Optical OPPM-CDMA receivers with chip-level detectors

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Abstract: A chip-level detector for optical overlapping pulse-position modulation code-division multiple-access (OPPM-CDMA) communication systems is proposed. The bit error rate of the proposed system is derived and compared to some traditional receivers under the constraints of fixed data rate and laser pulsewidth. These traditional receivers include OOK-, PPM- and OPPM-CDMA correlators. The throughput limitations of all these receivers are also presented and compared. The results reveal that a significant improvement in the performance is gained when using the proposed scheme. The throughput limitation of the OPPM-CDMA chip-level detection scheme is greater than that of an on–off keying CDMA correlation detection scheme by 7.5 times on average, when the bit error rate does not exceed 10^{-9}.

1 Introduction

One of the most serious drawbacks in the area of direct detection optical CDMA systems [1–5] when compared to optical TDMA systems is the throughput limitation of the former. This restricts full utilisation of the vast bandwidth offered by the optical channel. To overcome this limitation, the author has proposed utilising an overlapping pulse-position modulation (OPPM) scheme rather than on–off keying (OOK) or pulse-position modulation (PPM) schemes at the transmitter of the optical CDMA system [8]. The OPPM technique was first proposed by Lee and Schroeder [9] and further explored by a few authors [10–13]. It was shown that the OPPM scheme offers a higher capacity, than the PPM scheme, without the need to reduce the laser pulse width. Moreover, it retains some of the advantages of PPM systems over OOK systems: namely, the OPPM transmitter utilises the optical energy more efficiently and its receiver does not require a knowledge of the signal or noise power. The author has been able to show in [8] that, when using OPPM as the modulation technique in an optical CDMA system whose receiver employs a correlation detector, the throughput can be increased by a factor of 5 (on average) above that when using an OOK-CDMA system with a correlation receiver.

In [7], the author suggested a new detector (called a chip-level detector) that can be used in place of the correlator at the receiver side. The basic idea of this detector depends on the refinement of the set of measurement outcomes, which, in turn, increases the information collected by the receiver. The performance of this detector has been studied for both OOK- and PPM-CDMA systems, and it has been shown that its performance (in terms of the bit error rate) is much better than that of the correlation receiver and approaches that of the optimum receiver, even with a very low optical power [7]. Moreover, the complexity of the chip-level receiver is independent of the number of users, and, therefore, the system is much more practical than the optimum receiver but more complex than the correlation receiver.

To improve the performance of the optical CDMA systems even further, the author proposes in this paper, applying both the aforementioned techniques in optical CDMA systems; i.e. at the transmitter side an OPPM-CDMA scheme is adopted, whereas at the receiver end chip-level detection is used.

In the analysis, optical orthogonal codes (OOCs) are employed as the signature code sequences [1], and, to ensure minimal interference among the users, OOCs with periodic cross-correlations and out-of-phase periodic autocorrelations that are bounded by one only have been chosen. Moreover, this paper focuses on direct-detection shot-noise-limited (Poisson statistics) optical channels. Although, with the advent of optical fibre amplifiers, it is hard to justify the Poisson statistics, the aim of this initial study is to characterise the system limitations and gain some insights on the problem under consideration. Further studies taking into account the effect of the optical amplifiers and/or the avalanche-photodiode (APD) noise can be pushed out once the fundamentals have been settled. The most important limitation in these types of systems, however, is the multiple-user interference. This interference cannot be neglected and is considered in the analysis in this paper.

2 Optical OPPM-CDMA system transmitter

In an OPPM-CDMA communication system the transmitter is composed of N simultaneous sources of information (users). Each user produces continuous data symbols. It is assumed that the symbols can take values in the finite set $\{0, 1, ..., M-1\}$. The data of each user modulates a laser source using the OPPM scheme. Each modulated signal is then permitted to be spread over a spreading interval of width τ (called a slot). An overlap with depth $(1 - 1/\gamma)\,\tau$, $\gamma \in \{1, 2 ..., M\}$, is allowed between any two adjacent spreading intervals. Here γ is called the index of overlap. The spreading signature code sequence is assumed to have a length L and a weight w. If wrapped signals are allowed, then the OPPM time frame T is given by

$$T = \frac{M}{\gamma}\tau = \frac{M}{\gamma}LT_c \qquad (1)$$

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where T_c is the pulse width (chip time.) For the spreading sequence to fit properly within the spreading interval L/γ must be an integer. An example of the transmitted signal formats of a single user is shown in Fig. 1

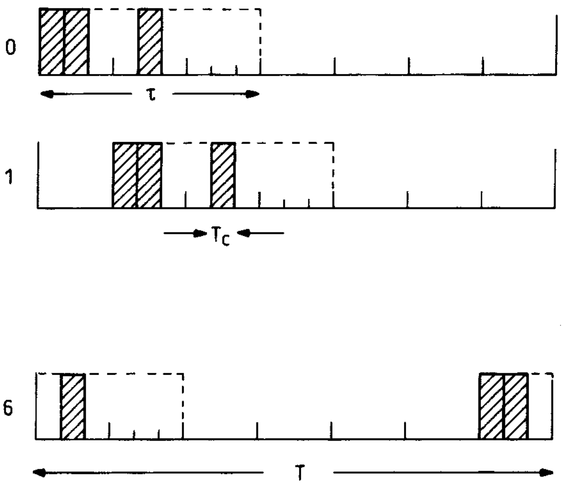

Fig. 1 *Example of transmitted signal formats of a single user in an OPPM-CDMA system*
With $M = 7$, $\gamma = 3$, $L = 9$ and $w = 3$. A signature code of 110010000 is assumed.

Kwon in [6] has introduced an optical CDMA system that can transmit multibits per sequence-period. In fact, multibits of the user's data have been mapped into shifted versions of the signature code allowing log L nats to be transmitted per sequence period. It should be emphasised that the multibits/sequence-period CDMA system can be considered as a special case of the optical OPPM-CDMA system. Indeed, if $M = \gamma = L$ is chosen, then the two systems become equivalent. It should be noted that, in his theoretical analysis [6], Kwon has considered only the correlation detection at the receiver side.

Optical PPM-CDMA systems [4, 5] can also be considered as special cases of optical OPPM-CDMA systems. Indeed, if $\gamma = 1$ is chosen, then the OPPM-CDMA system reduces to the PPM-CDMA system.

3 Optical OPPM-CDMA chip-level receiver

At the receiving end, the received waveform is composed of the sum of N delayed and attenuated signals from each user, in addition to the photodetector's dark current noise. The block diagram of the chip-level receiver is shown in Fig. 2. The photodetected received signal is integrated over each chip time, and then sampled at the end of each mark position of each slot, and passed to the decision subsystem to decide on the data. To describe the decision subsystem the photon count collected from chip number i, $i \in \mathcal{X} = \{1, 2, ..., w\}$, of the mark positions of slot number j, $j \in \mathcal{M} = \{0, 1, ..., M-1\}$, is denoted by Y_{ij}. As shown in Fig. 2, the sampled pulses will be passed to a bank of M pulse counters. Each counter $j \in \mathcal{M}$ counts the number of sampled pulses in slot j, for which photon count Y_{ij} exceeds a certain threshold θ. Of course this count should not exceed the code weight w and for the ideal case (with no interference) only one count will be equal to w and all the rest will be equal to zero. After collecting all the counts from all slots, the number of the slot, for which the count is equal to w and is greater than all the other counts, is declared to be equal to the transmitted symbol. It is obvious that the complexity of the OPPM-CDMA system implementation increases as M increases. Thus, for small values of M, the OPPM-CDMA system becomes much more simple than the multibits/sequence-period CDMA system. Indeed, for the latter M, the value should be chosen to be equal to L, which is very large in general. To make full use of the vast bandwidth available in optical networks, an equivalent all-optical receiver is shown in Fig. 3, where the received optical signal is optically sampled at the mark positions of each slot. The optical sampling (switching) can be realised in a similar way to that described in the active receiver of the multibits/sequence-period CDMA system in Fig. 1(b) of [6], or to that described in Fig. 3 of [7], namely an optical pulse from a receiver clock is aligned with the mark chip to be sampled out of the received CDMA chip stream. Both the optical clock and the CDMA signal are combined (resulting in the correct chip riding atop the clock waveform) and then the threshold is detected. Each detected sampled signal is then integrated over the entire time frame T and is further electronically sampled by the end of the time frame. Finally it is passed to the decision subsystem as described in Fig. 2 of this paper. In this system the optical sampling occurs at a rate of $1/T_c$, whereas the electronic sampling occurs at a rate of $1/T$.

4 Theoretical analysis

4.1 Decision rule

As mentioned in the preceding text, Y_{ij}, $i \in \mathcal{X} = \{1, 2, ..., w\}$, $j \in \mathcal{M} = \{0, 1, ..., M-1\}$, denotes the photon count

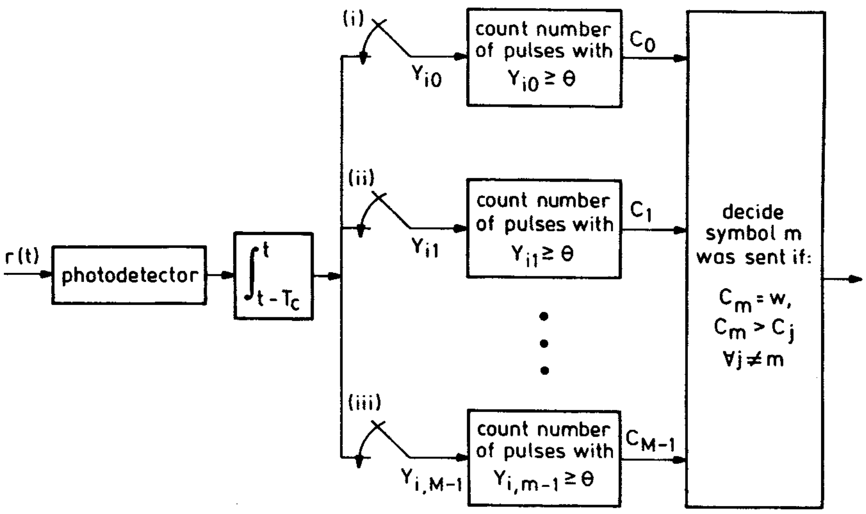

Fig. 2 *Optical direct-detection OPPM-CDMA chip-level receiver*
A signature code of 110010000 is assumed with $M = 7$ and $\gamma = 3$.
(i) Sample at end instants of chips 1, 2, 5; (ii) Sample at end instants of chips 4, 5, 8; (iii) Sample at end instants of chips 2, 19, 20

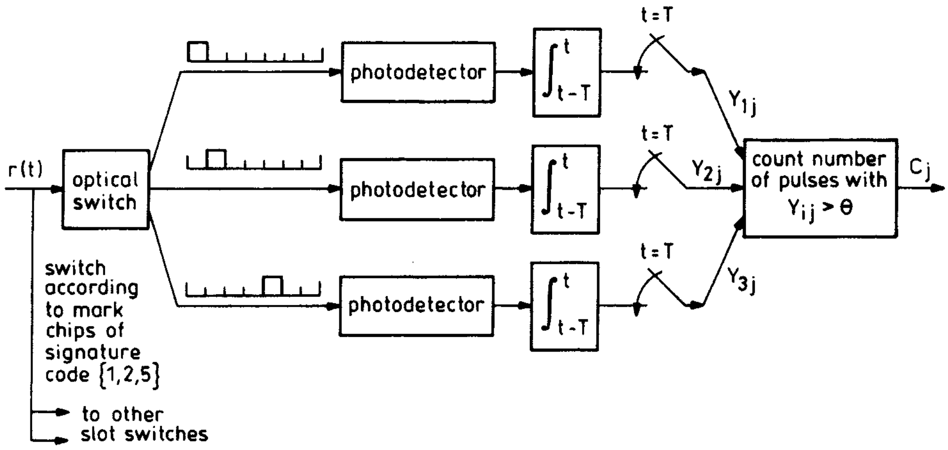

Fig.3 *All-optical version of the OPPM-CDMA chip-level receiver*

collected from chip number i of the mark positions of slot number j. As direct-detection shot-noise-limited optical channels have been considered, Y_{ij} is in fact a compound Poisson random variable. In view of the discussion given by the author in the preceeding section, the mathematical expression for the decision rule is as follows:

Symbol m is declared to be transmitted, if there exists $m \in \mathcal{M}$, such that

$$\begin{aligned} &(\forall i \in \mathcal{X}) \qquad Y_{im} \geq \theta \\ \text{and} \quad &(\forall j \in \mathcal{M}, j \neq m) \qquad Y_{ij} < \theta, \ \text{some } i \in \mathcal{X} \end{aligned} \tag{2}$$

Otherwise an incorrect decision is declared. Of course, the threshold θ should be optimised so as to achieve minimum bit error probability. Owing to the complexity of the expression for the error probability, numerical optimisation should be used when evaluating this optimum threshold. In order to simplify the analysis, $\theta = 1$ is chosen in this calculation of the error probabilities. Of course, the resulting error probability provides an upper bound to that of the optimal value of θ. Consequently, the decision rule when $\theta = 1$ reduces to:

Symbol m is declared to be transmitted if there exists $m \in \mathcal{M}$ such that

$$\begin{aligned} &(\forall i \in \mathcal{X}) \qquad Y_{im} \geq 1 \\ \text{and} \quad &(\forall j \in \mathcal{M}, j \neq m) \qquad Y_{ij} = 0, \ \text{some } i \in \mathcal{X} \end{aligned} \tag{3}$$

Otherwise an incorrect decision is declared.

Now, an upper bound on the probability of word error P_E will be developed, which can be written as follows:

$$P_E = \sum_{j=0}^{M-1} P[E|j] \Pr\{D = j\} \tag{4}$$

where $P[E|j]$ is the probability of error given that symbol j was transmitted and $\Pr\{D = j\}$ is the probability of transmitting data symbol j. In the case of equally likely data symbols, $\Pr\{D = j\} = 1/M$. It is easy to check that $P[E|j]$ is independent of j, and, consequently, $P[E|j] = P[E|0]$ for every j. Thus the word error probability reduces to

$$\begin{aligned} P_E &= P[E|0] \\ &= \Pr\{Y_{i0} = 0, \ \text{some } i \in \mathcal{X} \\ &\quad \text{or } Y_{ij} \geq 1 \quad \forall i \in \mathcal{X}, \ \text{some } j \neq 0 | D = 0\} \\ &\leq \Pr\{Y_{i0} = 0, \ \text{some } i \in \mathcal{X} | D = 0\} \\ &\quad + \Pr\{Y_{ij} \geq 1 \quad \forall i \in \mathcal{X}, \ \text{some } j \neq 0 | D = 0\} \end{aligned} \tag{5}$$

The last inequality is justified by using a simple probability axiom. The bit error rate P_b can then be deduced from the word error probability P_E using the formula $P_b = [M/2(M - 1)]P_E$. Further analysis on P_E requires the introduction of the interference random variables as presented in the following subsection.

4.2 Interference probability

Let κ_{ij}, $i \in \mathcal{X}$, $j \in \mathcal{M}$ be the number of pulses that cause interference to chip i of slot j. Further, let the vector $(\kappa_{1j}, \kappa_{2j}, \ldots, \kappa_{ij})^T$ be denoted by $\boldsymbol{K}_j^i$. Denote by p_1 the average probability that a single user interferes with the desired user at one particular mark position of its signature code. Assuming frame-level synchronisation among the transmitters, p_1 can be evaluated as follows. If the symbols transmitted by both the interfering and the desired users are within similar slots, a mark interference with probability w/ML occurs on average. On the other hand, if the active slot of the interfering user overlaps by $(1 - |j|/\gamma)\tau$, $|j| \in \{1, 2, \ldots, \gamma\}$, with that of the desired user, an interference with probability $(w/ML)(1 - |j|/\gamma)$ occurs on the average. Thus,

$$p_1 = \sum_{j=-\gamma}^{\gamma} \frac{w}{ML}\left(1 - \frac{|j|}{\gamma}\right) = \gamma \frac{w}{ML} \tag{6}$$

Consequently, the random vector $\boldsymbol{K}_j^i$ admits a multinomial distribution with parameters $\gamma w/ML$ and $N - 1$:

$$\Pr\{\boldsymbol{K}_j^i = \boldsymbol{L}_j^i\} = \frac{(N-1)!}{l_{1j}! l_{2j}! \cdots l_{ij}! s_{ij}!} \times \left(\frac{\gamma w}{ML}\right)^{N-1-s_{ij}} \left(1 - i\frac{\gamma w}{ML}\right)^{s_{ij}} \tag{7}$$

where

$$\boldsymbol{L}_j^i = (l_{1j}, l_{2j}, \ldots, l_{ij})^T \tag{8}$$

and

$$s_{ij} = N - 1 - \sum_{n=1}^{i} l_{nj} \qquad i \in \mathcal{X}, j \in \mathcal{M} \tag{9}$$

4.3 Upper bound on the word error probability

Consider the upper bound on PE from eqn. 5,

$$\begin{aligned} P_E &\leq \Pr\{Y_{i0} = 0, \ \text{some } i \in \mathcal{X} | D = 0\} \\ &\quad + \Pr\{Y_{ij} \geq 1 \quad \forall i \in \mathcal{X}, \ \text{some } j \neq 0 | D = 0\} \end{aligned} \tag{10}$$

The first term in the right-hand side of eqn. 10 is a probability of union events and can be expanded as follows:

$$\Pr\{Y_{i0} = 0,\ \text{some } i \in \mathcal{X} | D = 0\}$$
$$= -\sum_{i=1}^{w} (-1)^i \binom{w}{i} \Pr\{Y_{1,0} = Y_{2,0} = \cdots = Y_{i0} = 0 | D = 0\} \tag{11}$$

Each probability under the summation can be evaluated further as follows:

$$\Pr\{Y_{1,0} = Y_{2,0} = \cdots = Y_{i0} = 0 | D = 0\}$$
$$= \sum_{\boldsymbol{L}_0^i} \Pr\{Y_{1,0} = Y_{2,0} = \cdots = Y_{i0} = 0 | D = 0, \boldsymbol{K}_0^i = \boldsymbol{L}_0^i\}$$
$$\times \Pr\{\boldsymbol{K}_0^i = \boldsymbol{L}_0^i\}$$
$$= \sum_{\boldsymbol{L}_0^i} \Pr\{\boldsymbol{K}_0^i = \boldsymbol{L}_0^i\} \prod_{n=1}^{i} \Pr\{Y_{n0} = 0 | D = 0, \kappa_{n0} = l_{n0}\}$$
$$= \sum_{\boldsymbol{L}_0^i} \Pr\{\boldsymbol{K}_0^i = \boldsymbol{L}_0^i\} \prod_{n=1}^{i} \exp[-Q(1 + l_{n0})] \tag{12}$$

where Q denotes the average photons per chip pulse and Y_{n0} is a Poisson random variable with mean $Q(1 + l_{n0})$. Here, $Q \cdot l_{n0}$ is due to the interference and $Q \cdot 1$ is due to the desired user. Consequently,

$$\Pr\{Y_{1,0} = Y_{2,0} = \cdots = Y_{i0} = 0 | D = 0\}$$
$$= \exp[-Qi] \cdot \sum_{\boldsymbol{L}_0^i} \Pr\{\boldsymbol{K}_0^i = \boldsymbol{L}_0^i\} \exp\left[-Q \sum_{n=1}^{i} l_{n0}\right]$$
$$= \exp[-Qi] \cdot E\left\{\exp\left[-Q \sum_{n=1}^{i} \kappa_{n0}\right]\right\} \tag{13}$$

where $E\{\cdot\}$ denotes the expected value, but $(\kappa_{1j}, \kappa_{2j}, \ldots, \kappa_{ij})^T$ is a multinomial random vector with parameters $(\gamma w/M\ L)$ and $(N-1)$, c.f. Eqn. 7. Thus the summation $\Sigma_{n=1}^{i} \kappa_{n0}$ is a binomial random variable with parameters $(i\gamma w/ML)$ and $(N-1)$ and the last expected value is now immediate:

$$\Pr\{Y_{1,0} = Y_{2,0} = \cdots = Y_{i0} = 0 | D = 0\}$$
$$= \left[1 - i\frac{\gamma w}{ML} + i\frac{\gamma w}{ML} e^{-Q}\right]^{N-1} \cdot e^{-Qi} \tag{14}$$

By substitution in eqn. 11 the following is obtained:

$$\Pr\{Y_{i0} = 0,\ \text{some } i \in \mathcal{X} | D = 0\}$$
$$= -\sum_{i=1}^{w} (-1)^i \binom{w}{i} \left[1 - i\frac{\gamma w}{ML} + i\frac{\gamma w}{ML} e^{-Q}\right]^{N-1} \cdot e^{-Qi} \tag{15}$$

Now proceed to find an upper bound on the second term in the right-hand side of eqn. 10:

$$\Pr\{Y_{ij} \geq 1 \quad \forall i \in \mathcal{X},\ \text{some } j \neq 0 | D = 0\}$$
$$\leq \sum_{j=1}^{M-1} \Pr\{Y_{ij} \geq 1 \quad \forall i \in \mathcal{X} | D = 0\}$$
$$= (M - \gamma) \Pr\{Y_{i1} \geq 1 \quad \forall i \in \mathcal{X} | D = 0, \nu_1 = 0\}$$
$$+ \sum_{j=1}^{\gamma-1} \Pr\{Y_{ij} \geq 1 \quad \forall i \in \mathcal{X} | D = 0\} \tag{16}$$

where, for any $j \in \{1, 2, \ldots, M-1\}$, $\nu_j \in \{0, 1\}$ denotes the number of pulses that cause a hit (self-interference) in slot j due to the signature code pulses sent in slot 0 by the desired user. The first term in the right-hand side of the last inequality is due to the $M - 1 - (\gamma - 1)$ slots that do not have self-interference with slot 0, i.e. $\nu_j = 0$ with probability 1 for these slots. The second term, however, is due to the remaining $\gamma - 1$ slots. These slots interfere with slot 0 at a positive probability, i.e. $\Pr\{\nu_j = 1\} > 0$. Assuming uniformly distributed marks in the code sequences it is easy to see that $\Pr\{\nu_1 = 1\} = w(w-1)/(L-1)$. Denote $\Pr\{\nu_1 = 1\}$ by q. Hence,

$$\Pr\{Y_{ij} \geq 1 \quad \forall i \in \mathcal{X},\ \text{some } j \neq 0 | D = 0\}$$
$$\leq (M - \gamma) \Pr\{Y_{i1} \geq 1 \quad \forall i \in \mathcal{X} | D = 0, \nu_1 = 0\}$$
$$+ (1-q)(\gamma-1) \Pr\{Y_{i1} \geq 1\ \forall i \in \mathcal{X} | D = 0, \nu_1 = 0\}$$
$$+ q(\gamma - 1) \Pr\{Y_{i1} \geq 1 \quad \forall i \in \mathcal{X} | D = 0, \nu_1 = 0\}$$
$$\leq (M - \gamma) \Pr\{\kappa_{i1} \geq 1 \quad \forall i \in \mathcal{X}\}$$
$$+ (1 - q)(\gamma - 1) \Pr\{\kappa_{i1} \geq 1 \quad \forall i \in \mathcal{X}\}$$
$$+ q(\gamma - 1) \Pr\{\kappa_{i1} \geq 1 \quad \forall i \in \mathcal{X}^-\} \tag{17}$$

where the last inequality is justified due to the fact that given a '0' was sent, if $\kappa_{i1} = 0$ and $\nu_1 = 0$, then Y_{i1} should be zero as well. Moreover, if $\nu_1 = 1$ then $\kappa_{i_0 1} \geq 1$ with probability one for some $i_0 \in \mathcal{X}$. Here, $\mathcal{X}^- = \mathcal{X} - \{i_0\}$. By estimating the last probabilities:

$$\Pr\{\kappa_{i1} \geq 1 \quad \forall i \in \mathcal{X}\}$$
$$= 1 - \Pr\{\kappa_{i1} = 0,\ \text{some } i \in \mathcal{X}\}$$
$$= 1 + \sum_{i=1}^{w} (-1)^i \binom{w}{i} \Pr\{\kappa_{1,1} = \kappa_{2,1} = \cdots = \kappa_{i1} = 0\}$$
$$= 1 + \sum_{i=1}^{w} (-1)^i \binom{w}{i} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1} \tag{18}$$

$$\Pr\{\kappa_{i1} \geq 1 \quad \forall i \in \mathcal{X}^-\} - \Pr\{\kappa_{i1} \geq 1 \quad \forall i \in \mathcal{X}\}$$
$$= \sum_{i=1}^{w-1} (-1)^i \binom{w-1}{i} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1}$$
$$- \sum_{i=1}^{w} (-1)^i \binom{w}{i} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1}$$
$$= -(-1)^w \left(1 - \frac{\gamma w^2}{ML}\right)^{N-1}$$
$$+ \sum_{i=1}^{w-1} (-1)^i \left[\binom{w-1}{i} - \binom{w}{i}\right] \left(1 - i\frac{\gamma w}{ML}\right)^{N-1}$$
$$= -(-1)^w \left(1 - \frac{\gamma w^2}{ML}\right)^{N-1}$$
$$- \sum_{i=1}^{w-1} (-1)^i \binom{w-1}{i-1} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1}$$
$$= \sum_{i=1}^{w} (-1)^{i-1} \binom{w-1}{i-1} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1} \tag{19}$$

The required upper bound on P_E can now be written as

$$P_E \leq M - 1 + \sum_{i=1}^{w} (-1)^i \binom{w}{i} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1}$$
$$\times \left[M - 1 - (\gamma - 1)\frac{i(w-1)}{L-1}\right]$$
$$- \sum_{i=1}^{w} (-1)^i \binom{w}{i} \left(1 - i\frac{\gamma w}{ML} + i\frac{\gamma w}{ML} e^{-Q}\right)^{N-1} e^{-Qi} \tag{20}$$

4.4 Users–throughput product

One important parameter of performance evaluation in practice is the channel throughput. In the OPPM-CDMA system, the throughput (in nats/s) for each user can be obtained by

$$R_T \stackrel{\text{def}}{=} \frac{\log M}{T} = \frac{\gamma \log M}{M\tau} = \frac{\gamma \log M}{MLT_c} \quad \text{nats/s} \quad (21)$$

The throughput (in nats/chip) is, thus,

$$R_0 \stackrel{\text{def}}{=} T_T T_c = \frac{\gamma \log M}{ML} \quad \text{nats/chip} \quad (22)$$

In Fig. 8, the author has defined the users–throughput product (denoted by NR) as the product of the number of users times R_0:

$$NR \stackrel{\text{def}}{=} N \cdot R_0 = N \cdot \frac{\gamma \log M}{ML} \quad \text{nats/chip} \quad (23)$$

It has been shown that $NR_{\max}$ (defined as follows) is almost a constant quantity for optical CDMA channels and can be used as a figure of merit. Define $R_{0,\max}$ and $NR_{\max}$ as follows:

$$R_{0,max} \stackrel{\text{def}}{=} \max_{\substack{\gamma, M, L: \\ P_b^* \leq \epsilon}} R_0 \qquad NR_{max} \stackrel{\text{def}}{=} \max_{\substack{\gamma, M, L: \\ P_b^* \leq \epsilon}} NR \quad (24)$$

where

$$P_b^* = \frac{M/2}{M-1} P_E^* \quad \text{and} \quad P_E^* = \lim_{Q \to \infty} P_E :$$

$$P_E^* \leq M - 1 + \sum_{i=1}^{w} (-1)^i \binom{w}{i} \left(1 - i\frac{\gamma w}{ML}\right)^{N-1} \times \left[M - 1 - (\gamma - 1)\frac{i(w-1)}{L-1}\right] \quad (25)$$

5 Numerical results

In these numerical calculations the author has held both the rate of data transmission R_T and pulsewidth T_c as being fixed. The code length L was chosen so as to satisfy the constraint on throughput (in nats/chip): $R_0 = R_T \cdot T_c$. Given a number of users N, the code weight w is chosen to be the maximum weight that satisfies the code constraint [1]: $N \leq (L-1)/w(w-1)$. Fig. 4 shows the bit error rate for various modulation schemes against the average photons per nat for a fixed number of users ($N = 100$) and a constraint on the throughput ($R_0 = 10^{-4}$). The performance analysis and bit error rates for both OOK- and PPM-CDMA correlation and chip-level receivers can be found in [7], whereas the performance and bit error rate for OPPM-CDMA correlation receiver appear in [8]. The relation between the average transmitted photons per chip pulse Q and the average transmitted photons per nat μ is given by

$$Q = \begin{cases} \frac{\mu \log 2}{w} & \text{for OOK} \\ \frac{\mu \log M}{w} & \text{for OPPM} \end{cases} \quad (26)$$

From this Figure, notice that, if the average photons per nat exceeds 51, then OPPM-CDMA chip-level receiver gives the lowest error rate among all compared receivers. Furthermore, the error floor of OPPM-CDMA chip-level receiver is reached at a very small value of μ, which indicates that this kind of receiver is very efficient. A comparison between chip-level receivers with different values of γ is shown in Fig. 5 with $R_0 = 2 \times 10^{-4}$. For low values of μ the performance of OPPM-CDMA improves as γ decreases, but the error rate soon saturates and the performance improves as γ increases. This shows that the larger the value of γ, the smaller the error floor. The error floor of OOK-CDMA is not seen in Fig. 5 because it saturates at a slower rate. It is obvious that OOK-CDMA floor is smaller than that of PPM-CDMA. However, it is not better than OPPM-CDMA as can be see from Fig. 6, where the limits of the error probabilities against the number of users has been plotted as the average energy increases to infinity with R_0 still constrained as above. This Figure demonstrates that, even if there is no constraint on the average energy, OPPM-CDMA is still better than OOK-CDMA. Moreover, as shown in [7], that OOK-CDMA chip-level receiver is asymptotically ($\mu \to \infty$) optimal, thus, the OPPM-CDMA chip-level receiver performs better than the OOK-

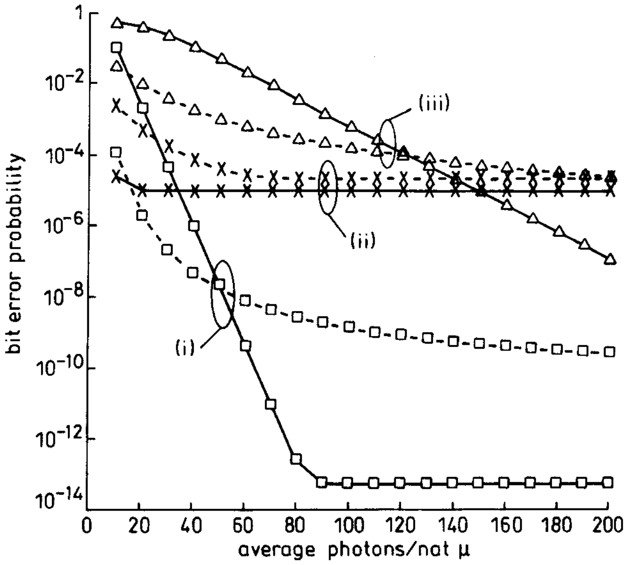

Fig. 4 *Comparison between the bit error rates of both correlation and chip-level receivers for OOK-, PPM- and OPPM-CDMA systems*
$R_0 = 10^{-4}$
$N = 100$, $M = 32$
- △ - OOK, correlator —△— OOK, chip
- × - PPM, correlator —×— PPM, chip
- □ - OPPM, correlator —□— OPPM, chip
(i) OPPM, $\gamma = 8$, $L = 8664$, $w = 9$; (ii) PPM, $L = 1083$, $w = 3$; (ii) OOK, $L = 6931$, $w = 8$

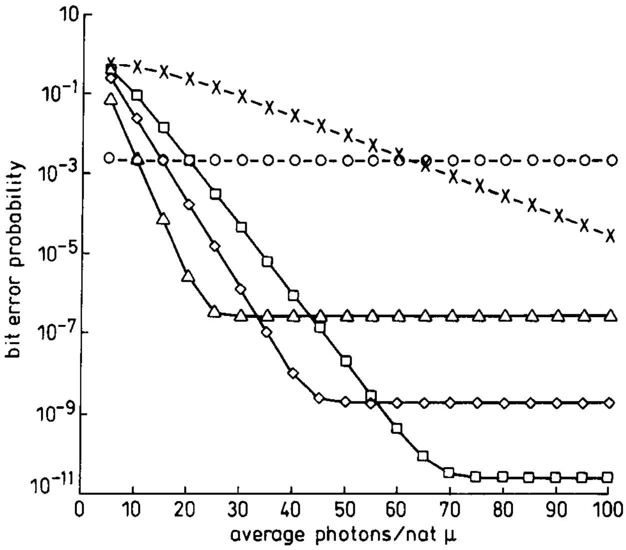

Fig. 5 *Comparison between the bit error rates of chip-level receivers for OOK-, PPM- and OPPM-CDMA systems with different values of* γ
$R_0 = 2 \times 10^{-4}$
$N = 100$, $M = 32$
- × - OOK, chip —◇— OPPM, chip, $\gamma = 8$
- ○ - PPM, chip —□— OPPM, chip, $\gamma = 16$
—△— OPPM, chip, $\gamma = 4$

CDMA optimum receiver. It should be emphasised that the bit error rate approaches its limit very quickly (very low optical power), as can be seen from Figs. 4 and 5. So unlimited energy is guaranteed to be achieved for $\mu \leq 500$, for example.

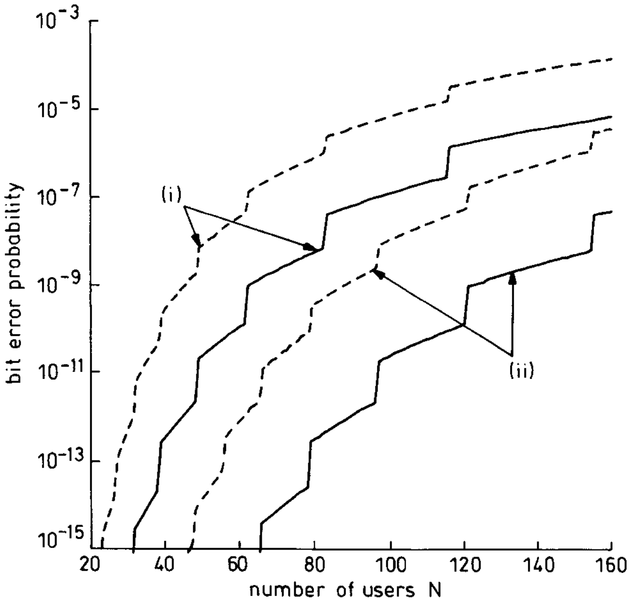

Fig. 6 *Comparison between the bit error rates of both correlation and chip-level receivers for OOK- and OPPM-CDMA systems with unlimited energy*
$R_0 = 2 \times 10^{-4}$
$N = 100$, $M = 32$
·········· correlator
——— chip-level
(i) OOK; (ii) OPPM, $\gamma = 16$

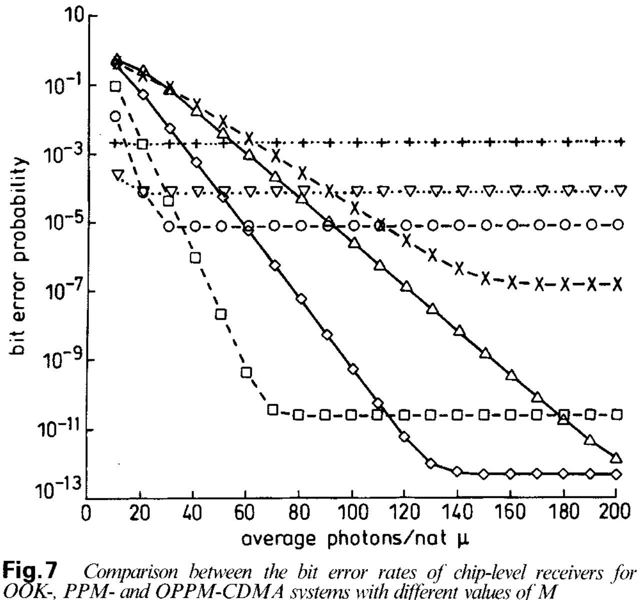

Fig. 7 *Comparison between the bit error rates of chip-level receivers for OOK-, PPM- and OPPM-CDMA systems with different values of M*
$R_0 = 2 \times 10^{-4}$
$N = 100$, $M = 16$
--×-- OOK, chip
····○···· PPM, chip, $M = 8$
····▽···· PPM, chip, $M = 16$
····+···· PPM, chip, $M = 32$
—△— OPPM, chip, $M = 8$
—◇— OPPM, chip, $M = 16$
—□— OPPM, chip, $M = 32$

The variation of the bit error rate of OPPM-CDMA system with different values of M is shown in Fig. 7, for fixed values of $\gamma = 16$ and $R_0 = 2 \times 10^{-4}$. It is obvious that, with low optical energies, the error probability improves as M increases, whereas it becomes worse with the increase of M for sufficiently large optical energies. The corresponding error probabilities for both OOK- and PPM-CDMA are depicted in the same Figure for convenience (PPM is equivalent to OPPM with $\gamma = 1$). From Figs. 5 and 7, it becomes evident that the best choice of the two parameters γ and M depends on the available laser power and the requirement on the quality of detection (bit error probability).

Maximum achievable throughput (in nats/chip) and users–throughput product are plotted in Figs. 8 and 9, respectively, against the number of users. Both correlation and chip-level receivers for both OOK- and OPPM-CDMA systems are considered. It is obvious, from the Figures, that OPPM-CDMA always gives a better throughput than OOK-CDMA and the best throughput is achieved when using OPPM-CDMA chip-level receivers. For a small number of users, the throughput limitations of both the correlation and chip-level receivers coincide with each other. This is because, for a small number of users, the main degradation is due to the shot-noise process of the photodetector rather than the multiple-user interference.

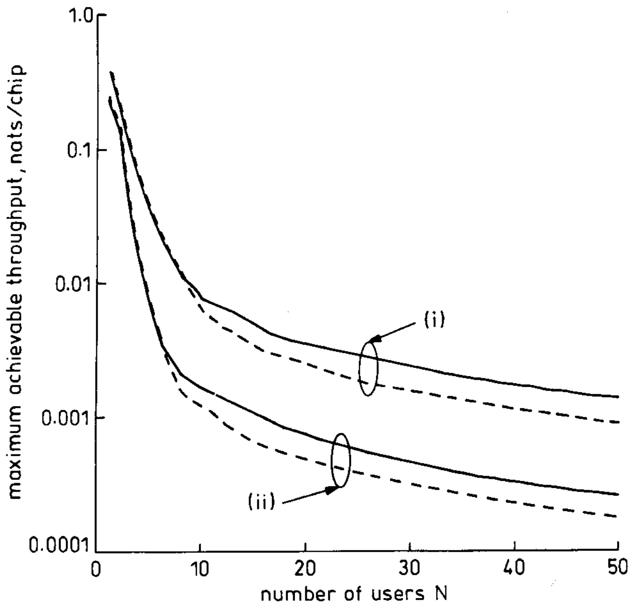

Fig. 8 *Comparison between the maximum achievable throughputs (in nats/chip) of correlation and chip-level receivers for both OOK- and OPPM-CDMA systems against the number of users when there is no limit on the average transmitted energy and bit error rate* $\leq 10^{-9}$
– – – – correlator
——— chip level
$\mu = \infty$
(i) OPPM; (ii) OOK

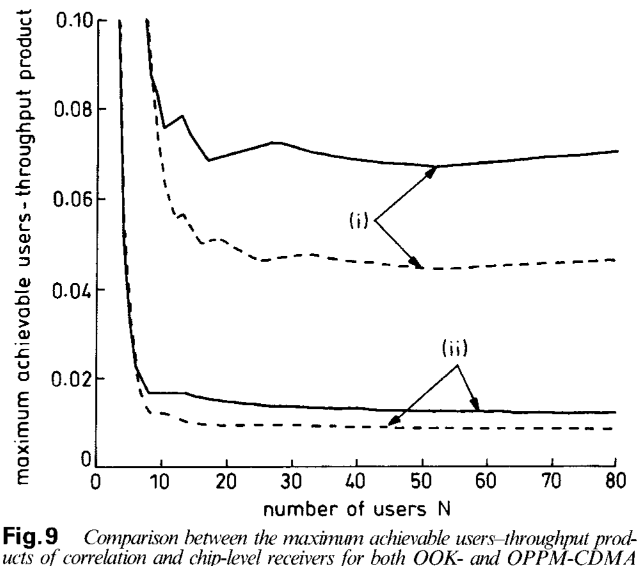

Fig. 9 *Comparison between the maximum achievable users–throughput products of correlation and chip-level receivers for both OOK- and OPPM-CDMA systems against the number of users when there is no limit on the average transmitted energy and bit error rate* $\leq 10^{-9}$
– – – – correlator
——— chip level
$\mu = \infty$
(i) OPPM; (ii) OOK

The users–throughput products for all receivers are almost constant for most of the time and can still be considered as a figure of merit. This indicates that, for a large enough value of N, the error probability is almost a function of the product $N \cdot R_0$ as one unit. This is not surprising, as this product is a measure to the total system capacity. The users–throughput products for the OOK-CDMA chip-level receiver, OPPM-CDMA correlation receiver and OPPM-CDMA chip-level receiver are 1.4, 5 and 7.5 times greater than that of the OOK-CDMA correlation receiver, respectively.

6 Concluding remarks

An OPPM-CDMA chip-level detector has been proposed for direct-detection optical CDMA communication systems. The performance in terms of the bit error rate and the throughput limitation has been compared to traditional correlation detectors and previously developed chip-level detectors. In the derivation of the bit error rate, a Poisson shot-noise limited model for the receiver photodetectors has been assumed. The author concludes that for almost any given average energy per bit, the OPPM-CDMA chip-level receiver performs much better than both the OOK- and the PPM-CDMA correlation and chip-level receivers, and better than the OPPM-CDMA correlation receiver. OPPM-CDMA chip-level receivers are very efficient and their error floors can be reached easily at very low average energies. The OPPM-CDMA chip-level receiver has a throughput limitation that is 7.5 times greater than that of the OOK-CDMA correlation receiver when $P_b \leq 10^{-9}$ and the transmitted optical energy is large enough. (This improvement factor depends on the value of the error constraint.)

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