New Combinatorial BER Bounds for Families of (0,1)–Matrix Codes

Enrico Jugl and Kay Iversen*

Technische Universität Ilmenau, P.O. Box 100565, D–98684 Ilmenau/Germany,
*Heinrich–Hertz–Institut für Nachrichtentechnik Berlin GmbH, Einsteinufer 37, D–10587 Berlin/Germany

Abstract— **In this paper we present new combinatorial bounds on the bit error ratio (BER) for families of (0,1)–matrix codes applied in hybrid wavelength/code–division multiple–access (WDMA/CDMA) systems. Such systems combine the advantages of WDMA and pure incoherent CDMA, ensuring nearly orthogonal transmission and large numbers of subscribers. A new family of time spreading/wavelength hopping codes is introduced and a comparison of the derived combinatorial BER bounds with numerical results for systems without and with hard–limiter is given.**

I. Introduction

During the past years the optical fiber has established as medium for high–speed point–to–point data transmission in long–haul networks. However, a different situation exists for the deployment of multipoint–to–multipoint local area networks (LAN), where the choice of a proper access technique to share the large bandwidth among the subscribers is significant. It is clear that the higher the required bit rates will be, the more important becomes the fact, that the transmission technology must merge with the switching technique. Fundamentally, there exist three techniques to ensure the mutual access of the subscribers: time–division multiple–access (TDMA), wavelength–division multiple–access (WDMA) and code–division multiple–access (CDMA). Optical TDMA needs considerable effort for synchronization and switching. Therefore implementation in LAN might be complicated. WDMA allows asynchronous orthogonal transmission, but actually with this method the number of wavelengths and consequently the number of available subscribers is limited due to technological constraints [1]. Optical CDMA [2],[3] is considered as an alternative access technique, but unfortunately, the system performance is degraded by multi–user interferences (MUI). Therefore, besides pure WDMA and CDMA especially hybrid techniques are subject of recent investigations, since in hybrid WDMA/CDMA systems the advantages of both schemes can be combined. Hence, comprehensive networks with nearly perfect orthogonal transmission can be expected. Moreover, since only a few wide–spaced wavelengths are needed, no costly wavelength stabilization is required. Generally, the serial or the parallel combination of time and wavelength coding is possible. In [4] we have analyzed a serial coding type, which combines incoherent CDMA with D–ary FSK signaling. The potential of parallel techniques based on code matrices was first shown by Tančevski [5], [6], [7], Mendez [8], and Yang [9], but until now there is a lack of BER bounds allowing easy calculation of the system performance.

In this paper we present some new combinatorial BER bounds for (0,1)–matrix codes. The performance is calculated without and with hard–limiter. During all investigations we take into account that by use of forward error correction (FEC, e. g. with Reed Solomon codes) the required BER of $\leq 10^{-9}$ is achieved if the channel BER is lower than 10^{-3} [10]. In this case the sequences are only used for the purpose of addressing but not to achieve the required BER. Moreover, simple implementation of FEC is possible by means of electrical FEC devices.

II. System and Signals

The principle of a transmitter/receiver pair is shown in fig. 1. To each subscriber a (0,1)–matrix code is assigned. Each code word $c_i(k,l)$, $0 \leq i \leq M-1$, of a family of M distinct code words consists of a $m \times n$ matrix (m rows = number of wavelengths λ; n columns = number of chips) with K ones – the code weight – placed at different positions ($0 \leq k \leq m-1$, $0 \leq l \leq n-1$). Matrices which have at most one dot per row are called *single pulse per row* (SPR) codes. The available data rate for each user yields

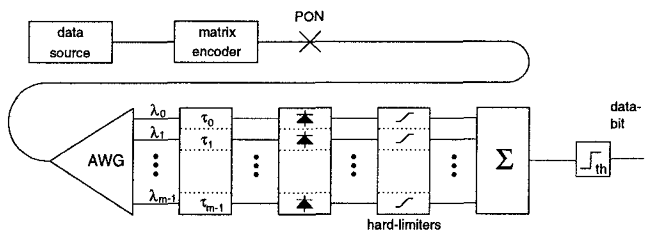

Fig. 1. System setup, PON – passive optical network, AWG – arrayed waveguide, th – threshold, λ – wavelength

$r_D = 1/(nT_{chip})$, where T_{chip} is the chip duration. The realization of the encoder is possible by a tunable laser or a laser array. The matched filter at the receiver is realized by an optical filter bank (e. g. arrayed waveguide, AWG) combined with optical delay lines, $\tau_0, \tau_1, \ldots, \tau_{m-1}$. In case of SPR matrices only a single delay line for each wavelength is necessary. To allow inexpensive implementation of the receiver front end, we suggest the use of SPR matrices. An additional improvement of the correlation properties is given by using hard–limiters which can be implemented easily in the electrical domain [11]. After decoding, a threshold device detects, if a data bit $d_i = 0$ or $d_i = 1$ was transmitted.

The correlation properties between two matrices i and j are defined by the following two–dimensional aperiodic correlation function based on the ambiguity function $\xi_{ji}(\tau)$ without any frequency shift

$$\xi_{ji}(\tau) = \begin{cases} \sum\limits_{k=0}^{m-1} \sum\limits_{l=0}^{n-1-\tau} c_j(k,l)c_i(k,l+\tau), & \tau \geq 0 \\ \sum\limits_{k=0}^{m-1} \sum\limits_{l=0}^{n-1-|\tau|} c_j(k,l+|\tau|)c_i(k,l), & \tau < 0 \end{cases} .$$

The maximum side–lobe of the aperiodic auto–correlation function (ACF) θ_a and maximum value of the aperiodic cross–correlation function (CCF) θ_c are given by

$$\theta_a = \max\{|\xi_{ii}(\tau)|\} , \quad \begin{cases} 0 \le i \le M-1 \\ 1 \le \tau \le n-1 \end{cases}$$

$$\theta_c = \max\{|\xi_{ji}(\tau)|\} , \quad \begin{cases} 0 \le i,j \le M-1, i \ne j \\ 1-n \le \tau \le n-1 \end{cases} .$$

Concerning the periodic correlation functions these correlation values might be increased by superposition and are denoted as $\tilde{\theta}_a$ and $\tilde{\theta}_c$, respectively. In the following the families of (0,1)–matrix codes are characterized by the quintuple $(M, m \times n, K, \theta_a, \theta_c)$.

III. Overview of Matrix Codes

In the following a brief introduction into a selected number of matrix codes is given. Prime–hop codes [5] and extended quadratic congruence/prime (eqc/prime) codes [7] have been proposed by Tančevski and Andonovič. Prime–hop codes employ well–known unidimensional prime sequences for both, time spreading and wavelength hopping. In contrast, eqc/prime codes use unidimensional eqc–sequences for the time–spreading pattern. In both cases, there exist a symmetric and an asymmetric construction method [6], [7] (cf. table I). In case of eqc/prime codes shifted versions of the code patterns (cyclic shifts of the wavelengths) can be used leading to a large number of available addresses. Another class of (0,1)–matrices which is based on optical orthogonal codes (OOC) was proposed in 1996 by Yang and Kwong [9], [12]. Different methods for algebraical construction of such multi–wavelength optical orthogonal codes (MWOOC) were investigated, preserving the code weight, the family size and the correlation values of the basic OOC–sequences. Recently we have proposed a more general algorithm for construction of SPR matrix codes, the so–called *unique distance codes* (UDC) [13]. The construction method is based on the Greedy algorithm allowing any desired matrix dimension and code weight. Quadratic code matrices, like Costas arrays [14], with a code weight equal to the number of available wavelengths show poor correlation properties and therefore these families are not further investigated. A summary of typical parameters of some code matrices is depicted in table I.

IV. Introduction of OOC/Prime Codes

In [7] it was shown, that a combination of (0,1)–sequences with good auto– and cross–correlation properties and prime codes for wavelength hopping leads to code matrices with a large family size and excellent correlation properties. Based on this idea we propose a hybrid code based on OOC for time spreading and prime codes for wavelength hopping. For the time spreading pattern the use of OOC with any desired code weight K and sequence length N is possible. However, to achieve a large number of addresses the code weight K should be chosen small (e. g. $K = 3$), corresponding to the Johnson bound [15]. The sequence length N determines also the time spreading factor n of the code matrix, $n = N$. In the following an OOC–sequence i is distinguished by a position block $B_i = \{b_{i,j}\}$, where $b_{i,j}$ denotes the position of a pulse with

$$B_i = \{b_{i,0}, b_{i,1}, \ldots, b_{i,j}, \ldots, b_{i,K-1}\},$$
$$0 \le b_{i,j} \le N-1, 0 \le j \le K-1, 0 \le i \le M_{OOC}-1 ,$$

where M_{OOC} is the family size. The number of wavelengths m has to be a prime number p_h and should be equal or higher than the weight of the basic OOC–sequence to guarantee SPR matrices. The wavelength hopping patterns H_q are calculated as follows

$$H_q = [qj + z]_{p_h} , \quad 1 \le q \le p_h - 1, \ 0 \le j \le K-1 ,$$

where j passes through the number of pulses of the OOC–sequence, the term z, $0 \le z \le p_h - 1$, denotes a cyclic shift and the operator $[\cdot]_{p_h}$ means modulo p_h calculation. The wavelength hopping pattern H_0 allocates the same wavelength for each pulse and is discarded. For $q \in \{1, 2, \ldots, p_h - 1\}$ every wavelength occurs only once in a hopping pattern. Consequently, there exist $p_h \cdot (p_h - 1)$ hopping patterns and M_{OOC} spreading patterns. This leads to a family size of $M_{cyc} = M_{OOC} \cdot p_h \cdot (p_h - 1)$, disregarding the cyclic shifts to $M = M_{OOC} \cdot (p_h - 1)$. The ACF of the proposed matrix code family has a maximum at zero time shift and is equal to zero otherwise. To specify the cross–correlation properties the following three cases have to be considered. First, the matrices employ the same position block but different hopping patterns. Second, there exists the same hopping pattern but different position blocks and third, different hopping patterns and different position blocks are available. All three cases show that the CCF is bounded by $\tilde{\theta}_c = 1$.

V. Combinatorial BER Bounds – Receiver without Hard–Limiter

In the following some combinatorial BER analyzes will be given leading to upper bounds. Knowing the average probability $\Pr_I$ for occurrence of a cross–correlation value equal to one by considering the four possible data transitions $0 \to 0$, $0 \to 1$, $1 \to 0$, $1 \to 1$ (corresponding to aperiodic CCF), the BER can be calculated for L active users by

$$\Pr_B \le \frac{1}{2} \sum_{i=K}^{L-1} \binom{L-1}{i} \Pr_I^i \left(1 - \Pr_I\right)^{L-1-i} . \quad (1)$$

An error occurs if the intended user transmits a data bit $d_i = 0$ and $i \ge K$ interfering users are active. The value 1/2 is the probability that the intended user is transmitting a data bit $d_i = 0$.

A. Multi–wavelength optical orthogonal codes (MWOOC)

In [12] a bound was specified for a particular type of MWOOC which is $\Pr_I \approx K^2/(2n^2)$.

B. Symmetric prime–hop codes

The total length of the cross–correlation functions of four data transitions as shown in the previous case yields $4 \cdot 2p_h^2$. Therefore $4p_h$ hits come into existence, and so the bound for the bit error probability yields

$$\Pr_B \le \frac{1}{2} \sum_{i=K}^{L-1} \binom{L-1}{i} \left(\frac{1}{2p_h}\right)^i \left(1 - \frac{1}{2p_h}\right)^{L-1-i} . \quad (2)$$

family	aperiodic		periodic		code weight	spreading length	wavelengths	family size
	ACF	CCF	ACF	CCF				
MWOOC [1]	1	1	1	1	K	n	m	$\frac{nm-1}{K(K-1)}$
symmetric prime-hop	0	1	0	1	p_h	p_h^2	p_h	$p_h(p_h-1)$
asymmetric prime-hop	0	2	0	2	p_s	p_s^2	p_h	$p_s(p_h-1)$
symmetric eqc/prime	0	2	0	2	p_h	$p_h(2p_h-1)$	p_h	$p_h(p_h-1)^2$
asymmetric eqc/prime	0	2	0	2	p_s	$p_s(2p_s-1)$	p_h	$p_h(p_h-1)(p_s-1)$
OOC/prime	0	1	0	1	K	n	p_h	$\frac{np_h-1}{K(K-1)}(p_h-1)$
cyclic OOC/prime	0	1	0	1	K	n	p_h	$\frac{np_h-1}{K(K-1)}p_h(p_h-1)$
UDC [2]	0	1	0	2	K	n	m	M

[1] if only SPR matrices are applied, the family size is reduced
[2] $\tilde{\theta}_c = 1$ is also possible, but the family size which results from the construction algorithm is reduced

TABLE I
SUMMARY OF TYPICAL PARAMETERS OF DIFFERENT MATRIX CODES

C. OOC/prime codes without cyclic shifts

Considering the aperiodic CCF between all matrices it can be found, that wavelength λ_0 contains always one hit. Thus, the probability for occurrence of a cross–correlation value equal to one at this wavelength λ_0 is

$$\mathrm{Pr}_0 = \frac{M^2 - M}{2n(M^2 - M)} = \frac{1}{2n} \, . \tag{3}$$

Only $M \cdot \frac{K-1}{p_h-1}$ code matrices generate one hit at each of the other wavelengths. Therefore, this probability is given by

$$\mathrm{Pr}_{m-1} = \frac{K-1}{p_h-1} \cdot \frac{M(K-1)/(p_h-1) - 1}{2n(M-1)} \, . \tag{4}$$

In summary the combinatorial BER bound amounts to

$$\begin{aligned} \mathrm{Pr}_B \;&\leq\; \frac{1}{2}\sum_{i=K}^{L-1}\binom{L-1}{i}\left[\mathrm{Pr}_0 + (p_h-1)\mathrm{Pr}_{m-1}\right]^i \\ &\cdot \left[1 - \mathrm{Pr}_0 - (p_h-1)\mathrm{Pr}_{m-1}\right]^{L-1-i} \, . \end{aligned} \tag{5}$$

D. OOC/prime codes with cyclic shifts

In this case the family size is increased and leads to $M_{cyc} = p_h \cdot M$. Only $M + (M_{cyc} - M) \cdot \frac{K-1}{p_h-1}$ matrices generate a hit at a single wavelength. Therefore, after performing some algebraical simplifications the probability for a hit at a single wavelength is given by

$$\mathrm{Pr}_m = \frac{K(M \cdot K - 1)}{2np_h(M_{cyc} - 1)} \, . \tag{6}$$

The combinatorial BER bound can be calculated as

$$\mathrm{Pr}_B \leq \frac{1}{2}\sum_{i=K}^{L-1}\binom{L-1}{i}(p_h\mathrm{Pr}_m)^i\,(1 - p_h\mathrm{Pr}_m)^{L-1-i} \, . \tag{7}$$

E. Eqc/prime codes

Here, in contrast to the considered code matrices, periodic cross–correlation values of at most $\tilde{\theta}_c = 2$ exist. Thus, the calculation method from (1) cannot be applied. The exact probability for occurrence of $\tilde{\theta}_c = 2$ is hard to determine. Therefore, an approximation is performed. Regarding the complete code family there exist $\binom{p_h}{2}$ possibilities to have coincidences of two wavelengths. Per possibility, a_2 coincidences occur. Consequently, the probability for occurrence of $\tilde{\theta}_c = 2$ yields to

$$\mathrm{Pr}_{I2} = \binom{p_h}{2} \cdot \mathrm{Pr}_2 = \binom{p_h}{2} \cdot \frac{a_2}{2nM(M-1)} \, , \tag{8}$$

where Pr_2 is assumed to be the probability for a single possibility to have two coincident wavelengths. The probability for a cross–correlation value equal to one can be calculated as follows

$$\mathrm{Pr}_{I1} = p_h \cdot \mathrm{Pr}_1 = p_h \cdot \frac{\left(M\frac{p_s}{p_h}\right)^2 - M\frac{p_s}{p_h} - \binom{p_h}{2}\frac{2a_2}{p_h}}{2nM(M-1)} \, , \tag{9}$$

where Pr_1 is the probability for a cross–correlation value equal to one per wavelength. The value $a_2 = g_1 + g_2$ can be calculated using the following approximations

$$\begin{aligned} g_1 &= 2p_s^2 - 6p_s + 4 + 8\sum_{i=1}^{\frac{p_s-3}{2}}\left[(p_s - 2i)^2 - (p_s - 2i)\right] \\ g_2 &= (p_s-3)(p_s-1)\left[p_s - 1 + (p_s-4)^2\right] \, . \end{aligned}$$

Since there exist cross–correlation values of $\tilde{\theta}_c = 2$, an error occurs if $l = \lceil \frac{K}{2} \rceil$ disturbing users are active, where $K = p_s$ and $\lceil\cdot\rceil$ means rounding up to the nearest integer. With these assumptions the bit error probability amounts to

$$\begin{aligned} \mathrm{Pr}_B \;&\leq\; \frac{1}{2}\sum_{i=l}^{L-1}\binom{L-1}{i}\sum_{j=0}^{i}\Big[\binom{i}{j}\mathrm{Pr}_{I1}^j\mathrm{Pr}_{I2}^{i-j}(1 - \mathrm{Pr}_{I1} \\ &-\mathrm{Pr}_{I2})^{L-1-i} \mid j + 2(i-j) \geq K\Big] \, . \end{aligned} \tag{10}$$

All different possibilities, how the cross–correlation values equal to one and two can be superimposed, are taken into account by summation over j. If condition $j + 2(i-j) \geq K$ is fulfilled, a contribution to the error probability is provided.

VI. Combinatorial BER Bounds – Receiver with Hard–Limiter

The hard–limiter cuts off the amplitudes per wavelength to "1". The normalized output amplitude y_{HL} is given by

$$y_{HL}(x) = \begin{cases} x & \text{for} \quad x \le 1 \\ 1 & \text{for} \quad x > 1 \end{cases} .$$

If L users are active simultaneously, bounds on the performance can be calculated using the following equation

$$\Pr_B \le \frac{1}{2} \sum_{i=K}^{L-1} \Pr(i) \Pr_{EE} = \sum_{i=K}^{L-1} \binom{L-1}{i} \left(\frac{1}{2}\right)^L \Pr_{EE} . \quad (11)$$

$\Pr(i)$ gives the probability that i interfering users transmit a data bit $d_i = 1$ simultaneously. The factor $1/2$ is the probability that the intended user transmits a data bit $d_i = 0$ (corresponding to uniformly distributed data bits). The term $\Pr_{EE}$ denotes the probability for an error event depending on the code family. An error is detected if K pulses of value "1" (only one pulse per wavelength) overlap at the sampling time, knowing that i jamming users transmit a data bit $d_i = 1$ (corresponding to periodic CCF).

A. *Symmetric prime–hop codes*

An error occurs if each wavelength gets exactly one cross–correlation value equal to one at the sampling time. Choosing K interfering users from i jamming users and considering all possibilities for disposition of these K pulses over the available wavelengths (permutations), the combinatorial BER bound is given by

$$\Pr_B \le \sum_{i=K}^{L-1} \binom{L-1}{i} \left(\frac{1}{2}\right)^L \binom{i}{K} K! \left(\frac{1}{p_h^2}\right)^K , \quad (12)$$

where $1/p_h^2$ is the probability for occurrence of a cross–correlation value equal to one at a single wavelength.

B. *OOC/prime codes without cyclic shifts*

The strategy is the same as in the case of symmetric prime–hop codes. However, only the probabilities for occurrence of cross–correlation values equal to one from (3) and (4) are used. Thus, the BER bound amounts to

$$\Pr_B \le \sum_{i=K}^{L-1} \binom{L-1}{i} \left(\frac{1}{2}\right)^L \binom{i}{K} K! (2\Pr_0) \left(2\Pr_{m-1}\right)^{K-1} . \quad (13)$$

C. *OOC/prime codes with cyclic shifts*

Here, also the same strategy is employed. Using (6) the bit error probability reaches

$$\Pr_B \le \sum_{i=K}^{L-1} \binom{L-1}{i} \left(\frac{1}{2}\right)^L \binom{i}{K} K! \left(2\Pr_m\right)^K . \quad (14)$$

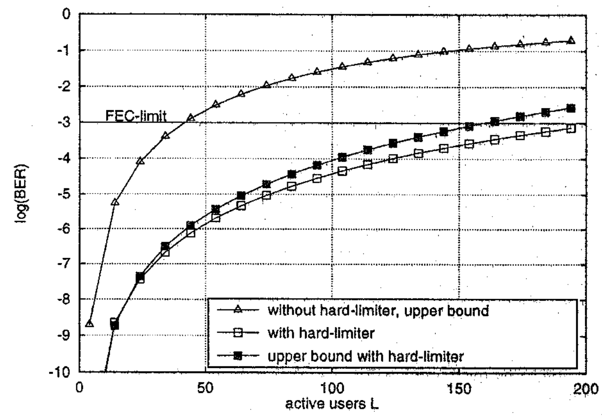

Fig. 2. Comparison of numerical results with combinatorial BER bounds using a $(624, 13 \times 45, 5, 0, 2)$–eqc/prime code

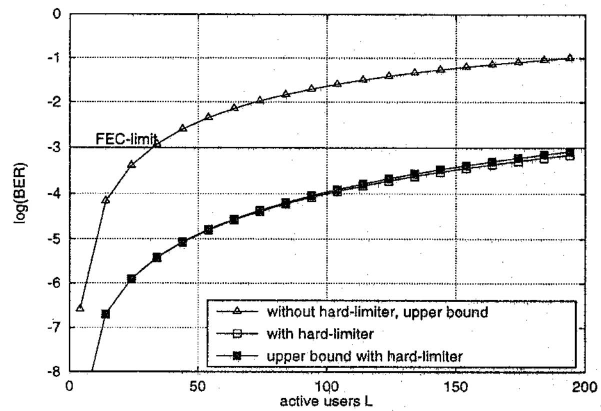

Fig. 3. Comparison of numerical results with combinatorial BER bounds using a $(1092, 13 \times 43, 3, 0, 1)$–OOC/prime code (cyclic)

D. *Eqc/prime codes*

In contrast to the calculations above, the index i in (11) is running from $l = \lceil \frac{K}{2} \rceil$. Here, several error events must be considered, because there are two different cross–correlation amplitudes. This will be taken into account by summation over j and z. Finally, the combinatorial BER bound using $\Pr_1$ as well as $\Pr_2$ from (9) and (8) is obtained as

$$\begin{aligned} \Pr_B \quad \le \quad & \sum_{i=l}^{L-1} \binom{L-1}{i} \left(\frac{1}{2}\right)^L \sum_{j=l}^{K} \binom{i}{j} j! \sum_{z=0}^{j} \Big[(2\Pr_1)^z \\ & \cdot (2\Pr_2)^{j-z} \mid z + 2(j-z) \ge K \Big] . \end{aligned} \quad (15)$$

VII. Evaluation of the Bounds

In the following the BER bounds are evaluated neglecting all noise impacts. Without hard–limiter the simultaneous transmission of all M users at a BER $\le 10^{-3}$ is not possible. The BER improvement using hard–limiters is obviously. In figs. 2 and 3 matrix code families with the same number of wavelengths ($m = 13$) and about the same number of chips ($n \approx 45$) are employed. Considering the cyclic shifted OOC/prime codes and the eqc/prime codes, nearly 200 users can be active at a BER lower than 10^{-3}. However, the proposed OOC/prime codes dispose of a higher family

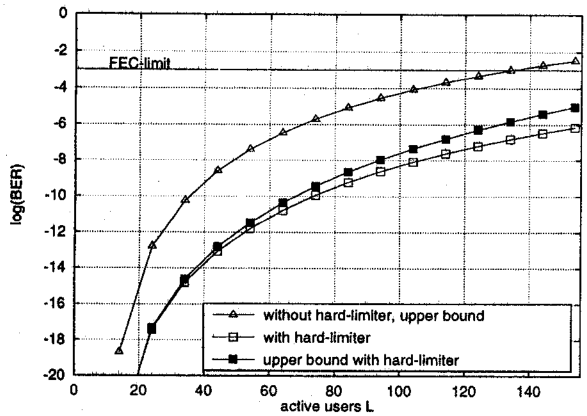

Fig. 4. Comparison of numerical results with combinatorial BER bounds using a $(156, 13 \times 169, 13, 0, 1)$–prime–hop code

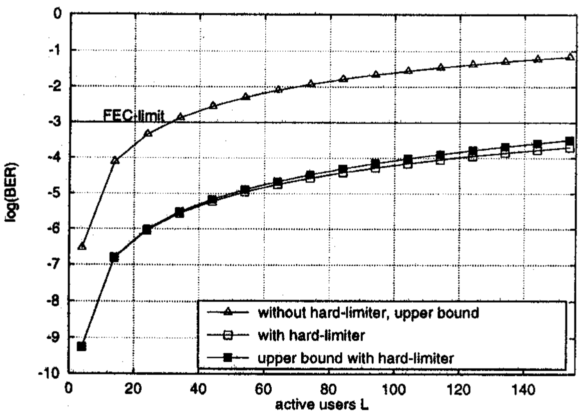

Fig. 5. Comparison of numerical results with combinatorial BER bounds using a $(156, 13 \times 79, 3, 0, 1)$–OOC/prime code

size (1092 possible addresses). In figs. 4 and 5 matrix code families with the same number of wavelengths ($m = 13$) and the same number of addresses ($M = 156$) are chosen. Due to the higher code weight of the prime–hop code the performance is better than using the OOC/prime code. However, employing OOC/prime codes the data rate can be redoubled ensuring the required BER of 10^{-9} (using FEC). Without hard–limiter the bounds from (2), (5), (7) and (10) are conform with the numerical results. With hard–limiter the calculated approximations from (12), (13), (14) and (15) are upper bounds. Especially for a larger number of active users they show higher differences compared to the numerical calculation, but they represent a good approximation.

VIII. Conclusions

In this paper we have presented for the first time some new combinatorial BER bounds using (0,1)–matrix codes in incoherent fiber–optic CDMA systems. Furthermore, a new code family which achieves an auto–correlation function with zero side–lobes and a periodic cross–correlation function of at most $\tilde{\theta}_c = 1$ was introduced. Applying hard–limiters the system performance can be increased significantly. The higher the number of wavelengths and the code weight will be, the better becomes the performance. Keeping in mind, that we only need a BER of about 10^{-3} to guarantee the demanded BER of 10^{-9} by using electrical FEC devices, the code weight can be chosen smaller leading to an increased family size. Considering the introduced OOC/prime code family and identical matrix dimensions ($m \times n$), the number of available network addresses can be increased substantially, in contrast to prime–hop codes and eqc/prime codes. Consequently it can be stated, that in hybrid WDMA/CDMA systems using a few wavelengths and electrical FEC devices, spreading lengths lower than the family size ($n \ll M$) can be achieved.

IX. Acknowledgments

The authors would like to thank Prof. D. Kreß and T. Kuhwald for many valuable discussions. This work was supported by the German Federal Ministry of Education, Science, Research, and Technology (BMBF) and the country of Berlin.

References

[1] D.J.G. Mestdagh, "Fundamental of Multiaccess optical Fiber Networks," *Artech House*, London/Boston, 1995.

[2] Iversen, K.,Mückenheim, J.,Hampicke, D.: "Theory of Fiber-Optic CDMA", *Proc. of the Fifth Communication Theory Mini-Conference (CTMC'96)*, in conjunction with IEEE GLOBE-COM'96, pp. 101–105, London, November 1996.

[3] Iversen, K.: "Comparison and Classification of All-Optical CDMA for Tera-Bit Networks", *International Conference on Integrated Optics and Fibre Communication, IOOC '95*, Hong Kong, Technical Digest, vol. 2, pp. 96–97, June 1995.

[4] Iversen, K.,Jugl, E., Kuhwald, T., Mückenheim, J.,Wolf, M.: "M-ary FSK Signalling for Incoherent All-Optical CDMA Networks", *Proc. IEEE GLOBECOM'96*, vol. 3, pp. 1920–1924, London, November 1996.

[5] Tančevski, L.,Andonovič, I.: "Wavelength Hopping / Time Spreading Code Division Multiple Access Systems", *IEE Electron. Lett.*, vol. 30, no. 17, pp. 1388–1390, August 1994.

[6] Tančevski, L., Andonovič, I.: "Incoherent Optical Code Division Multiple Access Systems", *Proc. IEEE Fourth ISSSTA'96*, vol. 1/3, pp. 424–430, September 22–25, 1996.

[7] Tančevski, L., Andonovič, I., Tur, M., Budin, J.: "Massive Optical LAN's Using Wavelength Hopping/Time Spreading with Increased Security", *IEEE Photon. Technol. Lett.*, vol. 8, no. 7, pp. 935–937, 1996.

[8] Mendez, A.J. and Gagliardi, R.M.: "Analysis, design, and measurement of bandwidth efficient matrix codes for ultradense, gigabit optical CDMA networks", *IEEE/LEOS Annual Meeting*, San Jose, CA", pp. 405–406, November 1993.

[9] Yang, G.-C., Kwong, W.C.: "Two-Dimensional Spatial Signature Patterns", *IEEE Trans. Commun.*, vol. 44, no. 2, pp. 184–191, February 1996.

[10] Mark R. Dale, Robert M. Gagliardi, "Channel Coding for Asynchronous Fiberoptic CDMA Communications," *IEEE Trans. Commun.*, vol. 43, no. 9, pp. 2485–2492, September 1995.

[11] Iversen, K., Hampicke, D., Mückenheim, J.: "Feasibility of incoherent all-optical CDMA with 165 subscribers all active at data rates of 155 Mbit/s", *European Conference on Networks and Optical Communications (NOC'96)*, vol. 3, pp. 109–116, Heidelberg, June 1996.

[12] Yang, G.-C., Kwong, W.C.: "Multi-Wavelength Optical Orthogonal Codes", *Proc. 29th Annual Conference on Information Sciences and Systems*, John Hopkins University, Baltimore, pp. 392-395, March 1995.

[13] Jugl, E., Kuhwald, T., Iversen, K.: "Algorithm for Construction of (0,1)-Matrix Codes", *IEE Electron. Lett.*, vol. 33, no. 3, pp. 227–229, January 1997.

[14] Golomb, S.W., Taylor, H.: "Constructions and Properties of Costas Arrays", *Proc. of the IEEE*, vol. 72, No. 9, pp. 1143–1163, September 1984.

[15] Chung, F.R.K., Salehi, J.A., Wei, V. K.: "Optical Orthogonal Codes : Design, Analysis and Applications," *IEEE Trans. Inform. Theory*, vol. 35, pp. 595–604, May 1989.