

On Error-Correction Coding for CDMA PON

Henrik Lundqvist, *Student Member, IEEE*, and Gunnar Karlsson, *Senior Member, IEEE*

Abstract—Optical-code-division multiple access (OCDMA) has been investigated as a multiple-access technique for a long time, but so far, it has not reached any practical success. We investigate the performance of low-complexity OCDMA systems with a realistic model of noise and interference; the main limitation of the system is beat noise. To improve the performance, we consider forward-error correction (FEC) and soft decoding using standard error-correcting codes. The achievable error rates are evaluated using simulations and show significant improvement when FEC is used. The results also show that frequency-hopping systems perform better than temporally coded systems when beat noise is taken into account.

Index Terms—Beat noise, error-correction coding, optical-code-division multiple access (OCDMA), soft decoding.

I. INTRODUCTION

PASSIVE optical networks (PONs) with point-to-multi-point topologies have important advantages in access networks. Less fiber and interfaces are required compared to point-to-point links, which saves significant costs, and no active components are used between the central office and the customer premises. Therefore, the reliability is high, the operational cost low, and it is simple to upgrade the network.

A multiple-access scheme is required since the fibers are partially shared. The standards for PONs are based on time-division multiple access, where the central node schedules the transmission of the different terminals. The scheduling can either be static or dynamic. Wavelength-division multiplexing (WDM) is considered to increase the capacity of PONs, either to add services on separate wavelengths or to separate users by assigning them to different wavelengths.

Optical-code-division multiple access (OCDMA) is an alternative multiple-access method for PONs. It has been studied for many years as a possible asynchronous access method for optical networks. The interest in OCDMA is mainly motivated by its flexibility in user allocation, support of varying bit rates, and security. However, there are also drawbacks that motivate further research in the area of error correction for OCDMA networks. Two of the main problems with OCDMA are 1) with incoherent receivers, the performance is limited due to unipolar signaling and 2) beat noise. Since there are no negative pulses, the interference is a bigger problem than for coherent systems. Good spreading codes should have as low cross correlation as possible, a high autocorrelation peak at 0, and no other

strong autocorrelation peaks. Possible solutions to mitigate the interference are coherent receivers or optical hard limiters, which would limit the optical power to make the channel appear to have fewer interfering users [30]. Unfortunately, limiters are hard to implement and will not be considered in this paper.

In this paper, we consider low-complexity implementations where the signal is encoded and decorrelated using optical components. Direct sequencing can be implemented using optical splitters and delay lines, whereas fast frequency hopping (FFH) can be implemented using a broadband light source and optical filtering by fiber Bragg gratings (FBG), which has been demonstrated as a promising approach [12], [14]. The receiver is assumed to be incoherent, which means that beat noise will be a major performance limitation. Beat noise occurs because of the square-law detection of the optical signal. Depending on whether the light source is coherent or incoherent, the characteristics are different, but in both cases, there are studies that indicate that beat noise can be the main limitation in the system [1], [10], [11], [27], [28]. An important property of the beat noise is that its variance is proportional to the square of the light intensity. Therefore, there is no gain in increasing the power. The noise is also stronger for 1's than for 0's, hence the channel is asymmetric.

For low-complexity optical receivers, which only implement matched filtering and sampling at the bit rate, there are two approaches to improve the performance in terms of allowing more users while maintaining a low bit error rate (BER). The first approach is to use longer spreading codes to reduce the interference. The second approach is to use error-correcting codes to reduce the error rate. Both methods expand the bandwidth to reduce the error rate. A combination of spreading code and error-correcting code is evaluated by Azmi *et al.* and the performance is found to be improved [5]. However, the solution requires detection at chip rate, which we try to avoid in this study. Therefore, we limit our study to separate spreading and error-correcting codes.

The contributions of this paper include a detailed investigation of the effect of beat noise on the performance of OCDMA. It is shown that beat noise is a major problem in particular for temporally encoded OCDMA systems. When error-correction codes and soft decoding is used, the performance is significantly improved, but it is hard to provide acceptable error rates for a large number of users.

In Section II, OCDMA is described and the most significant noise sources are identified. The systems studied are further described in Section III, and the channel models are presented. Section IV contains a description of the forward-error correction (FEC) methods used to improve the performance. Simulation results are presented in Section V, and finally, conclusions are given in Section VI.

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The authors are with the Laboratory for Communication Networks, KTH, Royal Institute of Technology, 164 40 Kista, Sweden (e-mail: henrik.lundqvist@imit.kth.se; gk@imit.kth.se).

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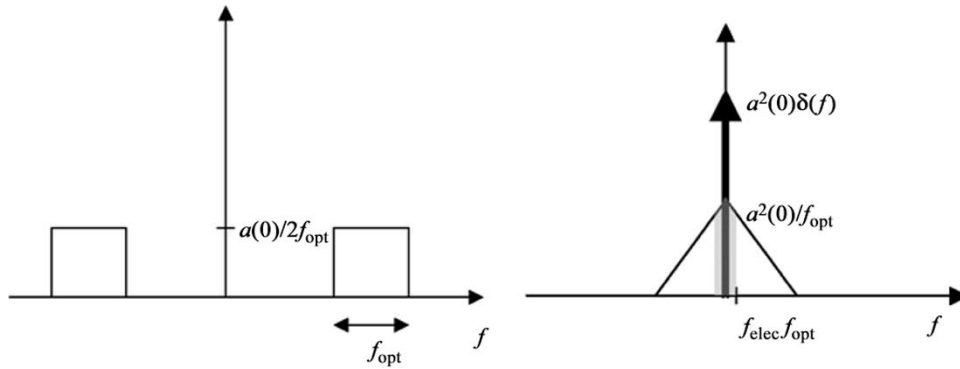


Fig. 1. Figure on the left shows the spectrum of the signal before the square law detector; the figure on the right shows the spectrum for the square of the signal. It consists of a Dirac pulse and a triangular spectrum. Since only the lowest frequencies are filtered out in the electrical domain, it is only the noise within the electrical bandwidth that has to be considered.

II. OCDMA NETWORKS

A. Limitations of OCDMA Networks

Optical networks suffer from several transmission impairments that have to be taken into account. In the case of an access network based on OCDMA, some impairments, such as nonlinearities, are irrelevant, whereas several others have to be taken into account. Dispersion can be a problem because of the large bandwidth of the signal, for example, for FH channels [23]. The power budget will be a significant factor in the network design because the signal is split between different users, rather than because of the distance. This also means that the noise will have a significant impact, especially beat noise. Thermal or shot noise will also contribute, depending on whether p-i-n or avalanche photodiode (APD) detectors are used, but usually, beat noise will dominate. Last, multiple-access interference will be a significant limitation. With advanced receivers deploying interference cancellation, this can be limited, but because of the high bit rates, it will be expensive to use such complex processing.

B. Beat Noise

Since beat noise is the most important problem in the networks considered here, we will treat this more thoroughly. For broadband incoherent light sources, the noise contains a beat noise component that depends on the power. The autocorrelation function $a(t)$ of a noise signal at a frequency f_0 can be written as

$$r_s(\tau) = a(\tau) \cos 2\pi f_0 \tau.$$

From signal theory, it is known that the autocorrelation of the square of a signal is given by

$$r_u(\tau) = r_{s^2}(\tau) = r_s^2(0) + 2r_s^2(\tau).$$

Since the signal will be squared in the detector, the resulting autocorrelation function is

$$r_u(\tau) = a^2(0) + a^2(\tau) + a^2(\tau) \cos 4\pi f_0 \tau.$$

The corresponding spectrum will then be

$$R_u(f) = a^2(0)\delta(f) + Q(f) + \frac{Q(f-2f_0)}{2} + \frac{Q(f+2f_0)}{2}$$

where $Q(f)$ is the spectrum corresponding to $a^2(t)$, and $\delta(f)$ is a Dirac impulse. If $a(t)$ has a rectangular spectrum, i.e., constant spectral density within its bandwidth, $Q(f)$ is a triangular spectrum. After low-pass filtering, the remaining spectrum is

$$R_u(f) = a^2(0)\delta(f) + Q(f).$$

For a broadband light source with constant spectral density within the frequency band, the corresponding spectrum is depicted in the left part of Fig. 1. The power of the noise is approximately proportional to the ratio of the optical bandwidth and the electrical bandwidth. This relation can be best explained by the right part of Fig. 1, where the low-frequency part of the spectrum $R_u(f)$ is shown. The part of the spectrum that contributes to the beat noise is within the electrical bandwidth, and the power is inversely proportional to the optical bandwidth. Therefore, the beat noise will be approximately proportional to the ratio of the electrical and optical bandwidths, multiplied by the square of the light intensity.

$$\sigma^2 = cI^2 \frac{f_{\text{elec}}}{f_{\text{opt}}}$$

where I is the light intensity, and f_{elec} and f_{opt} are the electrical and optical bandwidths, respectively. The constant c depends on the degree of polarization and the responsivity of the detector. In this paper, c has been set to 1, which is a reasonable value, since the responsivity is normally slightly less than 1 and the polarization between 1 and 2. Demeechai and Sharma derived expressions for the beat noise in OCDMA systems with Gaussian and Lorentzian spectra, and the beat noise is proportional to the bandwidth ratio and the square of the intensity in these cases also [10].

C. Related Work

Fathallah *et al.* described an FFH system, including the implementation with FBG [12]. Codes from [7] with more frequencies than the number of chips (asymmetric codes) are used.

Simulation results are presented, and a receiver is proposed, for which power measurements during a bit interval provide side information. The conclusion is that FFH works better than direct sequence (DS)-CDMA. The paper covers implementation from a component level to performance analysis, but noise is neglected in the performance evaluation.

The effect of beat noise in a CDMA PON is investigated by Ahn and Park in [1]. The spreading and correlation is done with electronics and the light source is coherent, so the beat noise only affects the chips that collide with interfering chips. Therefore, the beat noise has less impact than of networks with optical spreading and correlation.

Hayashi and Yahima propose to use received power in a bit period as side information to make erasures in the decoding process [13]. The suggested codes are Bose–Chaudhuri–Hocquenghen (BCH) codes, as in this paper, but only multiple-access interference (MAI) is considered. The performance is evaluated for different widths of the erasure zone and compared to hard decoding and uncoded transmission. It is shown that the BER decreases when erasure decoding is used. Erasure decoding can be considered as a simpler kind of soft decoding than the Chase algorithm.

An interference-limited synchronous CDMA network with prime codes is considered by Wu and Wu [30]. The performance improvements by using BCH codes and an ideal optical hard-limiter to reduce the interference are evaluated. The results show that the performance is improved when some of the bandwidth expansion is used for error correction. Dale and Gagliardi came to the same conclusion when they compared convolutional coding, Reed–Solomon (RS) coding, and pulse position modulation (PPM) as different means to increase the performance of OCDMA [9]. Since PPM lowers the throughput, it is also considered as a channel-coding scheme. Convolutional and RS-coding outperforms PPM but combinations of the different codings are not considered. The limiting factors are MAI and detector noise, but beat noise is neglected.

Muckenheim *et al.* introduced a combination of channel coding and retransmissions to achieve an improved performance [21]. An algorithm for setting the parameters is introduced, and the delay and throughput are evaluated. The investigation shows that the performance at the link layer is improved when channel coding is used.

Kim evaluates turbo codes for OCDMA systems with binary PPM [15]. It is assumed that APD detectors are used and that the limiting noise is shot noise. Argon and McLaughlin analyze the use of turbo product codes for DS-CDMA ON-OFF keying systems [2]. Since only interference is considered, and not noise, the channel is a Z-channel. It is shown how soft information can be extracted and how the decoding complexity can be reduced by approximations. With the longer code length of the turbo codes, the BER can be substantially reduced compared to shorter codes. These papers are interesting since they use more powerful coding, but the channel models neglect the main problem of OCDMA.

Channel models with several types of noise and interference are described for both DS-CDMA and frequency-hopping (FH) in [19] and [20]. Here, these models are put in context and a comparison of the two methods is made for systems where

beat noise is a major performance limitation. With these realistic channel models, it is also possible to implement error-correction coding with soft decoding algorithms.

III. CHANNEL MODELS

This section contains a short derivation of channel models, where both interference and beat noise are taken into account. The focus is on incoherent sources, such as light emitting diodes, which produce light with large bandwidth. Coherent light sources, such as lasers, which have a narrow bandwidth, are briefly covered. However, the receivers are always incoherent.

A. Temporal Coding

In this section, a model of the distribution of both noise and interference for temporally coded channels is described. The interference depends on the number of active users and the properties of the code. The optical orthogonal codes (OOCs) have attractive properties in terms of autocorrelation and cross correlation. The autocorrelation peak is equal to the weight of the code, there are no other side lobe peaks higher than 1, and the cross correlation of any two codes is never higher than 1 [25]. The price for these attractive properties is that there are few possible codewords, and hence, few possible users. For codes of length L and weight w , the maximum number of users is given by

$$n \leq \frac{L}{w(w-1)}.$$

There are other codes that allow more users (see, for example, Zhang *et al.* [31] or Azizoglu *et al.* [4]). The drawback of these codes is that they have worse correlation properties. The probability that the chips from a different user collide with the chips of the user of interest depends on the spreading code. For OOC, the multiple-access interference from $n-1$ other users can be calculated as

$$I = \sum_{i=0}^{n-1} \binom{n-1}{i} \left(1 - \frac{w^2}{2L}\right)^{n-1-i} \left(\frac{w^2}{2L}\right)^i.$$

For simplicity, it has been assumed that the chips from different users arrive synchronously. This gives an overestimation of the error probability [25]. In all simulations, we have assumed that there is also signal independent additive white Gaussian noise (AWGN), like for example thermal noise, but that the power of that noise is so low that the errors are mainly caused by interference and beat noise. The distribution of the beat noise can be approximated as Gaussian if the ratio of the optical and electrical bandwidth is large [27]. The approximation is motivated by central limit arguments since the large optical bandwidth creates multiple modes that are summed. The accuracy of the approximation is, therefore, relying on a large bandwidth ratio, and is less accurate at the tail

of the distribution [3], [24]. In this paper, we have used bandwidth ratios of 100 in most simulations, and since most of the simulations consider transmission with FEC, the BER does not have to be excessively low; therefore the approximation should be fairly accurate for the results presented. The thermal noise in the simulations would correspond to a BER of approximately 10^{-12} , if it had been the only noise source. The probability distributions of the signal, conditioned on a 0 and a 1, respectively, are

$$f(x|0) = \sum_{i=0}^{n-1} \binom{n-1}{i} \left(\frac{w^2}{2L}\right)^i \left(1 - \frac{w^2}{2L}\right)^{n-1-i} \\ \times N\left(x, \frac{i}{w}, \sqrt{\sigma_{\text{th}}^2 + i^2 \frac{\text{bwr}}{w^2}}\right) \\ f(x|1) = \sum_{i=0}^{n-1} \binom{n-1}{i} \left(\frac{w^2}{2L}\right)^i \left(1 - \frac{w^2}{2L}\right)^{n-1-i} \\ \times N\left(x, 1 + \frac{i}{w}, \sqrt{\sigma_{\text{th}}^2 + \left(1 + \frac{i}{w}\right)^2 \text{bwr}}\right).$$

In the equations, N is the probability density function (pdf) of a Gaussian distribution, and bwr is the ratio between electrical and optical bandwidth. As can be seen from the expression, the variance of the noise is proportional to the square of the total intensity of the user signal and the interference. The optimal threshold is chosen as the point where the conditional pdf's are equal. It is not obvious that there is only one such point for these pdf's, but for the parameters we have used in the simulations, it has been checked numerically that there is only one intersection point for a given number of users.

B. Frequency Hopping

FFH is an alternative to temporal codes, where each bit from a user is encoded both in time and frequency. A description of prime codes for FH is given by Kwong *et al.* [16]. The autocorrelation function for these codes has sidelobes that are higher than one; therefore they are not optimal from a synchronization point of view, since there is a risk that the receiver will lock its synchronization at a sidelobe, instead of the main lobe. However, prime codes can allow many simultaneous users in synchronous systems. Extended quadratic congruence/prime codes for FH are introduced by Tancevski and Andonovic and the possibility to eavesdrop is analyzed as well [29]. These are asymmetric codes that can handle many users with the maximum cross correlation equal to 2.

In the following analysis, it is assumed that symmetric codes are used so that the number of frequencies is equal to the weight of the code. The analysis could be extended to other types of codes, like the ones mentioned in the previous paragraph. The performance of different codes depends on many factors such as receiver type and channel model, but in general, most codes are at least as densely populated by ones as those we consider, therefore they are also sensitive to beat noise. For

a channel with $n - 1$ interfering users, f frequencies, and temporal length L , the multiple-access interference is

$$I = \sum_{i=0}^{n-1} \binom{n-1}{i} 2^{1-n} \sum_{j=0}^i \binom{i}{j} \left(1 - \frac{w^2}{fL}\right)^{i-j} \left(\frac{w^2}{fL}\right)^j.$$

This is essentially the same expression as that for the temporal codes, if the product of the temporal length L and the number of frequencies f is considered as the total code length. The first sum is the probability distribution for the number of users sending 1's, which is binomial with probability 0.5. The second sum is the probability distribution for the interference conditioned on i 1's.

When the expression for the interference is combined with the beat noise, we have to take into account the distribution of the interference over the frequency bands. If two chips from different users collide with the codeword we are interested in on different frequency bands, the intensity on each of the bands will be $2/w$. On the contrary, if they would interfere on the same frequency, the intensity will be $3/w$ on that frequency and $1/w$ on the other frequency. Since the beat noise power is proportional to the square of the intensity on each frequency, the first case will give a power proportional to 2×4 , and the latter will give $1 + 9$. The distribution of the interference over the frequencies can be modeled as multinomial. If the number of active interferers is j , the average number of interferer-interferer terms is

$$\left\langle \sum_{i=1}^f \binom{j_i}{2} \right\rangle = \frac{1}{f} \binom{j}{2}$$

where j_i is the number of interferers at frequency band i . If a 0 is sent, these are the only terms contributing to the beat noise. If a 1 is sent, there is also a contribution from the signal-interferer terms and from the chips that are not affected by interference. The number of signal-interferer terms is j , and the average number of frequency bands without any interference is $(1 - 1/w)^j$. Hence, the resulting pdf for the signals is given by the equation shown at the bottom of the next page.

For FH channels with coherent light sources, a corresponding expression was derived by Tancevski and Rusch [28]. Fig. 2 shows the probability distribution of the signal strength conditioning on the 0 and 1, respectively, for an FH channel with weight 5, temporal length 25, five frequencies, bandwidth ratio 100, and ten active users.

IV. ERROR CORRECTION CODING

A. Choice of Code

The OCDMA channels are not symmetrical, which could potentially lead to inefficiency when common error-correcting codes are used. However, the asymmetry occurs both due to MAI and asymmetric noise, and when an optimal threshold is chosen, it is not clear whether 1's or 0's will suffer from the highest error probability. It usually changes, depending on the number of active users. Therefore, it is not worthwhile to use

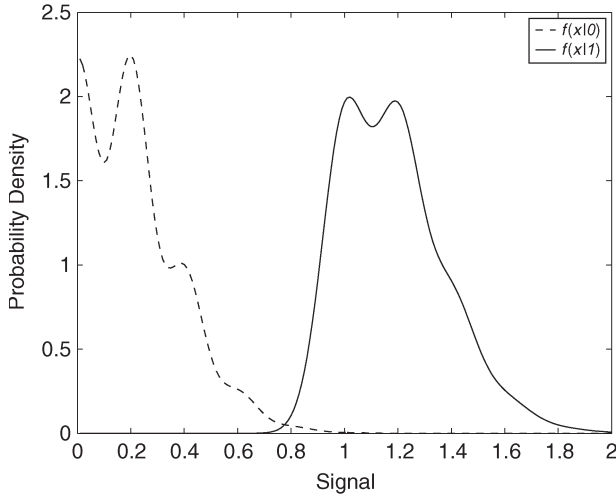


Fig. 2. Conditional probability density functions when a 0 and a 1 is sent over an FH channel with weight 5, temporal length 25, five frequencies, bandwidth ratio 100, and ten active users.

asymmetric error-correcting codes, since efficient implementation is more difficult and less studied. However, the asymmetry of the channel should be taken into account in the decoding, to use the added redundancy in the most efficient way. This is demonstrated in the results of our simulations.

B. Soft Decoding

It is impractical to implement ideal soft decoding for block codes since it involves calculating the distance metric from the received sequence to all allowed codewords. In order to implement soft decoding, nonideal approximations have to be made. One very useful soft decoding method is the Chase algorithm, where the idea is to choose the bits that have the “worst” distance metric and try different hypotheses for them [8]. First, hard decisions are taken about all bits, and then different bit patterns are added to the bit sequence, in order to get several candidate sequences. The added patterns are intended to test the most unreliable bits in the sequence. Then, all sequences are decoded, using hard decoding, and encoded again. The resulting codewords are compared to the received soft bits, and the codeword with the minimum distance is chosen. Since several sequences have to be encoded and decoded, the complexity is higher than for hard decoding, where only one sequence is decoded (Table I).

There are different versions of the Chase algorithm, which differ in how the test patterns are generated. The versions we have used are versions two and three, which generate $2^{\lfloor d/2 \rfloor}$ and

TABLE I
COMPLEXITY OF THE SOFT DECODING ALGORITHMS IN THIS STUDY
COUNTED AS NUMBER OF HARD DECODING ITERATIONS

Code	Algorithm	Complexity
BCH(63,57)	Chase-2	2
BCH(63,51)	Chase-2	4
BCH(63,45)	Chase-2	8
BCH(63,45)	Chase-3	2

$\lceil (d - 1)/2 \rceil$ sequences, respectively, where d is the hamming distance of the code. For Chase-2, $d/2$ bits are chosen, and all possible bit patterns for these bits are tested. For Chase-3, $d - 1$ bits are chosen, and the test patterns start with all 0’s and then each new pattern adds 1’s in two bit positions, starting from the bits with the worst metric.

The metric we use is the logarithm of the ratio between the pdf’s $f(x|1)$ and $f(x|0)$, which is the maximum likelihood decoding rule. Since the distributions are too complicated to be calculated in real time, a quantized estimation of the likelihood ratio is calculated and saved. A quantized soft decoder will also give more realistic results for an implementable receiver. Since we assume that we have knowledge about the number of active users during a coding block, we always use the appropriate distribution. In practice, it would be necessary to keep a table of the likelihood ratios for a different number of users and choose the right one depending on the estimated number of active users. For the uplink in a point-to-multipoint topology, the number of active users is actually known, since all senders have the same receiver. For the downlink, or in a multipoint-to-multipoint network, the receiver can measure the total received energy to estimate the number of active users during a block [22]. Estimations over shorter intervals will be less accurate and require more complex receivers.

It can also be noted that for hard decoding, the optimal threshold is given by the intersection between the two pdf’s. Note that all parameters, including the number of active users, have to be known also in this case. Throughout the paper, the optimal threshold is always used for the simulations of hard decoding.

V. SIMULATION RESULTS

The simulations presented focus on the performance of different receivers in systems with beat noise. The parameters give a good picture of such systems, without specifying the exact implementation. Hence, the results should apply to systems with different types of light sources, detectors, and possibly, amplifiers.

$$f(x|1) = \sum_{i=0}^{n-1} \binom{n-1}{i} 2^{1-n} \sum_{j=0}^i \binom{i}{j} \left(\frac{w}{L}\right)^j \left(1 - \frac{w}{L}\right)^{i-j} N\left(x, 1 + \frac{j}{w}, \sqrt{\sigma_{th}^2 + \left(\left(1 - \frac{1}{w}\right)^j + 2j + \frac{2}{\sqrt{L}} \binom{j}{2}\right) \frac{bwr}{w^2}}\right)$$

$$f(x|0) = \sum_{i=0}^{n-1} \binom{n-1}{i} 2^{i-n} \sum_{j=0}^i \binom{i}{j} \left(\frac{w}{L}\right)^j \left(1 - \frac{w}{L}\right)^{i-j} N\left(x, \frac{j}{w}, \sqrt{\sigma_{th}^2 + \left(\frac{2}{\sqrt{L}} \binom{j}{2}\right) \frac{bwr}{w^2}}\right)$$

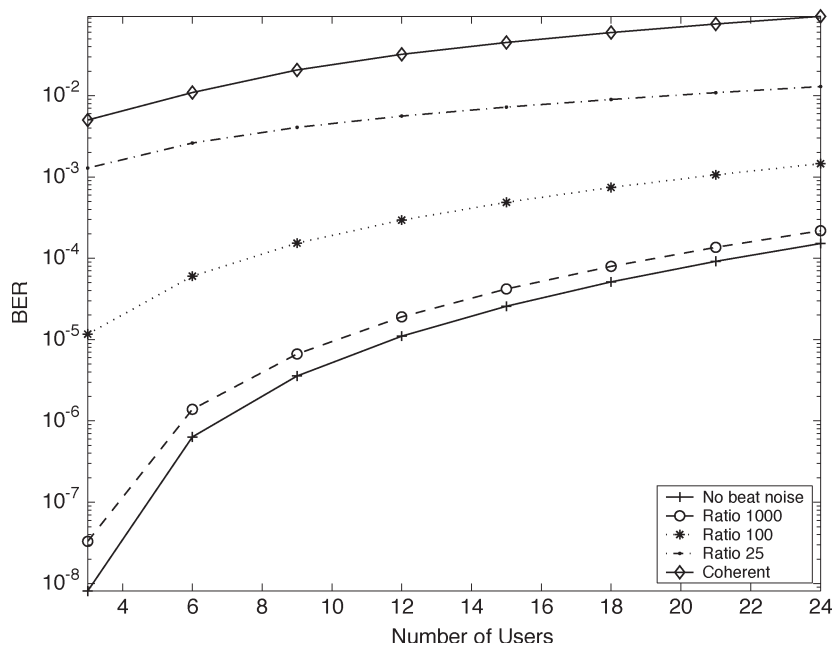


Fig. 3. Effect of the bandwidth ratio for an OOC channel. A ratio of 1000 is required to make the beat noise power comparable to interference and other noise sources in this example.

A. Simulation Method

In order to make the simulations, we have used a fast-simulation technique similar to the one described by Bian *et al.* [6]. The idea is to condition the simulation of a block on a number of errors in the block, which cannot be corrected by hard decoding. With that number of bit errors, the error probability for soft decoding will also be high enough to reduce the simulation time significantly. For multiuser channels, it is also necessary to take into account that the error probability depends on the interference. To generate an erroneous bit, we first randomly draw the amount of interference conditioned on a bit error; then the signal sample is generated accordingly. In addition, short codes are used to limit the simulation time. The simulation method that is used is further explained in [18]. It shall be noted that longer error correction codes could decrease the error rate even further. For example, turbo codes or low-density parity-check codes could be used. In fact, there is fast development in FEC hardware implementing different types of codes for optical transmission systems, and bit rates of tens of gigabits per second are achievable with commercial hardware today.

B. Coherent and Incoherent Light Sources

First, we evaluate how the performance depends on the degree of coherence of the signal. For the coherent temporally coded systems, it is assumed that the chips from the same user are added coherently. Hence, there is no beating between them, but light from interfering sources will cause beat noise.

The receiver is assumed to be incoherent since the complexity of a coherent receiver is higher. If a coherent receiver is implemented, it is also possible to use negative pulses by shifting the phase 180°. Therefore, both the interference and the noise could, at least in theory, be significantly reduced compared to the systems in this study [17].

Fig. 3 shows the BER for an OOC channel with code length 1008 and weight 7. The bandwidth ratios reach from 25 to 1000. In addition, a coherent light source is included, as well as the result when beat noise is neglected. From the figure, it can also be concluded that the error probability is substantially underestimated when beat noise is not taken into account. At bandwidth ratios as low as 25, the approximations made for the incoherent case are not very accurate at the tail of the distribution [24]. Actually, by comparing the curve for bandwidth ratio 25 with the other curves, in particular the coherent case where the Gaussian assumption is not used, it seems like the Gaussian assumption overestimates the error rate when there are few users. Note that the error rates in the figure are achieved when the number of active users is known and an optimal threshold is used.

The drawback of a large optical bandwidth is that the spectral efficiency is worse. For example, if OCDMA is used in combination with wavelength-division multiplexing (WDM), the optical bandwidth should not be larger than the distance between the wavelengths. In addition, a large bandwidth can lead to problems with high dispersion [23]. Therefore, the bandwidth ratios in this study are chosen significantly smaller than in the some other studies [9], [22].

C. Coding Gain

To evaluate the coding gain of FEC, systems with equal total bandwidth and equal throughput are compared with respect to the bit error probability. The bandwidth expansion is divided differently between error correction coding and spreading. If it is assumed that the same light source and detector are used, the optical bandwidth and the chip rate are fixed. However, if a shorter OOC is used, the extra bits can then be used for FEC without expanding the bandwidth further.

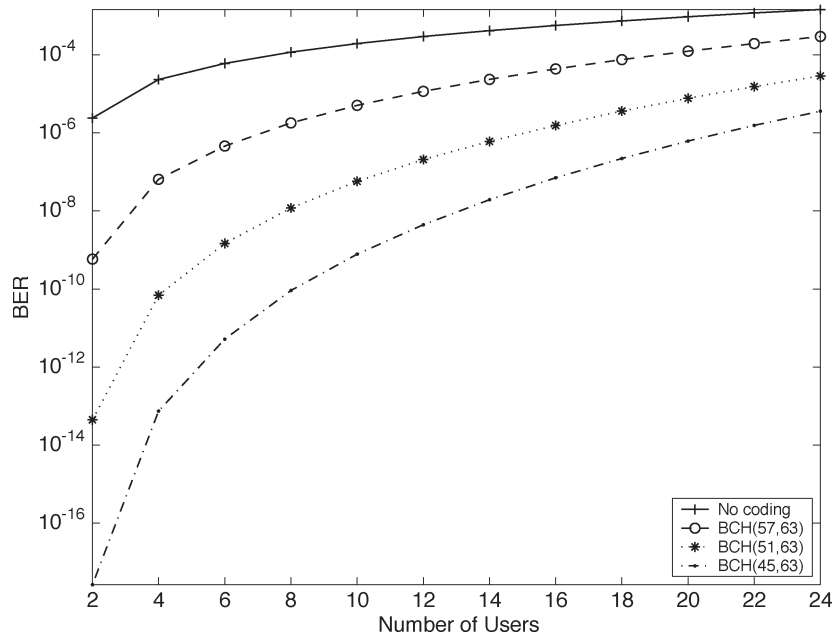


Fig. 4. The performance for equal total bandwidth expansion. FEC is more efficient than spreading.

In the simulations, the bandwidth ratio is 100, the weight is 7, and the code length is 1008 when no FEC is used. When FEC is applied, the length is reduced, for example it is 912 when BCH(63,57) coding is used, which corresponds to an identical total chip rate. Fig. 4 shows that, also in this case, FEC has an advantage. This is quite intuitive, if the length of the code is taken into consideration: the spreading codes can be thought of as a repetition code, which is less efficient than a more advanced channel code. Also, if the electrical bandwidth would be expanded to leave room for FEC, the BER would decrease since the coding gain is more substantial than the increased beat noise.

D. Frequency Spreading Versus Time Spreading

The bandwidth expansion can either be implemented through temporal coding, which is DS-CDMA, or by FH. FH offers an extra dimension in the code design, and can therefore be made more efficient. However, in order to investigate the effect of beat noise, we chose codes that make the performance identical when the beat noise is neglected. Since the frequency bands are assumed to be disjoint, the effect of beat noise is less severe for FH than for temporally coded systems. Fig. 5 shows the BER for OOC channels and FH channels, both when the beat noise is neglected and when it is taken into account. The length of the OOC is 343 and the weight is 7, the weight of the FH code is also, 7, the temporal length is 49, and the number of frequencies is 7; hence, the total code lengths are equivalent.

Another advantage of FH systems, which is not taken into account here, is that the power loss in the spreading and autocorrelation is not as severe as for direct sequencing, since the spectral slicing ensures that all energy in the signal can be used in the receiver as opposed to a power splitter [12]. An advantage for direct sequencing systems is that it is simpler

to expand the bandwidth. When all this is taken into account, together with the implementation possibilities, it is not trivial to make a completely fair comparison between temporal codes and FH. However, our results show clearly that FH systems are less affected by beat noise.

E. Hard Versus Soft Decoding

The gain that soft decoding can provide compared to hard decoding depends on the noise distribution. Therefore, we evaluate the performance of soft decoding for an FH channel with a different complexity of the soft decoding.

For a channel with AWGN, the gain of ideal soft decoding asymptotically approaches 3 dB for high SNR [8]. The Chase algorithm has slightly worse performance than ideal soft decoding and quantization also reduces the efficiency; therefore, a gain of 1.5–2 dB is more realistic.

Fig. 6 shows the BER as a function of the number of users on an OCDMA channel for hard decoding, Chase-2, and Chase-3 decoding, respectively. The temporal length of the FH code is 49 chips, the number of frequencies is 7, the weight is 7, the FEC code is BCH(63,45), and the bandwidth ratio is 100. It can be seen that Chase-3 does not provide much gain over hard decoding, whereas Chase-2 performs substantially better, in particular with fine quantization. The gain from using the different soft decoding methods is similar for the OCDMA channel as for an AWGN channel at similar error rates, and we have also verified that it does not depend notably on parameters such as the bandwidth ratio.

F. System Capacity

To increase the number of users in an OCDMA system, the codes can be shared between several users with reconfigurable encoders and receivers. Multiple-access protocols similar to

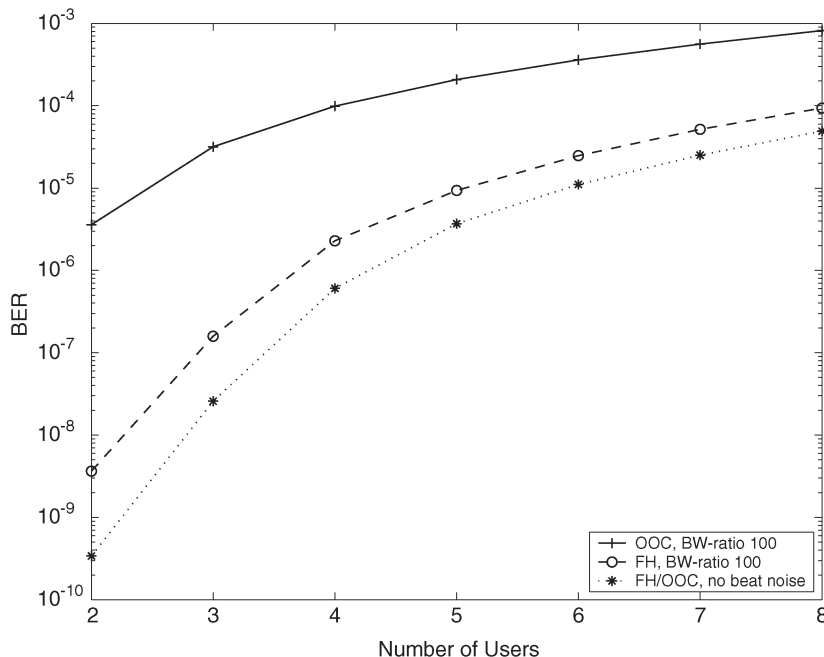


Fig. 5. Performance of temporal coding and FH is identical as long as the beat noise is neglected, but FH is better when beat noise is taken into account.

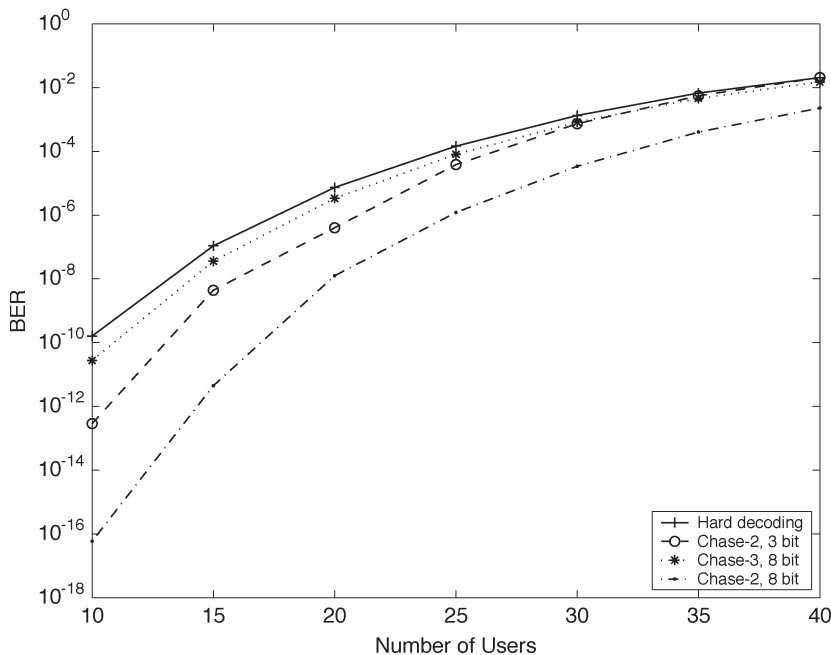


Fig. 6. Simulation results for an FH channel. Soft decoding can decrease the bit error probability substantially, if enough bits are used in the quantization. The more complex method performs better, as expected.

those suggested by Shalaby can be used to provide the necessary mechanisms [26]. Another possibility is that several users are connected to each optical network units (ONU). To illustrate how this can offer connectivity to a higher number of users, we consider the system from the previous simulation, with the results plotted in Fig. 6.

If reconfigurable FBGs are used, as suggested in [12], we can make some simple approximations of how many customers could be supported. We assume that a medium-access protocol is used to make sure that the number of active senders is limited to, for example, 17, which would give a BER of 10^{-9} .

Furthermore, we assume that the average load from each user during the busy hour is 0.2 and that the arrival process is a Poisson process. Note that there is a clear relation between the degree of multiplexing and the generated load from each user; if the codes are configured on a per-session basis, each user will occupy a channel for longer times than if the reconfiguration is made on shorter time scales. A load of 0.2 may be realistic if the configuration is made per session. If the acceptable blocking probability is 1% during the busy hour, the maximum number of users that the system can support is 61 according to the Engset formula.

VI. CONCLUSION

We have investigated passive optical network (PON) based on code-division multiple access (CDMA) and how forward-error correction (FEC) can be used to reduce bit error rate (BER). Since these types of networks have a problem with error floors, FEC is an important component when designing them. The optical code-division multiple access (OCDMA) channels are complex, and therefore offer an important research problem. A fundamental problem with OCDMA is that the noise in an optical receiver increases when the light intensity is increased. This is a consequence of the physical properties of light and will therefore always limit the capacity of an OCDMA system where several signals are superposed.

Most studies of OCDMA use simple channel models where the beat noise is neglected. As our results show, that does not give a good estimation of the performance. The main objective of this study was to study a model where both the limiting factors, beat noise and interference, are taken into account and to find methods to improve the performance. The interference can be reduced by interference cancellation or multiuser detection at the receiver, but the noise will limit the performance once the interference is reduced. Therefore, it does not make sense to use receivers that are too advanced. In order to decrease the error rate without using overly complex equipment, the bandwidth has to be expanded. Our results show that it is beneficial to do that by using error correction codes in addition to spreading codes.

Even though the study provides guidelines on how to reduce the error probability of OCDMA, it cannot be claimed that a sufficient solution has been arrived at to make it ready for deployment with these additions. It is probably necessary to await further developments in optical component technology before the advantages overshadow the problems.

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Henrik Lundqvist (S'03) received the M.Sc. degree from Linköping Institute of Technology, Linköping, Sweden, in 1998. He is currently working toward the Ph.D. degree at the Department of Microelectronics and Information Technology of KTH, Royal Institute of Technology, Kista, Sweden, since October 1999.

He worked at Nokia networks with signal processing for global system for mobile communications (GSM) and universal mobile telecommunications system (UMTS) before joining KTH. His research interests include error-correction coding, optical networks, and quality of service.

Gunnar Karlsson (S'85–M'87–SM'99) received the M.Sc. degree from Chalmers University of Technology, Göteborg, Sweden in 1983 and the Ph.D. degree from Columbia University in 1989, New York, NY.

He has previously worked for IBM Zurich Research Laboratory, Zurich, Switzerland, and for the Swedish Institute of Computer Science (SICS), Kista, Sweden. Since March 1998, he has been a Professor at the Department of Microelectronics and Information Technology of KTH, Royal Institute of Technology, Kista, Sweden. He has been Visiting Professor at the Swiss Federal Institute of Technology (EPFL), Lausanne, Switzerland, and at the Helsinki University of Technology in Helsinki, Finland. His research interests lie within the general field of multimedia networking.