{I,\Xi}\}$ and all $\tau_{Q,b}\in\{\tau_{Q,1}, \tau_{Q,2}, \cdots, \tau_{1,\Xi}\}$. Considering $n(t)$ additive white gaussian noise (AWGN), after baseband conversion one gets the $y(t) = s(t, \boldsymbol{\gamma}) + n(t)$. I and Q metrics for $b = 1, 2, \cdots, \Xi$, are then

(5) $$\Lambda_i(b)=\int_{T_s} y_{I,i}(t)\tau_{I,b}(t)\,dt+\int_{T_s} y_{Q,i}(t)\tau_{Q,b}(t)\,dt = \Lambda_{I,i}(b)+\Lambda_{Q,i}(b).$$

In more detail, for the same b, the branch metrics are

(6a) $$\Lambda_{I,i}(b)=\int_{iT_s}^{(i+1)T_s} y(t)\cdot\cos\left[2\pi h\gamma_b\, q(t)\right]dt$$

(6b) $$\Lambda_{Q,i}(b)=\int_{iT_s}^{(i+1)T_s} y(t)\cdot\sin\left[2\pi h\gamma_b\, q(t)\right]dt\,.$$

Finally, having all the metrics, the problem is solved by a maximum likelihood sequence detector (MLSD). The detection complexity of CPM schemes is measured in terms of Ξ and the total number of states, being that number $S = q\times M^{L-1}$, for even p and $S = q\times M^{L-1}$ for odd p. In the case of full response systems ($L = 1$), S corresponds to the number of physical phase states. The number of phase transitions is therefore $\Xi = S\times M$. For this reason the number of 2Ξ filters becomes intolerable for high M and/or weak h.

As a result, MLSD must search for the sequence having maximum cumulative metric given by the inner product

(7) $$\Lambda_i(b)=\left\langle y(t,\gamma_i),\tau_b(t)\right\rangle.$$

IV. Projections and metric calculus

Metrics are calculated on a F-dimensional Walsh space, generated by F Walsh functions [3] of order k denoted as $w_{F,n}(t)$; $n = 1, 2, 3, \cdots, F = 2^k$; each one with $F = 2^k$ symbols, being them $w_{F,n}[j]$, $j = 0, 1, \cdots, F=2^k$, for $k \in Z^+$:

(8) $$\tilde{w}_{F,n}(t)=\frac{1}{\sqrt{T_s}}\sum_{j=0}^{F-1} w_{F,n}[j]\cdot\mathrm{rect}\left[\frac{t-(T_s/(2F))-j(T_s/F)}{T_s/F}\right]$$

with $n = 0, 1, \cdots, F-1 = 2^u-1$, $u\ k \in Z^+$, and $\mathrm{rect}(t) = 1$ for $<|t|<1/2$ and zero elsewhere. Symbols $w_{F,n}[j]$ $k \in \{-1, +1\}$ and are defined by a recursive method that builds *Walsh-Hadamard matrixes* [3]. Applying (7), it can be proved that the b^{th} metric in the Walsh space when applying a MLSD criterion is given by

(9) $$\Lambda_i(b)=\left[\sum_{n=1}^{F}\int_{iT_s}^{(i+1)T_s} y(t)\cdot\tilde{w}_{F,n}(t)\,dt-\int_{iT_s}^{(i+1)T_s} s(t,\gamma_b)\cdot\tilde{w}_{F,n}(t)\,dt\right]^2$$

for $b = 1, 2, \cdots, \Xi$. Metric calculus is made merely using the projection of the received baseband signal $y(t)$ into the Walsh space. Those projections coefficients are

(10) $$c_{i,n}=\frac{1}{\sqrt{T_s}}\int_{iT_s}^{(i+1)T_s} y(t,\gamma_i)\cdot w_{F,n}(t-iT_s)\,dt$$

From (9), the transition metrics are

(11) $$\Lambda_i(b)=\frac{1}{\sqrt{T_s}}\sum_{n=1}^{F}\left|c_{i,n}-c_{b,n}\right|^2,\ \text{for } b=1, 2, \cdots, \Xi,$$

where $c_{i,n}$ are the projection coefficients of the transition during symbol interval i, as given by (10), and $c_{b,n}$ are projection coefficients of the b^{th} transition belonging to the set of Ξ possible ones. Using the projection vectors and (7), (11) becomes

(12) $$\Lambda_i(b)=\frac{1}{\sqrt{T_s}}\sum_{n=1}^{F} c_{i,n}c_{b,n}\ ,\ b=1, 2, \cdots, \Xi.$$

These coefficients can be easily determined by:

(13) $$c_{i,n}=\frac{1}{\sqrt{T_s}}\sum_{j=0}^{F-1} w_{F,n}[j]\int_{(i+j/F)T_s}^{(i+(j+1)/F)T_s} y(t,\gamma_i)\,dt\,.$$

Moreover, each integrator does not need to be dumped at the end of every T_s/F sub-interval. By sampling the continuous integration it is possible do know the partial integration values making

$$c_{i,n} = \frac{1}{\sqrt{T_s}} \sum_{j=1}^{F} w_{F,n}[j] \left[\left(\int_{iT_s}^{t} y(t,\gamma_i)\, dt \right) \Big|_{t=j\frac{T_s}{F}} - \left(\int_{iT_s}^{t} y(t,\gamma_i)\, dt \right) \Big|_{t=(j-1)\frac{T_s}{F}} \right] , \quad iT_s < t < (i+1)T_s . \tag{14}$$

The calculation on (14) only requires two integrators, a sampling procedure and a calculus unit, independently of the CPM scheme.
The vector of Ξ metrics is the column vector

$$\ddot{\mathbf{E}}_i = \left[d_i^2(1) \;\; d_i^2(2) \;\cdots\; d_i^2(b) \;\; d_i^2(b+1) \;\cdots\; d_i^2(\Xi) \right]^{\mathrm{T}} . \tag{15}$$

The received i^{th} transition has a description on the Walsh space given by the projection vector

$$\mathbf{c}_i = \left[c_{i,1} \;\; c_{i,2} \;\cdots\; c_{i,n} \;\cdots\; c_{i,F} \right] , \quad i=1, 2, \cdots, N_S. \tag{16}$$

Each possible transitions is stored on similar vectors:

$$\mathbf{c}_b = \left[c_{b,1} \;\; c_{b,2} \;\cdots\; c_{b,n} \;\cdots\; c_{b,F} \right] , \quad b=1, 2, \cdots, \Xi. \tag{17}$$

Coefficients, $c_{b,n}$, can be determined and memorized in advance. Vectors $\mathbf{c}_b$ can form matrix $\mathbf{C}$ of dimensions $\Xi \times F$

$$\mathbf{C} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_b \\ \vdots \\ \mathbf{c}_\Xi \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,n} & \cdots & c_{1,F} \\ c_{2,1} & c_{1,2} & \cdots & c_{1,n} & \cdots & c_{1,F} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{b,1} & c_{b,2} & \cdots & c_{b,n} & \cdots & c_{b,F} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{\Xi,1} & c_{\Xi,2} & \cdots & c_{\Xi,n} & \cdots & c_{\Xi,F} \end{bmatrix} . \tag{18}$$

Having $\mathbf{C}$, the incremental distance vector (metrics) is

$$\ddot{\mathbf{E}}_i = \begin{bmatrix} d_i^2(1) \\ d_i^2(2) \\ \vdots \\ d_i^2(b) \\ \vdots \\ d_i^2(\Xi) \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & c_{1,n} & \cdots & c_{1,F} \\ c_{2,1} & c_{1,2} & \cdots & c_{1,n} & \cdots & c_{1,F} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{b,1} & c_{b,2} & \cdots & c_{b,n} & \cdots & c_{b,F} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{\Xi,1} & c_{\Xi,2} & \cdots & c_{\Xi,n} & \cdots & c_{\Xi,F} \end{bmatrix} \cdot \begin{bmatrix} c_{i,1} \\ c_{i,2} \\ \vdots \\ c_{i,n} \\ \vdots \\ c_{i,F} \end{bmatrix} = \mathbf{C} \cdot \mathbf{c}_i^{\mathrm{T}} , \quad i=1, 2, \cdots, N_S. \tag{19}$$

conducting to the column vector containing the Ξ metrics.

V. Test schemes

In order to research the behaviour of the receiver we have used the $h = 1/2$ full response M-ary schemes presented in Table I (MSK on the first line), taking advantage of their very low number of states ($S = 4$). Those simple schemes happen to be catastrophic, that is, their MNSED has a local mean for the used $h = {}^1/_2$, bein the real $d^2_{\min}$ very distant from its upper bund [2]. That concerns only to the MLSD block and should not influente the research on the metric calculus using the given CPM space approximation.
From [2,4,5] we point out two optimum full response mono-h CPM schemes also characterized in Table 1.

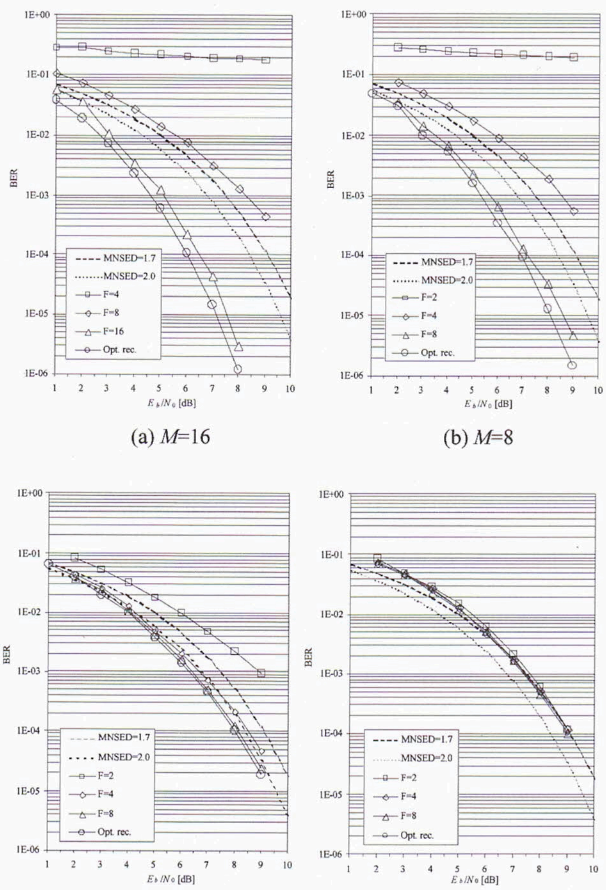
Table 1.

h	M	S	$B_{99.0}T_b$	$d^2_{\min}$	G [dB]	Ξ	2Ξ
1/2	2	4	1.20	2.0	0	8	16
	4	4	1.30	2.0	0	16	32
	8	4	1.55	3.0	1.76	32	64
	16	4	(a)	(a)	(a)	64	128
9/20	4	40	1.18	3.60	2.56	160	320
	8	40	1.40	5.40	4.31	320	640

Table 1 positions where "(a)" is found are not available; they are obtained in Section VI. The selected schemes of $h = 0.45 = 9/20$ are the best 4-ary and 8-ary CPFSK schemes in terms of power gains within the regiom of used spectral efficiencies which preserve an acceptable number of states ($S = 40$). These two schemes of $h = 0.45$ share another interesting feature: they are examples of rare schemes with a MNSED coincident with their upper bound curves (determined by [1,2]).

VI. Results

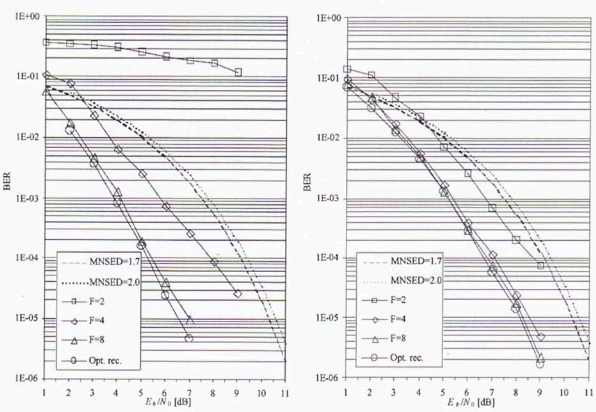
Results for performance in terms of bit error rate (BER) for detection under AWGN are depicted in Figures 1 and 2.
The results for the optimum reception of 1REC, $h = 1/2$, $M = 16$ plotted in Figure 1 (a) were achieved for the fist time as a result of the presented research: a gain of ≈3 dB can be detected, corresponding to $d^2_{\min} \cong 4$ (half the bound value for $d^2_{\min}$ calculated by [1].
For better power gain assessment all figures include both BER curve for ideal antipodal modulation ($d^2_{\min} = 2$) and BER curve associated to $d_{\min} = 7.1$, proposed by [6] to describe real MSK. It can be seen that that an increasing number of Walsh functions, F, is required



(a) *M*=16 (b) *M*=8

(c) *M*=4 (d) *M*=2 (MSK)

Fig. 1. Effect of the Walsh space dimension for h = 1/2, 1REC schemes.



(a) *M*=8 (b) *M*=4

Fig. 2. Effect of the Walsh space dimension for optimum = 9/20, 1REC schemes.

when a greater *M* scheme is considered. For all tested schemes a number of Walsh functions equal to *M* (i.e. $F = M$) assures near optimum performance. For $F > M$ no significant gains were detected. A decreasing value of *F* implies an abrupt loss.

This method was firstly proposed by [7] for schemes 3RC (partial response scheme) with $M = 2$ and $M = 4$ and a varying *h*. It was also seen there that power penalty decreases for small modulations indexes (which are the interesting ones in terms of bandwidth). This fact is coherent with the greater smoothness on the phase transitions of low *h* schemes (less abrupt signals) which brings CPM signals closer to the Walsh space. Those results from [7] also show that, for those schemes, even when $F = 2$ the power penalty is always <0.5 dB. For $F = 4$ and for F=8 the loss is always <0.4 dB and <0.1 dB respectively for schemes having h<0.7. These impressive results were also verified on other partial response quaternary schemes with GMSK pulses with $L = 5$ and $L = 6$, and $h = 1/4$, 1/5 and 1/6 [8].

From the attained results it can be said that the rule $F \geq M$, found out for the simple but catastrophic schemes, can be extrapolated to the interesting schemes of $h = 9/20$, presented in section V, which were also tested under AWGN. More, simulations for the optimum receiver confirms the expected gains showed in Table 1 for these h=9/20 schemes: $G \approx 2.6$ dB for $M = 4$ and $G \approx 4.3$ dB for $M = 8$. When applying the Walsh space to the optimum $h = 9/20$ schemes one gets for $M = 8$ with $F = 8$ a BER curve as close as 0.2 dB from the optimum detection curve, as seen in Figure 2 (a). For $M = 4$ with $F = 4$ the power loss is less than 0.1 dB - Figure 2 (b). Also notice that $h = 0.45$ assures smother transitions than $h = 0.5$.

VII. Conclusions

The first results of [7] where extended in this paper and some patterns were found to predict the error robusteness of receivers using this low complexity front-end which completes CPM metrics based on a Walsh space. The good approximation of CPM signals by such simple functions is justified by the fact that CPM signals are inherently narrowband signals.

By assessing bit error rate performance with different Walsh space dimensions it was found that similar patterns occur for different *M*-ary schemes. A decrease on the order of the used set of Walsh functions degrades performance, being this effect more important for schemes with a higher *M*.

It was established that near-optimum performance is attained when using a Walsh space dimension as small as *M*. The use of a superior number of functions permits little performance improvement. The rule is valid at least for schemes with $h \leq 0.5$ (with are the most interesting ones in terms of bandwidth) and $M \leq 16$ (the feasible ones in terms of complexity for MLSD) and proved to remain valid when applied to full response optimum gain schemes (equal to the local power upper bound).

As a particular a case, it was showed that MSK can be detectable in a quasi-optimum manner just sampling twice a continuous integrator during each symbol interval.

The metric calculus made with this simple technique can still be applied when using symmetry relations to derive metrics among different quadrants [9]. Its joint application with both [9] and the use of the M-algorithm ruled by the results in [10], enabled the definition of a very low quasi-optimum receiver analysed in [11,12] using the optimum schemes selected and tested here.

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References

[1] Anderson, J.; Aulin, T.; Sundberg, C.-E.: Digital Phase Modulation. New York: Plennum Press, 1986.

[2] Aulin, T.; Sundberg, C.-E.: Continuous Phase Modulation - Part I: Full Response Signalling. IEEE Trans. on Comm. **Com-29** (1981), 196-209.

[3] Franks, L.E.: Signal Theory. Prentice-Hall, 1969.

[4] Aulin T.; Sundberg, C.-E.: Minimum Euclidean Distance and Power Spectrum for a Class of Smoothed Phase Modulation-Codes with Constant Envelope. IEEE Trans. on Comm. **Com-30** (1982), 1721-1729.

[5] Sasase, I.; Mori, S.: Multi-*h* Phase-Coded Modulation. IEEE Communications Mag. **29** (1991), 46-56.

[6] Murota, Z.; Hirade, K.: GMSK Modulation for Digital Mobile Radio Telephony. IEEE Trans. on Comm. **Com-29** (1981).

[7] Tang, W.; Shwedyk, E.: A Quasi-Optimum Receiver for Continuous Phase Modulation. IEEE Trans. on Comm. **48** (2000), 1087-1090.

[8] Svensson, T.; Svensson, A.: Reduced Complexity Detection of Bandwidth Efficient Partial Response CPM. Proc. of IEEE Vehicular Tech. Conf. '99, Houston, Texas, May 1999, 1296-1300.

[9] Monteiro, F.; Rodrigues, A.: Simple Metrics Derivation for a Discrete Time Continuous Phase Modulations Receiver. Proc. of WPMC '01 – 4th International Symp. on Wireless Personal Multimedia Communications, Aalborg, Denmark, Sept. 2001, 395-400.

[10] Monteiro, F.; Rodrigues, A.: The M-algorithm on the Detection of CPM Schemes on the Minimum Euclidian Distance Upper Bound. Proc. of ECWT '04 – European Conf. on Wireless Technology, Amsterdam, The Netherlands, October 2004.

[11] Monteiro, F.; Rodrigues, A.: CPM Reception Combining Complexity Reduction Techniques for Schemes on Minimum Euclidian Distance Upper Bound and MSK. Proc. of ISIT 2004 – IEEE International Symp. on Information Theory, Chicago, USA, June 2004, 220.

[12] Monteiro, F.; Rodrigues, A.: Assessment of a Quasi-Optimum Very Low Complexity CPM Receiver over Flat Rayleigh Fading Channels. Proc. of VTC '04 Spring – IEEE Semiannual Vehicular Technology Conf., Milan, Italy, May 2004, 1139-1143.

Francisco A.T.B.N. Monteiro received the *Licenciatura* degree in electrical and computer engineering (telecommunications profile) from the Instituto Superior Técnico (IST), Technical University of Lisbon, Portugal, in February 1999, and his M.Sc. degree in January 2003, from the same university.

He is a researcher at the Telecommunications Institute at IST since 1998. He was a teaching assistant at IST from May 1998 until June 2000 and from October 2001 onwards he is a teaching assistant at ISCTE, Lisbon, Portugal. From September 2000 until September 2001 he was funded by the Portuguese Foundation for Science and Technology for his contribution for a national project at the Telecommunications Institute. His M.Sc. dissertation was the recipient of the 3rd place at the Innovation Young Engineer Prize awarded by the Portuguese Engineers Association in December 2002. Mr. Monteiro was also awarded the Young Engineer Prize from the European Microwave Association for a paper presented at the European Conference on Wireless Technology in October 2004, in Amsterdam.

António Rodrigues received the B.Sc. and M.Sc. degrees in electrical and computer engineering from Instituto Superior Técnico (IST), Technical University of Lisbon, Portugal, in 1985 and 1989, respectively, and the Ph.D. degree from the Catholic University of Louvain, Louvain-la-Neuve, Belgium, in 1997.

Since 1985, he has been with the Department of Electrical and Computer Engineering, IST, where he is currently an Assistant Professor. He is a researcher at the Telecommunications Institute at IST, Lisbon.

His research interests include mobile and satellite communications, spread spectrum systems, radio resource management, modulation, and coding.

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