Jayalath, Dhammika and Tellambura, Chintha (2000) Adaptive PTS approach for reduction of peak-to-average power ratio of OFDM signal. *Electronics Letters* 36(14):pp. 1226-1228.

mission signal was measured with the use of a liquid He cooled Cu:Ge infrared detector having a fast response time (< 1ns). A typical result is shown in Fig. 2. The Figure shows an exponential decay time of 15ns due to two-body recombination of the photogenerated electron-hole plasma.

To demonstrate the operation of the thinned-silicon PC switch, time-domain electrical waveform measurements were performed on the signal line. A typical electrical pulse, with a full-width-half-maximum of 15ps, is presented in Fig. 3. The small peak appearing at ~35ps is due to an electrical reflection from the end of the transmission line. Given that the 15ns lifetime for the carriers is well in excess of the 15ps electrical pulse duration shown, we conclude that a process much faster than carrier recombination is responsible for the termination of the electrical pulse. Indeed, the delayed electrical grounding action of the buried metal layer is responsible for driving the potential on the signal line back down to ground at a rate limited solely by the electrical time constant. The thinned-silicon PC switch is, therefore, capable of generating electrical pulses 1000 times shorter in duration than the carrier lifetime.

The rise time for the electrical signal (τ_{rise} = 0.8ps) is very fast, implying that the electrical time constant for the bias line to signal line switching process is small. By modelling the displacement and conduction currents across the PC gap with the parallel combination of a capacitor, C, and a time varying conductor

$$G(t) = \begin{cases} 0 & t < 0 \\ G & t \geq 0 \end{cases} \quad (1)$$

an insight into the rising edge time constant, τ_{rise}, can be found through the relation [7]

$$\frac{1}{\tau_{rise}} = \frac{1}{2Z_oC} + \frac{G}{C} \quad (2)$$

It is readily apparent from the linear relationship between $1/\tau_{rise}$ and G that the small electrical rise time of Fig. 3 is a direct result of a large charge carrier density at the silicon surface between the bias line and the signal line (which implies a large G). Also evident from Fig. 3 is that the electrical fall time (τ_{fall} = 25ps) associated with the illumination of the ground plane is relatively long. By direct analogy with the electrical rise time case, it is apparent that the effective charge carrier density between the signal line and the ground plane is of diminished value relative to the charge carrier density at the surface and, therefore, the electrical response time for the grounding process is longer. By both decreasing the substrate thickness and increasing the illumination intensity, however, the charge carrier density associated with the grounding process can be increased and the duration of the electrical pulse further decreased. In fact, for sufficiently large carrier densities the electrical pulse duration limit, corresponding to the temporal delay of the optical excitation pulse through the substrate, can be approached.

Conclusion: We have successfully demonstrated the operation of a microstrip PC switch capable of generating 15ps electrical pulses. By fabricating the switch on a thinned-silicon substrate, a delayed grounding process was employed to terminate the electrical pulse. Indeed, the resulting electrical pulse duration was 1000 times shorter than the 15ns carrier lifetime in FZ-Si and can be further decreased by decreasing the substrate thickness and increasing the illumination intensity. In addition to the current experimental device work, preliminary theoretical studies have been successful in describing the device operation [8].

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Adaptive PTS approach for reduction of peak-to-average power ratio of OFDM signal

A.D.S. Jayalath and C. Tellambura

An adaptive partial transmit sequence (PTS) technique is presented for the reduction of the peak-to-average power ratio (PAP) of an orthogonal frequency division multiplexing (OFDM) signal. The main problem for PTS is how to minimise the number of iterations necessary for locating the optimal weighting factors (which increases exponentially with the number of sub-blocks). In the proposed adaptive PTS approach, the iterations are stopped once the PAP drops below a preset threshold. For an OFDM system with 256 subcarriers and QPSK data symbols, adaptive PTS reduces the 0.1% PAP by 4dB, while PTS (non-adaptive) reduces it by 4.1dB. The complexity of adaptive PTS is just 2% of that of PTS.

Introduction: Orthogonal frequency division multiplexing (OFDM) is a promising solution for high data rate transmission in frequency-selective fading radio channels [1]. Recent advances in VLSI technologies have regenerated interest in this technique for transmitting information through overlapping carriers. Current areas of applications for OFDM include digital audio broadcasting, asynchronous digital subscriber lines, digital video broadcasting and wireless local area networks (LAN). OFDM is commonly implemented using discrete Fourier transform (DFT) techniques. Unfortunately, a central disadvantage of OFDM is potentially high peak-to-average power ratio (PAP) values. In practice, peak signal levels are constrained by design factors such as battery power (in portable equipment) or regulatory limits that prevent adjacent channel interference. The use of nonlinear amplifiers and digital hard limiting causes inefficiency, interference and performance degradation.

These drawbacks have motivated the search for PAP reduction techniques and a large number of solutions have recently been proposed. In the partial transmit sequence technique (PTS), the input data frame of N symbols is partitioned into M sub-blocks. The N/M subcarriers in each sub-block (except the first sub-block) are weighted by a constant factor; $M - 1$ weighting factors are then selected such that the resultant PAP is minimised. Unfortunately, finding the best weighting factors is a highly complex and nonlinear optimisation problem. For this reason, some attempts have been made to reduce the complexity of the optimisation: the authors of [2] presented a suboptimal iterative flipping algorithm while those of [3] derived an alternative optimisation criterion. With full optimisation, the maximum 0.1% PAP reduction is ~4.2dB for a 256 QPSK-carrier system.

In this Letter, we propose an adaptive PTS technique for reducing the PAP. To explain the key idea behind this method, consider an OFDM system with, say, M sub-blocks. Assume that the weighting factors are binary. To obtain the optimal weighting factors for each input data frame, 2^{M-1} combinations should be checked in order to obtain the minimum PAP. Since many input data frames already have low PAP values, searching all these combinations is unnecessary in most cases. Consequently, the key idea in adaptive PTS is to establish an early terminating threshold. In other words, the search is terminated as soon as the PAP drops below the threshold, rather than after all the 2^{M-1} combinations have been searched. Of course, if the threshold is set to a small value, adaptive PTS will be forced to search all the combinations. Similarly, if the threshold is set to a large value, adaptive PTS will search only a fraction of the 2^{M-1} combinations. In this way the threshold effects a tradeoff between PAP reduction and complexity.

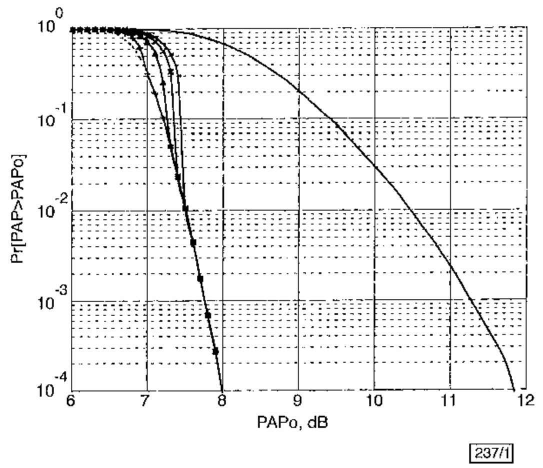

Fig. 1 *CCDF of OFDM signal with PTS*

- · uncoded
—■— L = 7.5 (AIT = 16)
—△— L = 7.25 (AIT = 36)
– – – – non-adaptive (AIT = 128)
-×- L = 7.4 (AIT = 22)
—+— L = 7 (AIT = 72)
AIT: average number of iterations; L: threshold peak factor

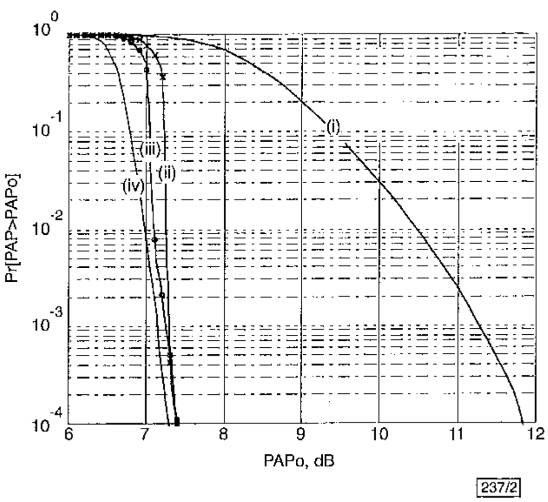

Fig. 2 *CCDF of OFDM signal with ordinary PTS and APTS*

M = 16 and N = 256
(i) uncoded
(ii) L = 7.2 (AIT = 38)
(iii) L = 7.0 (AIT = 104)
(iv) *PTS* optimum for 16 sub-blocks

It should be noted that the PAP of a continuous-time OFDM signal cannot be computed precisely by the use of the Nyquist sampling rate, which amounts to N samples per symbol. In this case, signal peaks are missed and PAP reduction estimates are unduly optimistic. Oversampling by a factor of 4 is sufficiently accurate and is achieved by simply computing the $4N$-point zero-padded IDFT of the data frame. This is carried out by taking a $4N$ length fast Fourier transform (FFT) of N data symbols and $3N$ zeros. We assume oversampling by a factor of 4 throughout this Letter.

Adaptive PTS technique:

(i) *Ordinary PTS:* For PTS, the input data block is partitioned into disjoint sub-blocks or clusters which are combined to minimise the PAP. We define the data block $\{X_n, n = 0, 1, ..., N-1\}$ as a vector $\mathbf{X} = [X_0 X_1 \ldots X_{N-1}]^T$ and turn the input data frame $\mathbf{X}$ into M disjoint sub-blocks, represented by the vectors $\{\mathbf{X}_m, m = 1, 2, ..., M\}$, such that

$$\mathbf{X} = \sum_{m=1}^{M} \mathbf{X}_m \qquad (1)$$

Here, it is assumed that the sub-blocks consist of a contiguous set of subcarriers and are of equal size. The objective of the PTS approach is to form a weighted combination of the M sub-blocks

$$\mathbf{X}' = \sum_{m=1}^{M} b_m \mathbf{X}_m \qquad (2)$$

where $\{b_m, m = 1, 2, ..., M\}$ are weighting factors. They are further assumed to be pure rotations (i.e., $b_m = e^{j\phi_m}$). The weighting factors are chosen to minimise the PAP of $\mathbf{X}'$. To reduce the complexity of this minimisation, we use a suboptimal choice by limiting all b_m to +1 or –1. Without any loss of performance we can set $b_1 = 1$ and observe that there are $(M-1)$ binary variables to be optimised. Let $Y_{n,m}$ for $n = 0, 1, 2, ..., 4N-1$, $m = 1, 2, ..., M$, be the $4N$ point IDFT of $\mathbf{X}_m$, appropriately zero-padded. Using the linearity property of the IDFT, we obtain the optimal PAP as [4]

$$PAP = \min_{b_1,\ldots,b_M} \left(\max_{0 \le n \le 4N} \left| \sum_{m=1}^{M} b_m y_{n,m} \right|^2 \right) \qquad (3)$$

In ordinary PTS, the PAP in eqn. 3 is computed for all the binary combinations and hence requires 2^{M-1} iterations.

(ii) *Adaptive PTS:* In the PTS approach described above, one main difficulty is the optimisation of the phase factors used for combining the sub-blocks. In this Section we describe an adaptive algorithm for combining the PTSs. As above, we only consider binary (i.e. 1 and –1) weighting factors and we divide the input data block into M sub-blocks. As a first step, assume that $b_m = 1$ for all m and compute the PAP of the combined signal (eqn. 2). If it is less than a set threshold L, then stop the optimisation immediately. If not, invert the first phase factor ($b_1 = -1$) and recompute the resulting PAP. If it is less than L, retain b_1 as part of the final phase sequence and stop the optimisation. The algorithm continues in this fashion until the PAP is less than L or all or part (K) of the 2^{M-1} combinations are searched.

Let $b = [b_1, b_2, ..., b_M]$. The adaptive algorithm can now be written as follows:

Set $b = [1, 1, ..., 1]$
Set IterCount = 1
while $PAP(\mathbf{X}') > L$ or IterCount < K
change b by one bit
Itercount ++

Here, K can be set to 2^{M-1} or a lesser value. The maximum number of iterations of this technique is K, and the minimum is 1. The actual number of iterations varies from one input frame to another. We characterise the complexity of this scheme by the average number of iterations per input frame.

Results: In the following results, 10^5 random OFDM symbols were generated to obtain CCDFs. We assumed 256 subcarriers throughout and used QPSK data symbols with the energy normalised to unity.

Fig. 1 shows the complementary cumulative distribution function (CCDF), $Pr(PAP > PAP_o)$ for $M = 8$. The 0.01% PAP of the original OFDM signal was ~11.8dB. Ordinary PTS improved it by 3.75dB. Curve (ii) shows results for APTS with a threshold value (L) of 7.5dB. In the region CCDF < 10^{-2}, both techniques provided identical performances. Ordinary PTS requires 128 iterations per OFDM symbol while APTS requires only 16 (on average) iterations per OFDM symbol. This amounts to an 87% reduction in complexity.

Results are also shown for APTS with L of 7.4, 7.25 and 7.0dB. These require 22, 36 and 71 iterations (on average) and reduce the complexity up to 83, 72 and 44%, respectively. Therefore, it is evident that the complexity of APTS can be greatly reduced by limiting the number of iterations by selecting a suitable threshold value. Lower threshold values yield better performance but result in higher complexity.

Fig. 2 shows results for 16 sub-blocks (M = 16). Strictly speaking, the optimal PTS curve requires 32768 iterations per OFDM symbol, which cannot be implemented at all. We therefore used 2000 randomly-generated binary weighting patterns, computed the PAP of each and subsequently took the minimum PAP as the optimal PAP [2]. Curves (ii) and (iii) show the performance of APTS with K = 1000 and threshold limits of 7.2 and 7.0dB, respectively. Curves (ii) and (iii) correspond to an average of 38 and 104 iterations, yielding complexity reductions of 98 and 94.8%, respectively, when compared to the optimum result. The performance loss is only ~0.1dB for CCDF = 10^{-3}. By contrast, the flipping algorithm [2] requires only 16 iterations in this case, but results in a performance loss of 1dB. It is evident that the adaptive approach is a promising solution for considerably reducing the complexity of PTS.

Conclusion: We have presented an adaptive PTS technique for reducing the PAP of an OFDM signal. By eliminating unnecessary iterations that do not contribute significantly to the reduction of the PAP, both the PAP and complexity can be reduced simultaneously. Complexity reduction of the order of 98% is achieved with little degradation in performance. This adaptive approach can also be used in conjunction with other PAP reduction schemes.

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Class of complex sequences with near optimal correlation properties

Yaming Zhang and Xuelong Zhu

A new family of complex valued pseudorandom sequences for CDMA systems is presented. The performance of this new sequence set is compared with well-known sequence sets, and it is shown that the new family of sequences exhibits better performance over both Rayleigh and Rician fading channels.

Introduction: An inherent problem in designing sequences for CDMA systems operating over multipath fading channels is the dual requirement of desirable auto-correlation (AC) characteristics and minimal cross-correlation (CC) values between sequences. It has been noted [1, 2] that the AC properties of a set of sequences come at the expense of CC properties and vice versa. Thus, these properties may well be viewed as mutually exclusive criteria, and at best, a compromise must be sought.

In some multipath environments, the maximum delay spread is less than the symbol interval. For such a situation, we propose a new family of sequences that enables a compromise between the AC and CC properties to be achieved.

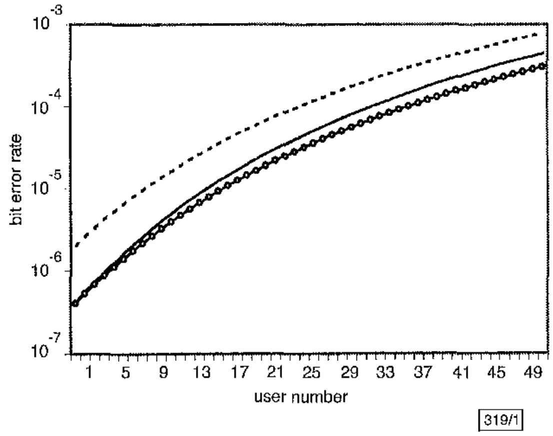

Fig. 1 *Simulation result over Rayleigh fading channels*

- - - - Gold-63
——— FZC-67
–O— C3-63
E_b/N_0 = 6dB, Rayleigh

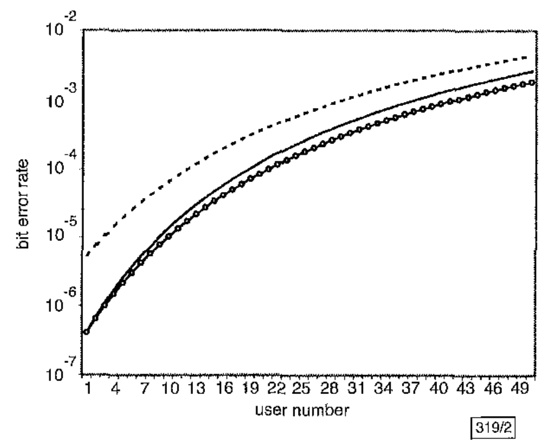

Fig. 2 *Simulation result over Rician fading channels*

- - - - Gold-63
——— FZC-67
–O— C3-63
E_b/N_0 = 6dB, Rician

New sequence family (C3): Let N be the sequence length, where $N = pq$, p is an odd prime number and q is an arbitrary positive integer number.

The set of sequences is defined by

$$U_{p,q} = \{a_{n,m}; 0 \leq n \leq q-1, 1 \leq m \leq p-1\}$$

while the kth element of a given sequence $a_{n,m}$ is defined by

$$a_{n,m}(k) = \exp\left\{ j\frac{\pi[mqk(k+1)+2nk]}{N} \right\} \quad 0 \leq k \leq N-1$$

Property (i): The new sequence family contains the FZC [3] sequence set the length of which is a prime number.

Consider the situation where $q = 1$: the new sequence family is then equal to the FZC sequence set with length p.

Property (ii): The auto-correlation magnitude of the new sequence family is given by

$$\left\{ N\underbrace{0\,0\,\Lambda\,0}_{p-1}\,N\underbrace{0\,0\,\Lambda\,0}_{p-1}\,\Lambda\Lambda\,N\underbrace{0\,0\,\Lambda\,0}_{p-1} \right\}$$