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Multiple access interference cancellation in Manchester-coded synchronous optical PPM-CDMA network

H. Ghafouri-Shiraz · M. M. Karbassian · F. Liu

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Abstract A new interference cancellation technique for direct-detection optical code-division multiple-access (OCDMA) network employing pulse-position modulation (PPM) is proposed in this paper. The multiple access interference (MAI) estimation is achieved by pre-reserving one of optical spreading code sequences at the receiver based on the correlation property of padded modified prime codes (PMPC). The estimated interference is then cancelled out after photo-detection process. Additionally, the transmitted signal is Manchester-coded to further improve the system performance. Based on this proposed interference canceller in a shot-noise limited regime, we have obtained an expression for the upper bound of the bit-error probability (BEP) taking into account effects of both MAI and shot-noise. This BEP is compared with that of a PPM-OCDMA without cancellation. Finally, the receiver structure of the proposed optical network unit (ONU) is fairly simple to compare with the conventional cancellation schemes.

Keywords Multiple access interference · Prime code families · Synchronous optical CDMA

1 Introduction

The optical code-division multiple-access (OCDMA) technique, as a potential candidate for multiplexing in high-speed local area networks (LAN) have lately attracted considerable

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attentions (Kwong et al. 1991; Liu and Tsao 2000; Wakafuji and Ohtsuki 2003; Shalaby 1999; Lee et al. 2001; Liu et al. 2007; Wu et al. 2004; Shalaby 1998; Karbassian and Ghafouri-Shiraz 2007) due to appreciating the low propagation loss and the huge available bandwidth offered by specially single-mode optical fibers. Synchronous OCDMA (S-OCDMA) has some advantages over asynchronous OCDMA (A-OCDMA) ones (Kwong et al. (1991)). Namely, in S-OCDMA the number of available signature codes is larger than A-OCDMA, because the time-shifted version of codes can also be used in the former. Moreover, under bit-error rate (BER) constraint, S-OCDMA can accommodate greater number of simultaneous users than A-OCDMA; however, strict synchronization is required.

However, the most commonly used modulation format in OCDMA is on–off keying (OOK) (Liu and Tsao 2000; Wakafuji and Ohtsuki 2003; Shalaby 1999) with power detection. In a coherent OOK-OCDMA, the most severe issues are the coherent signal interference and incoherent multiple access interference (MAI). Moreover, by changing the number of active users, a dynamic threshold level setting is required to maintain a wider power margin in decoder/receiver setup. Also, the OOK-OCDMA is very vulnerable in terms of interception that could be easily broken by simple power detection even without any knowledge of the code.

Pulse-position modulation (PPM) (Lee et al. 2001; Liu et al. 2007; Wu et al. 2004; Shalaby 1998; Karbassian and Ghafouri-Shiraz 2007) as an energy efficient modulation excels OOK if the average power rather than chip-time is the limiting factor and also securer than OOK regarding detection. In practical OCDMA though the chip-time is important but power issues come to critical point in individual optical network units (ONU) as well.

In OCDMA, MAI degrades the general performance rapidly due to incomplete orthogonal signature codes. To minimize the interference error-floor, several MAI estimation and reduction techniques have been proposed. In Wakafuji and Ohtsuki (2003) the authors have proposed optical double hard-limiters for an OOK-OCDMA, while it brings more complexity and elements to the system implementation. By utilizing the modified prime codes (MPC) in Shalaby (1999) author has suggested an interference estimation technique for synchronous OOK-OCDMA. In their system, one code in each group (P groups in MPC, where P is a prime number) has been pre-reserved in order to estimate the interference to the desired user at the receiving end. The estimated interference is then used to adapt a threshold level that is placed after the optical correlator. Besides that, each individual receiver requires $P + 1$ correlators; one serves for signal detection and P are used for interference estimation to eliminate the effect of MAI. In Lee et al. (2001) authors also utilized the special property of MPC to propose an interference canceller for synchronous PPM-OCDMA system. Similarly, each receiver composes of P correlators, while $(P - 1)$ of them are served for MAI estimation caused by the sharing users in the same group and the desired user. The performance improvement of the PPM-OCDMA is at the cost of very complicated receiver structure in Shalaby (1999) and Lee et al. (2001). In our study, padded modified prime code (PMPC) introduced in Liu and Tsao (2000) is utilized and PPM as a modulation scheme has been grasped. The proposed cancellation method with PMPC provides more available spreading sequences and outperforms existing schemes, besides that it simplifies ONU architecture. Liu and Tsao (2000) have introduced PMPC and a cancellation scheme for S-OCDMA, although OOK has been used as a modulation scheme in their analysis.

In our analysis, Manchester codes are also systematically assigned to users as a source coding to further enhance the performance. The effect of optical Poisson shot-noise and MAI are taken into account, while photo diodes' dark-current and thermal-noise are neglected due to their minor effect as compared to MAI and shot-noise.

The rest of the paper is organized as follows. In Sect. 2, a PPM-OCDMA (without cancellation) is recalled but by using PMPC sequences and a bit-error probability (BEP) is mentioned as well. Section 3 is dedicated to the description of the proposed interference reduction in detail and Manchester-coded PPM-OCDMA is also investigated with an analysis of upper-bounded BEP. The scheme with only cancellation is explained in Sect. 4. The numerical results and evaluations of different schemes and data-rate are presented in Sect. 5. The study is concluded in final section.

2 PPM-OCDMA

The interesting property of PMPC is its unit cross-correlation within the entire code family. As compared to the other prime code family with same code-length (Liu et al. 2007) and others such as perfect difference codes (PDC) (Wu et al. 2004), it uses unipolar (i.e., power saving) and also it provides an almost orthogonal correlation property in an appropriate code-length. According to the PMPC sequences (Liu and Tsao 2000), for prime number P the number of sequences (users) in the entire code family is P^2 with code-length of $P^2 + P$. The correlation function (C_{mn}) between codes m and n, where $m, n \in \{1, 2, \ldots, P^2\}$, is given by:

$$C_{mn} = \begin{cases} P+1, & \text{if } m = n, \quad \text{auto-correlation} \\ 1, & \text{if } m \neq n, \quad \text{cross-correlation} \end{cases} \tag{1}$$

Correlation values of PMPC with data stream of "11010" as an example are illustrated in Fig. 1 for $P = 5$. By assuming N active users ($P^2 - N$ idle users) and each user transmits *M-ary* continuous data symbols, a column vector $\mathbf{S_n}$ of size M for user #n is defined. If user #n transmits symbol i, $S_{n,i} = 1$ while $S_{n,j} = 0$ for any $j \neq i$, where $i, j \in \{0, 1, \ldots, M-1\}$, i.e.,

$$\mathbf{S_n} = \left[S_{n,0}, S_{n,1}, \ldots, S_{n,i}, \ldots, S_{n,M-1}\right]^T = [0, 0, \ldots, 1, \ldots 0]^T \tag{2}$$

On the other hand, BEP based on the modulation scheme can be written as:

$$P_b = \frac{M}{2(M-1)} P_E \tag{3}$$

where P_E is probability of symbol-error rate. Let us define an interference random vector $\mathbf{k} = (k_0, k_1, \ldots, k_j, \ldots, k_{M-1})^T$ of size M, where the random variable k_j represents the number of interference pulses introduced to time slot j. Vector $\mathbf{u} = \left(u_0, u_1, \ldots, u_j, \ldots u_{M-1}\right)^T$ is the realization of $\mathbf{k}$, referring to Eq. 5 in Shalaby (1998), obviously P_E decreases when Q increases, where Q denotes the average received power per laser pulse ($Q = (\mu \cdot \ln M)/(P+1)$) and μ is a number of photons per laser pulse that is a parameter proportional to received power. Refereeing to Shalaby (1998), by taking the limit of $Q \to \infty$ the lower-bounded P_E can be derived and rewritten as below by employing PMPC in that all the sequence groups are now taking into consideration for interference.

$$P_E \geq \sum_{u_1=P+2}^{N-1} \binom{N-1}{u_1} \frac{1}{M^{u_1}} \left(1 - \frac{1}{M}\right)^{N-1-u_1} \sum_{u_0=0}^{\min\left\{\begin{array}{l} u_1 - P - 2, \\ N-1-u_1 \end{array}\right\}} \binom{N-1-u_1}{u_0} \frac{1}{(M-1)^{u_0}} \left(1 - \frac{1}{M-1}\right)^{N-1-u_1-u_0}$$

$$+ 0.5 \sum_{u_1=p+1}^{\frac{N+P}{2}} \binom{N-1}{u_1} \frac{1}{M^{u_1}} \left(1-\frac{1}{M}\right)^{N-1-u_1}$$
$$\binom{N-1-u_1}{u_1-P-1} \frac{1}{(M-1)^{u_1-P-1}} \left(1-\frac{1}{M-1}\right)^{N-2u_1+P} \tag{4}$$

3 Manchester-coded PPM-OCDMA with interference cancellation

Multiple users accessing the network cause MAI and then form an unavoidable error-floor and obviously degrade the performance. If the MAI can be estimated and removed, the performance can be improved greatly and more users can be accommodated to access the network simultaneously. Utilizing the property of PMPC, an interference canceller is proposed for PPM-OCDMA. The estimated interference is then subtracted from the received signal after photo-detection. Signaling format at each point of a transmitter model with Manchester codes could be observed in Lee et al. (2001) for further details.

In this new technique, only one code is reserved for the MAI estimation at the receiver end and the total number of available sequences becomes $P^2 - 1$ from previously $P^2 - P$ as describes in Shalaby (1999) and Lee et al. (2001). By assuming N active users are in the network, hence number of idle users becomes $P^2 - 1 - N$. Furthermore, Manchester codes are assigned to users systematically. The coding scheme is as follows: the laser pulses are signaled using the first half-chip interval ($T_c/2$ where T_c is the chip interval) for the users whose spreading sequences are in the first $(P^2 - 1)/2$ out of $(P^2 - 1)$, while for the rest of (half) users the laser pulses are signaled in the second half-chip interval (regarding the Manchester encoding). Then as a reference signal (sequence) to estimate the interference, only one sequence is reserved at the receiver. As an example for a network with $P = 3$, which has $P^2 = 9$ sequences (users), the laser pulses of users #1 to #4 are encoded in the first half-T_c while the remained users (#5 to #8) are signaled in the second half-T_c and sequence #0 is reserved as a reference sequence for cancellation purpose. Consequently, only those users whose laser pulses are assigned in the same half-chip interval are able to introduce interference to each other. We assume the spreading sequence of the desired user is assigned in the first half-chip interval. A random variable H denotes the number of active users whose laser pulses are encoded in the first half-chip interval and variable h is the realization of H. By assuming user #1 as the desired user, $(h - 1)$ users possibly contribute interference while $(N - h)$ users do not. The number of possible combinations for assigning $(h - 1)$ users to $((P^2 - 1)/2) - 1$ codes is multiplied by the number of possible combinations for assigning $(N - h)$ users to $(P^2 - 1)/2$ codes, and at last divided by the total number of possible combinations for assigning $(N - 1)$ users to $(P^2 - 2)$ codes. The probability distribution of H is thus expressed as:

$$P_H(h) = \frac{\binom{((P^2-1)/2)-1}{h-1}\binom{(P^2-1)/2}{N-h}}{\binom{P^2-2}{N-1}} \tag{5}$$

where $h \in (h_{\min}, h_{\min+1}, \ldots, h_{\max})$, $h_{\min} = \max\left\{1, N - \frac{P^2-1}{2}\right\}$ and $h_{\max} = \min\left\{N, \frac{P^2-1}{2}\right\}$.

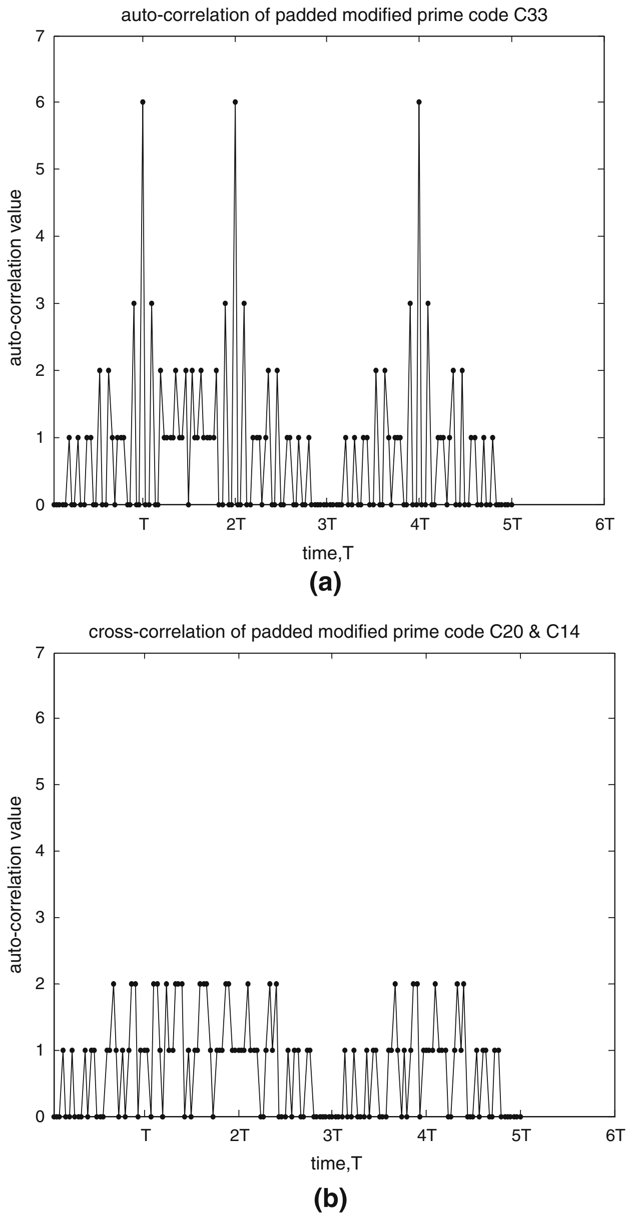

Fig. 1 Correlation functions of PMPC sequences for $P = 5$. (**a**) Auto-correlation of code sequence C_{33} for data stream of "*11010*". (**b**) Cross-correlation of code sequences C_{20} and C_{14} (different groups) for data stream of "*11010*". (T is the synchronization time where correlation values must be followed regarding the data.)

The receiver model with the proposed canceller is shown in Fig. 2. Received signal $r(t)$ is split into two equal parts by an 1×2 optical splitter and fed into two optical tapped-delay lines (OTDL). The upper path (main branch) is used to extract data signal while the lower path (reference branch) is used to estimate MAI and shot-noise. In main branch the signal is correlated with the receivers' own spreading sequence by the OTDL while in reference

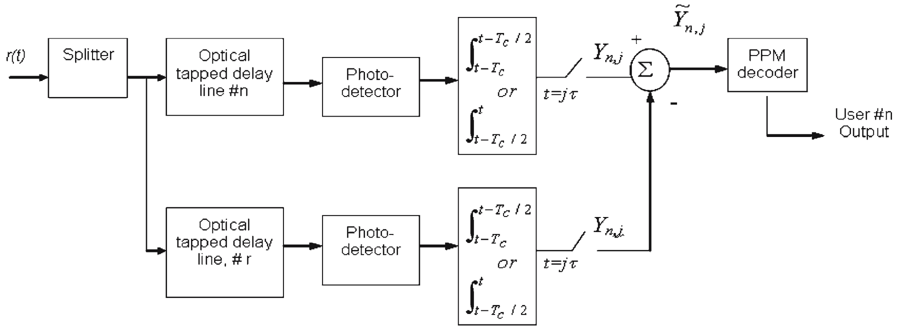

Fig. 2 Receiver model for the Manchester-coded PPM-OCDMA with interference canceller

branch the signal is correlated with the reserved spreading sequence (reference) by the OTDL to approximate the MAI. Besides that, due to the same characteristic photo-detectors in both paths and also signals pass the same length of fiber, shot-noise and beat-noise are also then estimated and reduced through the subtraction as shown in Fig. 2. The interesting point is the utilized correlators (OTDLs in branches) have exactly the same configurations for all receivers. As compared with the schemes in Shalaby (1999) and Lee et al. (2001), each receiver needs only two correlators instead of $P + 1$ (P for reference branches and one for main branch). Thus, this cancellation technique remarkably simplifies receivers' structures as well as reduces implementation costs.

The 'mark' positions of the corresponding spreading sequence determine the structure of the OTDL. However, the amount of delay is not only controlled by the mark positions of the spreading sequence, but also by the laser pulse-position within the chip. We assume the last code is reserved for the reference branch; the laser pulses are located in the first half-chip interval for users #1 to #$(P^2 - 1)/2$ for both main and reference branches. Similarly, for users from #$((P^2 - 1)/2)+1$ to #$(P^2 - 1)$ the laser pulses are located in the second half-chip interval for both branches. De-multiplexed signal is converted to electrical signal by the photo-detectors. Then integration is performed over half-chip duration due to Manchester-coded signals (see Fig. 2). For receiver #n, if $n \in \{1, 2, \ldots, (P^2 - 1)/2\}$ the integration is over the first half-chip duration while for $n \in \{((P^2 - 1)/2 + 1), ((P^2 - 1)/2 + 2), \ldots, (P^2 - 1)\}$, the integration is performed over the second half-chip interval, as shown in Fig. 2. The outputs of the integrators are directed to the samplers. M outputs are obtained from the sampler in both main and reference branches. Denote photon-count collected by the receiver #n in main and reference branches by random Poisson vectors $\mathbf{Y}_n = (Y_{n,0}, Y_{n,1}, \ldots, Y_{n,j}, \ldots, Y_{n,M-1})^T$ and $\mathbf{Y}_r = (Y_{r,0}, Y_{r,1}, \ldots, Y_{r,j}, \ldots, Y_{r,M-1})^T$ where $j \in \{0, 1, \ldots, M - 1\}$, $n \neq r$, respectively. $Y_{n,j}$ and $Y_{r,j}$ are conditional Poisson random variables. In main branch, the amount of photon-count collected over time slot j (denoted by $Y_{n,j}$) is contributed with MAI, shot-noise and data if symbol j is sent. In reference branch, the photon-count collected within time slot j (denoted by $Y_{r,j}$) contains only MAI and shot-noise (without data), in that the data is removed because of further spreading in multiplication of intended user code sequence with reference code sequence. Hence, the Poisson vector in main branch is given by:

$$\mathbf{Y}_n = Q(P + 1)\mathbf{S}_n + Q\mathbf{I} \tag{6}$$

Similarly, the Poisson vector in reference branch is given by:

$$\mathbf{Y_r} = Q\,[\mathbf{I} + \mathbf{S}_n] \tag{7}$$

Interference random vector $\mathbf{l} = (l_0, l_1, \ldots, l_{M-1})^T$ of size M is given by:

$$\mathbf{l} = \sum_{n=2}^{(P^2-1)/2} \mathbf{S_n} \tag{8}$$

Each variable l_j represents the number of interference pulses in slot j. The conditional probability of multinomial random interference vector $\mathbf{k}$ is given by:

$$P_{\mathbf{k}|H}\left\{\mathbf{k} = (l_0, l_1, \ldots, l_{M-1})^T \,|H = h\right\} = \frac{1}{M^{h-1}} \cdot \frac{(h-1)!}{l_0! l_1! \ldots l_{M-1}!} \tag{9}$$

where $\sum_{j=0}^{M-1} l_j = h-1$. To cancel MAI the value obtained from the reference branch is subtracted from the value obtained from the main branch. The vector $\tilde{\mathbf{Y}}_n = (\tilde{Y}_{n,0}, \tilde{Y}_{n,1}, \ldots, \tilde{Y}_{n,j}, \ldots, \tilde{Y}_{n,M-1})^T$ is then defined by:

$$\tilde{\mathbf{Y}}_n \underline{\underline{\mathrm{def}}} \, \mathbf{Y}_n - \mathbf{Y_r} \tag{10}$$

where $\tilde{Y}_{n,j} = Y_{n,j} - Y_{r,j}$. The output of the subtraction is directed to the PPM decoder and following decision rule is applied: if $\tilde{Y}_{n,i} > \tilde{Y}_{n,j}$ for every $j \neq i$, symbol i is declared to be the correct one, otherwise error occurs. We assume user #1 is the intended one; the conditional BEP is given by:

$$P_E^h = \frac{1}{M} \sum_{i=0}^{M-1} \Pr\left\{\tilde{Y}_{1,j} \geq \tilde{Y}_{1,i}, \text{some } j \neq i | S_{1,i} = 1, H = h\right\} \tag{11}$$

where P_E^h denotes the conditional symbol-error probability when $h-1$ of N users introduce interference to the desired user. BEP can be written as follow:

$$P_b = \frac{M}{2\,(M-1)} \sum_{h=h_{\min}}^{h_{\max}} P_E^h \cdot P_H\,(h) \tag{12}$$

By employing a union bound on the error-rate, the calculation becomes simpler, thus:

$$\begin{aligned}
P_E^h &\leq \sum_{j=0}^{M-1} \Pr\left\{\tilde{Y}_{1,j} \geq \tilde{Y}_{1,0}, \quad \text{some } j \neq 0 | S_{1,0} = 1, H = h\right\} \\
&\leq (M-1)\Pr\left\{\tilde{Y}_{1,1} > \tilde{Y}_{1,0} | S_{1,0} = 1, H = h\right\} \\
&= (M-1) \sum_{\mathbf{l}} \Pr\left\{\tilde{Y}_{1,1} \geq \tilde{Y}_{1,0} | \mathbf{k} = \mathbf{l}, S_{1,0} = 1, H = h\right\} P_{\mathbf{k}|H}\left\{\mathbf{l}|h\right\} \\
&\leq \sum_{\mathbf{l}} P_{\mathbf{k}|H}\left\{\mathbf{l}|h\right\} \cdot \eta\,(\mathbf{l}, h)
\end{aligned} \tag{13}$$

where

$$\eta\,(\mathbf{l}, h) = (M-1)\Pr\left\{\tilde{Y}_{1,1} \geq \tilde{Y}_{1,0} | \mathbf{k} = \mathbf{l}, S_{1,0} = 1, H = h\right\} \tag{14}$$

Using Chernoff bound on $\eta\,(\mathbf{l}, h)$, hence:

$$\begin{aligned}
\eta\,(\mathbf{l}, h) &= (M-1)\Pr\left\{\tilde{Y}_{1,1} \geq \tilde{Y}_{1,0} | \mathbf{k} = \mathbf{l}, S_{1,0} = 1, H = h\right\} \\
&= (M-1)\Pr\left\{Y_{1,1} - Y_{r,1} \geq Y_{1,0} - Y_{r,0} | \mathbf{k} = \mathbf{l}, S_{1,0} = 1, H = h\right\} \\
&\leq (M-1) E\left\{z^{(Y_{1,1} - Y_{r,1} - Y_{1,0} + Y_{r,0})} | \mathbf{k} = \mathbf{l}, S_{1,0} = 1, H = h\right\} \quad \text{for } z > 1
\end{aligned} \tag{15}$$

where $E\{\cdot|\cdot\}$ denotes the conditional expectation operator. By performing the last expectation and taking logarithm to $\eta(\mathbf{l}, h)$, thus:

$$\ln \eta\,(\mathbf{l}, h) \leq \ln(M-1) - Ql_1(1-z) - Ql_1(1-z^{-1}) - Q(P+1+l_0)(1-z^{-1}) \\ -Q\,(l_0+1)\,(1-z) \tag{16}$$

Setting $z = 1+\delta$, $\delta > 0$, (16) can be written as below where z denotes the number of pulses interfering with the intended user:

$$\begin{aligned}\ln \eta\,(\mathbf{l}, h) &\leq \ln(M-1) - Ql_1(-\delta) - Ql_1(\delta-\delta^2) \\ &\quad -Q(P+1+l_0)(\delta-\delta^2) - Q\,(l_0+1)\,(-\delta) \\ &= \ln(M-1) + Ql_1\delta^2 - QP\delta + Q(P+1+l_0)\delta^2\end{aligned}$$

or

$$\eta\,(\mathbf{l}, h) \leq (M-1)\exp\left[-QP\delta + Q(P+1+l_0+l_1)\delta^2\right] \tag{17}$$

Searching for tightest δ to minimize the interference, we have:

$$\delta = \frac{P}{2(P+1+l_0+l_1)} \tag{18}$$

Substituting (18) into (17), then:

$$\eta\,(\mathbf{l}, h) \leq (M-1)\exp\left[-Q\frac{P^2}{4\,(P+1+l_0+l_1)}\right] \tag{19}$$

and,

$$\begin{aligned}P_{\mathbf{k}|H}(\mathbf{l}|h) &= P_{k_0,k_1|H}\,(k_0 = l_0, k_1 = l_1|H = h) \\ &= \binom{h-1}{l_0}\left(\tfrac{1}{M}\right)^{l_0}\left(1-\tfrac{1}{M}\right)^{h-1-l_0}\binom{h-1-l_0}{l_1}\left(\tfrac{1}{M-1}\right)^{l_1} \\ &\quad \left(1-\tfrac{1}{M-1}\right)^{h-1-l_0-l_1}\end{aligned} \tag{20}$$

Hence, the conditional symbol-error probability can be upper-bounded as below:

$$\begin{aligned}P_E^h &\leq \sum_{l_0,l_1}\eta\,(l_0, l_1)\cdot P_{k_0,k_1|H}\,(k_0 = l_0, k_1 = l_1|H = h) \\ &= (M-1)\sum_{l_0,l_1}P_{k_0,k_1|H}\,(k_0 = l_0, k_1 = l_1|H = h)\cdot\exp\left[-Q\frac{P^2}{4\,(P+1+l_0+l_1)}\right] \\ &= \sum_{l_0=0}^{h-1}\binom{h-1}{l_0}\left(\frac{1}{M}\right)^{l_0}\left(1-\frac{1}{M}\right)^{h-1-l_0}\sum_{l_1=0}^{(h-1-l_0)}\binom{h-1-l_0}{l_1} \\ &\qquad \left(\frac{1}{M-1}\right)^{l_1}\left(1-\frac{1}{M-1}\right)^{h-1-l_0-l_1}\times(M-1)\exp\left[-Q\frac{P^2}{4\,(P+1+l_0+l_1)}\right]\end{aligned} \tag{21}$$

It can be noticed that $if\ Q \to \infty$, then $P_E^h = 0$.

4 PPM-OCDMA with interference canceller (without Manchester codes)

The system with interference canceller without Manchester codes is very similar to the scheme shown in Fig. 2 and discussed in previous section. The only difference is in the range of integrations. Due to the Manchester-coded information source (Fig. 2), integration is performed over half-chip duration for detection, since the 'mark' positions of a spreading sequence occupy only half-chip duration. However, in the case of non-Manchester-coded method, integration is performed over entire chip duration T_c.

In this model all active users have possibility to contribute MAI. Therefore the interference vector $\mathbf{k}$ is similar to (9) where $h = N$ in this case. Similarly Poisson vectors $\mathbf{Y}_n$ and $\mathbf{Y}_r$ represent photon-count collected by both main and reference branches and calculations are similar to Sect. 3. The BEP is also the same as (3). For a symmetrical channel with equal likely data symbols, we assume user #1 is the desired one. P_E is upper-bounded as:

$$\begin{aligned} P_E &\leq \sum_{j=0}^{M-1} \Pr\left\{\tilde{Y}_{1,j} \geq \tilde{Y}_{1,0}, \quad \text{some } j \neq 0 \ \ |S_{1,0} = 1\right\} \\ &\leq (M-1) \sum_{\mathbf{l}} \Pr\left\{\tilde{Y}_{1,1} \geq \tilde{Y}_{1,0} | \mathbf{k} = \mathbf{l}, S_{1,0} = 1\right\} P_{\mathbf{k}}\left\{\mathbf{k} = \mathbf{l}\right\} \\ &\leq \sum_{\mathbf{l}} P_{\mathbf{k}}\left\{\mathbf{k} = \mathbf{l}\right\} \cdot \eta\left(\mathbf{l}\right) \end{aligned} \tag{22}$$

where $\eta(\mathbf{l})$ is also the same as (19).

Then, upper-bounded BEP achieved as:

$$\begin{aligned} P_E &\leq \sum_{l_0, l_1} \eta\left(l_0, l_1\right) \cdot P_{k_0, k_1}\left(k_0 = l_0, k_1 = l_1\right) \\ &= (M-1) \sum_{l_0, l_1} P_{k_0, k_1}\left(k_0 = l_0, k_1 = l_1\right) \cdot \exp\left[-Q \frac{P^2}{4\left(P + 1 + l_0 + l_1\right)}\right] \\ &= \sum_{l_0=0}^{N-1} \binom{N-1}{l_0} \left(\frac{1}{M}\right)^{l_0} \left(1 - \frac{1}{M}\right)^{N-1-l_0} \cdot \sum_{l_1=0}^{(N-1-l_0)} \\ &\quad \binom{N-1-l_0}{l_1} \left(\frac{1}{M-1}\right)^{l_1} \left(1 - \frac{1}{M-1}\right)^{N-1-l_0-l_1} \\ &\quad \times (M-1) \exp\left[-Q \frac{P^2}{4\left(P + 1 + l_0 + l_1\right)}\right] \end{aligned} \tag{23}$$

5 Discussions of results

In this section, by the aid of the equations derived in above calculations, bit-error rate (BER) performance is evaluated in the following three PPM-OCDMA schemes:

(i) Without cancellation;
(ii) With proposed cancellation;
(iii) Proposed Manchester-coded cancellation.

For (i) the BER is considered using Eqs. 3 and 4. In (ii), Eqs. 3 and 23 are employed. And for the (iii), Eqs. 5, 12, 20 and 21 are utilized in the calculation.

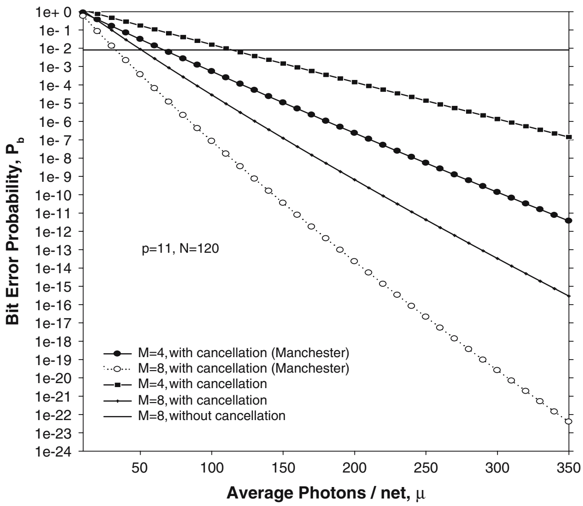

Fig. 3 BER performance of different PPM-OCDMA schemes under given conditions verses the average photons per nat (μ) for $P = 11$ in the case of full load ($N = P^2 - 1 = 120$) when $M = 4$ and 8

In the analysis, μ is given by $\mu = Q(P + 1)/\ln(M)$ which is proportional to received signal power indicated as a number of photons per nat (laser pulse).

Figure 3 shows BER comparison for these three schemes when μ is variant and $N = 120$ (full loaded for $P = 11$ where $N = P^2 - 1$). The figure illustrates the BER for (i) when $M = 8$, $\mu = \infty$ ($Q \to \infty$) and the BERs for (ii) and (iii) when $M = 4$ and 8. It can be seen that the BER performance improves as μ and M increase. The improvement for the receivers with interference canceller is significant especially for greater values of M and μ, however, the increase is limited and higher M brings more complexity in ONU architecture. In fact, the BER of the receivers with interference canceller is reduced to zero if μ approaches infinity (i.e., very high received power). However (i) has a fixed unreliable BER (due to the limit of $Q \to \infty$) which is improved only with greater values of M, in cost of implementation complexity. In addition, it can be observed that the BER can be further improved by using Manchester coding with proposed cancellation method due to extra enhanced interference reduction as explained in Sect. 3.

When the time-slot can be doubled, the increase of PPM slots is more effective. However, slots cannot be increased unlimited and when we have limited resource to increase number of slots due to hardware limitation and expenses in detector components, Manchester encoding is a wise option and advantageous as an extra source coding. Due to the fact that, the desired signal count is equal to $P + 1$ in PMPC (auto-correlation value) which grows as P increases; while interference count from another users is always '1' (cross-correlation value) irrespective of the value of P, hence the BER performance is expected to be improved by higher P value. On the other hand, there is also limitation for P since the higher P, the more assigned users and OCDMA performance is basically degraded by extending the number of users and decreasing the network and/or single user bit-rate because of longer code-length ($P^2 + P$). Thus, for a practical OCDMA network the optimum values based on required specifications should be set up and considered.

One of the important parameters of the performance evaluation in practice is data-rate (bit-rate). For a given user, the rate of data transmission (throughput) is given by amount of information transmitted per second by this user.

Refer to what have been defined, T is the duration of each *M-ary* time-frame, and each chip-time has the duration of T_c. The spreading-sequence of length L ($L = P^2 + P$ in PMPC) must be exactly fitted into time-slot τ where $\tau = L \cdot T_c$. The throughput for PPM-OCDMA, $R_{\mathrm{T-PPM}}$ is defined as below (Karbassian and Ghafouri-Shiraz 2007):

$$R_{\mathrm{T-PPM}} = \frac{\log M}{T} = \frac{\log M}{M\tau} = \frac{\log M}{MLT_c} \text{ nats/s} \tag{24}$$

The natural number '*e*' is taken as the basis of '*log*' function. Since the pulse-width T_c is always fixed, for the sake of convenience the throughput-pulse-width product $R_{\mathrm{O-PPM}}$ is defined as following:

$$R_{\mathrm{O-PPM}} = R_{\mathrm{T-PPM}} \cdot T_c = \frac{\log M}{MLT_c} \cdot T_c = \frac{\log M}{ML} \text{ nats/chip} \tag{25}$$

It is noted that the throughput-pulse-width product $R_{\mathrm{O-PPM}}$ is proportional to throughput $R_{\mathrm{T-PPM}}$ for a fixed pulse-width of T_c. In addition, the users-throughput product, denoted by *NR*, as the product of number of users times $R_{\mathrm{O-PPM}}$, is defined by:

$$NR_{\mathrm{PPM}} = N \cdot R_{\mathrm{O-PPM}} = N \cdot \frac{\log M}{ML} \text{ nats/chip} \tag{26}$$

NR is measure of the total data-rate (bit-rate) from all users transmitted within the channel. In practice, we are interested in characterizing the maximum throughput that can be achieved when keeping the BEP below a prescribed threshold. Therefore, the parameters M and L are allowed to vary to maximize the throughput under the constraint that $P_b \le \varepsilon$. Then we have:

$$R_{\mathrm{O-PPM,max}} = \max_{\substack{M,L \\ P_b \le \varepsilon}} R_{\mathrm{O-PPM}}, \quad NR_{\mathrm{PPM,max}} = \max_{\substack{M,L \\ P_b \le \varepsilon}} NR_{\mathrm{PPM}} \tag{27}$$

Figure 4 displays variations of BER versus the number of simultaneous users (N) for the three receivers when $\mu = 200$ ($\mu = \infty$ for (i)), $P = 11$ and $M = 4$ and 8. It is obvious

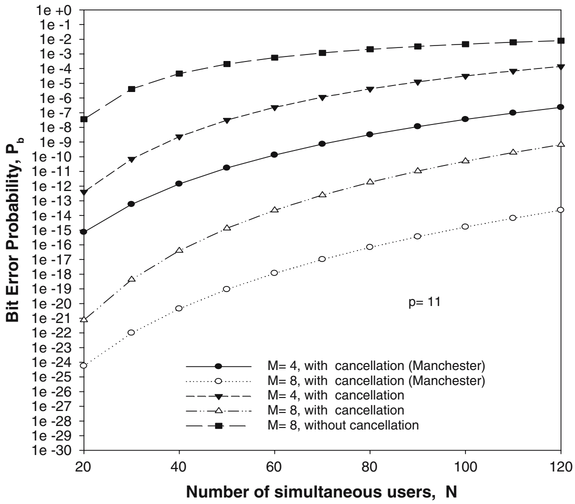

Fig. 4 BER performance of different PPM-OCDMA schemes in that $\mu = \infty$ for scheme (i) and $\mu = 200$ for schemes (ii) and (iii) verses the number of simultaneous users N for $M = 4$ and 8, when $P = 11$ ($N = 120$ Full-load as $N = P^2 - 1$)

that (i) becomes unreliable as the number of users increase due to rapidly increased MAI, however (ii) and (iii) with the proposed interference canceller and coding can effectively remove the MAI. It may be observed from both figures that performance of the configuration with only cancellation and $M = 8$ is better than the one with cancellation and Manchester codes of $M = 4$. As aforementioned, the study is focused on cancellation technique; however in situations that increasing the number of slots (M) is impossible or brings difficulties to the system architecture or implementation, Manchester coding is a supporting option.

6 Conclusion

A new interference cancellation technique has been proposed and studied for an optical synchronous PPM-CDMA network. The cancellation is performed by the aid of correlation property of PMPC as optical spreading sequences. We have obtained the bit-error probabilities (i.e., BER) for receiver structures with MAI cancellation as well as composition with Manchester coding. This technique can also be utilized with the unipolar codes having the same group correlations property. As advantages, this new MAI cancellation simplifies the receiver configuration due to reducing the number of correlators in OTDLs that results less implementation expenses and also increases the network capacity. The numerical results indicate that MAI has been effectively reduced and the performance of the receivers with this canceller has been improved. The network data-rate (bit-rate) as a throughput analysis has also been introduced. Finally, where extending slot in system architecture is impractical, Manchester encoding can be a viable choice.

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