We have also performed an optical heterodyne experiment to measure the dependence of the generated microwave power on the input optical power. Two optical wavelengths, separated by 10 GHz, were amplified by an EDFA and then coupled to a photodetector. An optical attenuator and polarisation controllers were used to control the input optical power and the input polarisations. The generated RF signal was collected with a 40 GHz GGB Industries Picoprobe and measured using an HP8487A power sensor-power meter. The measured RF power increases quadratically with the input optical power (Fig. 4), indicating the photodetector is linear at 10 GHz for the entire optical power range. The maximum linear RF power of 9 dBm is limited by the available optical power.

Conclusion: We have successfully fabricated a parallel feed travelling wave *pin* photodetector with an integrated 1×4 MMI power splitter. The DC photocurrent is linear till 52.2 mA, which is the highest current reported for detectors operating at 1.55 μm wavelength. The RF bandwidth measurement from 0.045–20 GHz shows no saturation for up to 15 dBm of input optical power. The optical heterodyne output of the detector is linear up to 9 dBm of 10 GHz RF power.

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S. Murthy and M. C. Wu (*Electrical Engineering Department, University of California, Los Angeles, CA 90095, USA*)

E-mail: sanjeev@icsl.ucla.edu

D. Sivco and A. Y. Cho (*Lucent Technologies, Bell Laboratories, Murray Hill, NJ 07974, USA*)

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OFDM-CPM signals

I.A. Tasadduq and R.K. Rao

A class of orthogonal frequency division multiplexing–continuous phase modulation (OFDM-CPM) signals is introduced in which binary data sequence is mapped to complex symbols using the concept of correlated phase states of a CPM signal. Various types of signals are defined as a function of parameter *h* and pulse duration. An investigation of bit error rate and peak-to-average-power ratio performance of these signals is also presented.

Introduction: Orthogonal frequency division multiplexing (OFDM) is a good candidate for wireless communication owing to its excellent properties in frequency-selective fading environments [1].

While in the literature OFDM-PSK, -QAM, -DPSK and -DAPSK have been considered [2–4], OFDM–continuous phase modulation (CPM) signals that use the concept of correlated phase states of a CPM signal have not been considered to date. One of the advantages of OFDM-CPM signals is that correlation amongst adjacent OFDM symbols can be systematically introduced by an appropriate choice of parameter h (in typical CPM signals h is modulation index). Furthermore, this correlation can be exploited to control bit error rate (BER).

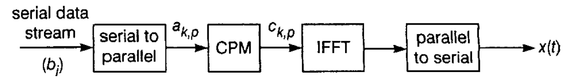

Fig. 1 *OFDM-CPM transmitter*

OFDM-CPM signalling scheme: As shown in Fig. 1, serial bit stream $b_i, i = 0, 1, 2, \ldots$ with bit duration of T_b seconds is converted into blocks of N bits represented by $a_{k,p}; k = 0, 1, 2, \ldots$ and $p = 0, 1, 2, \ldots, N-1$, where N denotes the number of carriers and $a_{k,p} = \pm 1$, e.g. $a_{0,p}$ would denote the first block of N bits and $a_{1,p}$ the second block of N bits, and so on. The CPM mappers transform the incoming $\{a_{k,p}\}$ into appropriate complex numbers $\{c_{k,p}\}$, i.e.

$$c_{k,p} = \cos(\theta_{k,p}) + j\sin(\theta_{k,p}) \tag{1}$$

with

$$\theta_{k,p} = a_{k,p}\pi h + \pi h \sum_{q=0}^{k-1} a_{q,p} + \phi \tag{2}$$

where parameter h defines the CPM mapper and ϕ represents the initial mapping point. In (2) the angles $\theta_{k,p}$ depend not only on the current data but also on the past data. Current value of θ is determined by adding $+\pi h$ (for data $a+1$) or $-\pi h$ (for data $a-1$) to the previous value of θ. The complex numbers from the output of CPM mappers that lie on a circle are passed through pulse-shaping filters $g(t)$, modulated by orthogonal carriers and summed to give the transmitted OFDM symbol, i.e.

$$x(t) = \sum_k \sum_p c_{k,p} g(t - kT) e^{j(2\pi/T)pt}, \qquad 0 \le t < \infty \tag{3}$$

where

$$g(t) = \begin{cases} \dfrac{1}{\sqrt{T}} & 0 \le t \le LT \\ 0 & \text{elsewhere} \end{cases} \tag{4}$$

In (3), $T(=NT_b)$ is the OFDM symbol duration and in (4) $L = 1$ for full response signalling. The parameters h and L can be chosen in various ways. Some of the OFDM-CPM signals are described below.

A. Single-h OFDM-CPM signals: In this case, the value of h remains constant for all OFDM symbols. By choosing h to be rational and $0 < h < 1$ it is possible to have a finite number of points in the CPM constellation. Fig. 2 shows the constellation diagram of CPM mapper for $h = 1/2$ and $h = 1/4$.

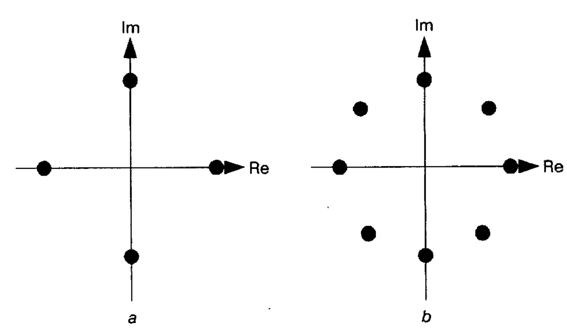

Fig. 2 *Constellation diagram of CPM mapper*
a $h = 1/2$
b $h = 1/4$

B. Multi-h OFDM-CPM signals: The value of h is cyclically chosen from a set of K values, i.e. the value of h employed during the ith symbol is given by $h_{i \,\mathrm{modulo}\, K}$. For example, the complex numbers of a four-carrier OFDM-CPM signal with $H_2 = \{1/2, 1/4\}$ for the first two blocks of data sequences are shown below (assuming initial mapping points to be $1 + j0$):

$$[a_{k,p},\ a_{k+1,p}] \Rightarrow [c_{k,p},\ c_{k+1,p}]$$

$$\begin{bmatrix} +1 & -1 \\ +1 & +1 \\ -1 & +1 \\ +1 & -1 \end{bmatrix} \Rightarrow \begin{bmatrix} +j & \frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}} \\ +j & \frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}} \\ -j & \frac{1}{\sqrt{2}} - j\frac{1}{\sqrt{2}} \\ +j & \frac{1}{\sqrt{2}} + j\frac{1}{\sqrt{2}} \end{bmatrix}$$

C. Asymmetric OFDM-CPM signals: While in multi-h OFDM-CPM signals h values are independent of data bits $a_{k,p} (= \pm 1)$, in asymmetric multi-h signals h is made a function of $a_{k,p}$, i.e. the value of h during the ith symbol interval is chosen h_{+i} or h_{-i} accordingly as data is a $+1$ or -1, respectively. This gives better flexibility to the designers to optimise system performance.

D. Partial response OFDM-CPM signals: In (4), by making $L > 1$, the pulse duration can be extended to more than one OFDM symbol. Using a value of $L = 2, 3, \ldots$ systematic correlation can be furthered among OFDM symbols which in turn can be exploited for improvement in system performance.

BER performance: We simulated various OFDM-CPM systems for a two-path channel with and without guard interval. The channel impulse response is given by

$$h(t) = \alpha_1 \delta(t) + \alpha_2 \delta(t - \tau) \qquad (5)$$

where α_1 and α_2 are the levels of direct and delayed paths and τ is the delay. Other system parameters are: number of carriers $(N) = 32$, bit rate $(R_b) = 800$ kbit/s, carrier frequency $(f_c) = 910$ MHz, Doppler shift $= 5$ Hz, guard interval $(T_g) = 0.25$ T, $\alpha_1/\alpha_2 = 10$ dB and $\tau = 0.0625$ T. Fig. 3*a* shows the BER performance for various signalling schemes without any guard interval. The plot also shows the performance of an OFDM-BPSK system for comparison. It can be seen that an OFDM-CPM system with $h = 3/5$ and observation interval $(n) = 2$ performs better than the OFDM-BPSK system. The performance improves further when n is extended to five symbols. Using multiple values of h improves BER even further for $H_2 = [7/14\ 8/14]$ and $n = 3$. Fig. 3*b* shows BER of a similar system with guard interval. It is evident that OFDM-CPM systems perform substantially better than OFDM-BPSK systems; in addition, multi-h OFDM-CPM signals give the best BER for the chosen values of h.

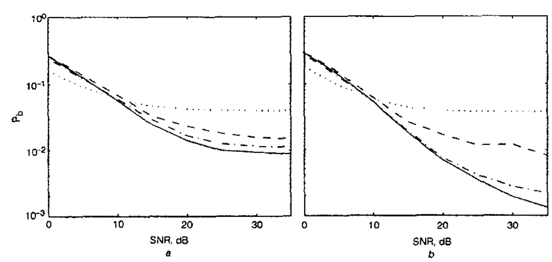

Fig. 3 *Bit error rate for various signalling schemes*

a Without guard interval
b With guard interval
.....	OFDM-BPSK
---	single-h OFDM-CPM ($h = 3/5$, $n = 2$)
-·-·	single-h OFDM-CPM ($h = 3/5$, $n = 5$)
——	multi-h OFDM-CPM ($H_2 = [7/14\ 8/14]$)

Peak power performance: Peak-to-average-power-ratio (PAPR) is an important issue in OFDM system design. Therefore, we investigated the PAPR performance of the proposed class of signals. Fig. 4*a* shows the complementary cumulative distribution function (CCDF) plot of a 32-carrier OFDM-CPM system with $h = 0.3$ and $L = 1$. Since the OFDM-CPM signals are correlated, coding schemes that avoid high PAPR sequences do not help in reducing PAPR. However, schemes that reduce PAPR at the output of inverse fast Fourier transforms (IFFT) work better, e.g. weighting the OFDM-CPM signals after taking the IFFT reduces PAPR [5]. Fig. 4*a* also shows PAPR performance with Gaussian weighting. Here we oversample the OFDM symbol by a factor of 4. Fig. 4*b* shows a plot of PAP_0 against values of h when $\Pr[PAPR > PAP_0] = 10^{-3}$ with and without Gaussian weighting. Although, in general, PAPR is independent of the mapping scheme, we can see that in the case of OFDM-CPM signals PAPR is dependent upon the values of h. It can be seen that $h = 0.4$ performs better in terms of PAPR than other values of h while $h = 0.9$ gives the worst PAPR.

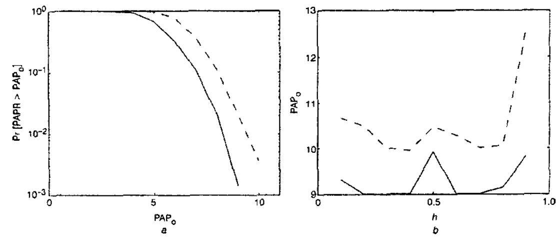

Fig. 4 *Peak power performance of OFDM-CPM signals*

a CCDF of OFDM-CPM signals ($h = 0.3$)
b PAP_0 of OFDM-CPM signals for various h values when $\Pr[PAPR > PAP_0] = 10^{-3}$
---	non-weighted
——	with Gaussian weighting

Conclusions: OFDM-CPM is a novel signalling scheme that gives flexibility to the system designer. Various types of signals can be generated by appropriately choosing the values of h, L and observation interval (n). At the receiver we observe n OFDM symbols and arrive at an optimum decision on one of the symbols. BER performance of OFDM-CPM systems is better than OFDM-PSK systems. For the detection of OFDM-CPM signals we can use multiple-symbol-observation receivers. The optimum receiver proposed in [6] for single-carrier CPM signals can be modified and used for detection of OFDM signals. The Viterbi algorithm (VA) is computationally less expensive which can also be used for the detection of OFDM-CPM signals. The performance of these signals in multipath fading channels with AWGN is to be thoroughly investigated for various values of h, L and observation interval.

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I.A. Tasadduq and R.K. Rao (*Department of Electrical & Computer Engineering, Elborn College, 1201 Western Road, The University of Western Ontario, London, ON N6G 1H1, Canada*)

E-mail: iatasadd@uwo.ca

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