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Increasing transmission efficiency with advanced signal processing

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Abstract. Optical CDMA is an advanced and flexible communication technology with a potential to offer very energy efficient and highly scalable networking. In addition it can also deliver increased physical layer privacy and on-demand bandwidth sharing management. We have developed, extensively investigated, and experimentally demonstrated highly scalable approach to incoherent OCDMA which can very efficiently increase the number of simultaneous users. In addition, the introduction of an advanced photonic signal processing results in an overall system power budget improvement by nearly 3dB. Error-free operation with the BER less than 10^{-12} was achieved. We have also shown that with demonstrated approach we can dramatically improve number of simultaneous network users (up to ten times) while keeping the related hardware count unchanged. By comparing this results to DWDM concept, this substantial increase in number of simultaneous users did *not* require to add any additional wavelength laser sources and was achieved by employing just *three* communication wavelengths.

Key words

Optical CDMA, DWDM, network scalability, all-optical signal processing, energy efficiency.

1. Introduction

Today widely used Dense Wavelength Division Multiple Access (DWDM) in data and telecom networks offers many advantages. However, in DWDM systems the number of network users is govern by the number of wavelength channels available and therefore must be supported by the equal number of wavelength sources. The effect is called hard limit on the number of simultaneous users.

Code Division Multiple Access (CDMA) is another approach to data transmission which is widely used in the mobile networks world wide, including the USA. Its optical version Optical CDMA (OCDMA) has been intensively studied since the mid-1980s. Until recently, the interest into practical application of Optical CDMA has been limited primarily due to the unavailability of cheep complex photonic components and a lack of adequate optical technologies. However, recent improvements in fiber optic and photonic technologies substantially helped to advance the OCDMA practicality.

In our incoherent approach to OCDMA we have developed advanced and highly flexible scheme which offers superior scalability, suppresses Multi Access Interference (MAI) while at the same time improves the overall system power budget and therefore is more energy efficient. We demonstrated by simulations and experimentally that introduction of advanced photonic signal processing in conjunction with a proper OCDMA code selection will dramatically improve overall system performance, will help to increase number of simultaneous users while on other hand keeps the original hardware count unchanged, thus delivering energy more efficient approach to data transmission. OCDMA soft blocking capabilities also offer several advantages over traditional approaches - for example used by DWDM or OTDM - which they both suffer from hard blocking limitations.

2. Improving Coding Efficiency

In the search for advanced coding schemes, Tancevski and Andonovic introduced the prime-hop code [1]-[2] having every pulse of every binary code sequence of the original prime code encoded at a distinct wavelength. This resulted in a class of two-dimensional (2-D) optical orthogonal codes with zero autocorrelation side lobes and at most one cross-correlation function. Thus for a given prime number p, p different wavelengths are used providing a factor of p more code sequences than the original prime code. However the prime-hop codes cardinality has been still limited and not flexible enough if compared to the family of carrier-hopping prime codes [3].

The performance of an OCDMA system based on the (LxN, w, 0, 1) carrier-hopping prime code (L is the number of wavelengths, N is the number of chips, and w is the code weight) can be easily calculated. The probability q to overlap one of the pulses in a signature matrix x with a pulse in another matrix y can be determined by realizing that the carrier-hopping prime

code has at most one pulse per row and column in each matrix and therefore [3]:

$$q = (1/2)\, w^2\, (LN\,x)^{-1} \qquad (1)$$

where the factor 1/2 comes from the assumption of equiprobable transmissions of data bit zero or one. The parameter x is equal to a chip width divided by the bandwidth of the all-optical sampler used by the OCDMA receiver (explain later).

The error probability P_e in such wavelength-time approach to carrier-hopping prime code and additional introduction of hard limiting by the receiver will be then given by the equation:

$$P_e = \frac{1}{2}\sum_{i=0}^{Th}(-1)^i\binom{w}{i}\left(1-\frac{iq}{w}\right)^{K-1} \qquad (2)$$

where T_h denote the decision threshold of the receiver and K the total number of simultaneous users in the system, respectively. (For optimal system operation T_h is usually set to be equal to a code weight w).

As the Equation 2 indicates the error probability improves with an increasing number of wavelengths L and/or with the increasing number of chips N. Because of code properties, the carrier-hopping prime code through the adjustment of the number of wavelengths, or the number of chips, or both, can deliver the targeted BER for the targeted number of simultaneous users K, thus provide flexibility and at the same time very robust system performance with much larger cardinality and the also increased number of simultaneous users. It is also note worthy to mentioned that it can also enhance privacy by a random fashion dynamic code allocation. In addition we found because no sidelobes are present, 2-D carrier-hopping time-spreading prime codes are the preferred choice for the use in applications with a time gated OCDMA receiver design. We have proposed and demonstrated such a receiver and used it also to suppress MAI noise. The implementation of this type of receiver delivers further improvements in a system scalability directly leading to additional increase in number of simultaneous users while maintaining the hardware count at the previous unchanged level.

3. Experimental Results

Based on the above, 2-D (3,11) carrier-hopping time-spreading prime codes (three wavelengths (λ_1, λ_2, λ_3) and 11 chips) were implemented. The number of chips was determined based on a 12.5 GHz photodiode used in the conventional OCDMA receiver. The testbed architecture used was an optical bus running at 1.25Gbit/sec data rate. Wavelengths were obtained by spectral slicing of optical supercontinuum with 200 GHz thin film filters (TFFs) each centered at λ_1 = 1550.12 nm, λ_2 = 1551.72 nm, λ_3 = 1553.33 nm, and λ_4 = 1544.06 nm, respectively. Wavelengths λ_1 through λ_3 were used by OCDMA transmitters to generate 2D-OCDMA carrier-hopping time-spreading prime codes. The wavelength λ_4 was dedicated as a control signal needed to enable to

implement a 2ps-TOAD-based all-optical DeMUX technique [4] which for comparison was used in conjunction with a traditional OCDMA receiver during the later second stages of our investigation. As it is evident from the Fig. 1 such approach was implemented only for the receiver Rx-D. Remaining receivers Rx-A and Rx-B were using a conventional OCDMA detection approach throughout all our investigation.
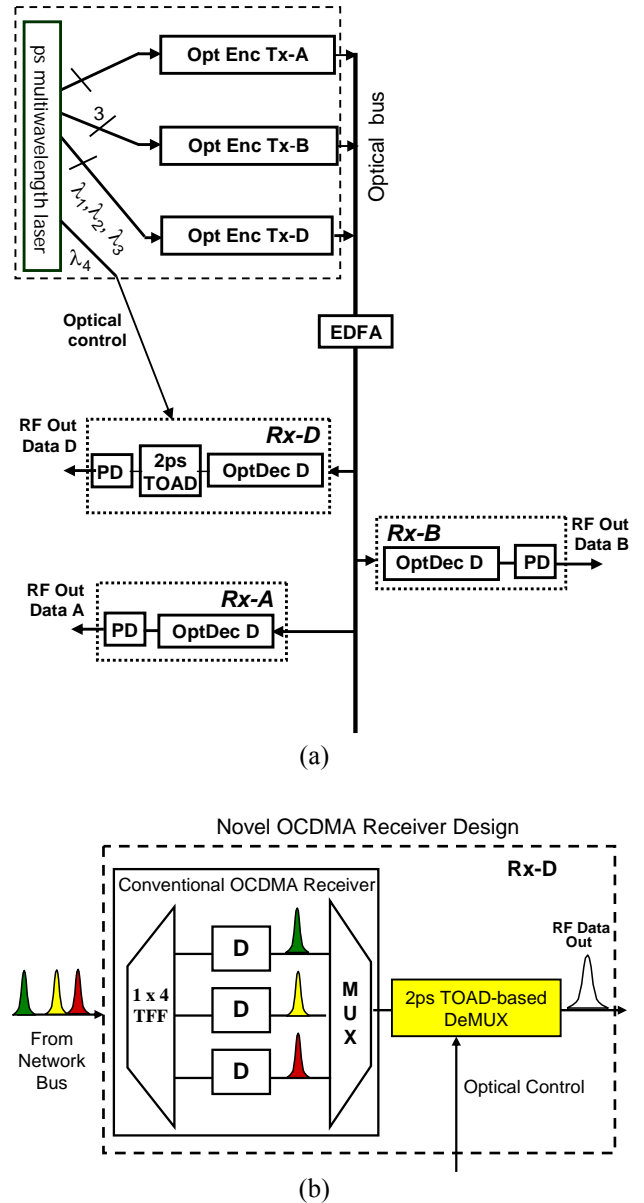

(a)

(b)

Fig. 1a). System network architecture; (b) Schematic diagram of the novel OCDMA receiver.
1 x 4 TFF -thin film filters; D-optical tunable delay line; MUX -optical power multiplexer.

In order to demonstrate that the OCDMA system can benefit from the proposed approach first, a conventional design of an incoherent OCDMA receiver Rx-D was used to decode incoming OCDMA data from the network (see inset of Fig 1b) for more details). In this case the decoded signal (see Fig. 2a) consisted of the correlation peak which corresponds to received data from the transmitter Tx-D plus the MAI noise created by transmitting activities of simultaneous users Tx-A and Tx-B also
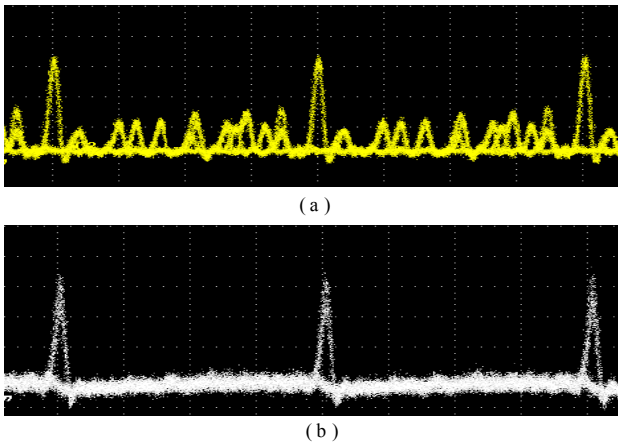
(a)

(b)

Fig. 2a). Output from receiver Rx-D tuned to transmitter Tx-D. Correlation peak (actual data) are surrounded by MAI noise caused by the presence of other transmitters on the network; b) Output from Rx-D equipped with 2ps-TOAD-based all-optical DeMUX. Only signal from transmitter Tx-D is present; MAI noise is effectively suppressed.
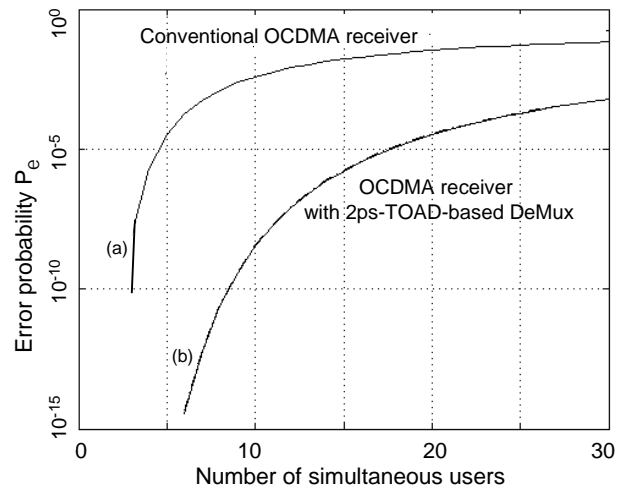

Fig. 3. Simulation results showing an error probability as a function of the number of simultaneous users. Top curve: Incoherent OCDMA receiver Rx-D not equipped with the time gate; bottom curve: Receiver Rx-D with 2ps all-optical time gating capabilities.

present on the network. Later, in the second stage of our investigation, this conventional receiver but now using a 2ps-TOAD-based all-optical DeMUX technique [4] was used to process the same received signal from the transmitter Tx-D (see Fig. 1b) for mare details). This resulted in a complete elimination of MAI noise which can be clearly seen in Fig. 2b) where no MAI is present anymore.

To quantitatively evaluate performance of 1.25Git/s OCDMA system with the conventional or a newly designed receiver deployed, calculations of error probability P_e as a function of number of simultaneous users were performed. Obtained results are shown in Fig. 3. The upper curve (a) is for the conventional OCDMA receiver Rx-D and predicts error-free operation for up to four simultaneous users. In our experiments BER better than 10^{-12} was measured when using a PRBS $2^{31}-1$, no error floor was observed. These calculations also predict, that the error rate will increase with any further increases in number of simultaneous users thus imposing limitations on system scalability.

Curve (b) in Fig. 3 represents calculation results when the same receiver Rx-D but coupled with 2ps-TOAD-based all-optical DeMUX is used. The implementation of such advanced receiver resulted in a significant increase in number of simultaneous users and also delivered quite dramatic BER improvements. The analyses for example indicates:

- If the BER is kept at 10^{-9}, the predicted number of simultaneous users will nearly triple by growing from four to ten (if compared to case (a)).

- In addition, if a Forward Error Correction technique, FEC is used to improve the raw BER from 10^{-4} to a desired level say 10^{-9}, the calculations based on curve (b) predict that up to thirty simultaneous users could operate on the same network thus delivering a ten tenfold increase in number of simultaneous users. Please note only *three* wavelengths (compare to *thirty* needed in a DWDM approach) are required.

The Fig. 4 shows experimental data where, correspondingly, the BER measurements were taken when a conventional OCDMA receiver Rx-D alone was used to process data from transmitter Tx-D (triangles), from Tx-D + Tx-A (squares), and from Tx-D + Tx-A + Tx-B (circles), respectively. The untreated impact of the MAI noise on the receiver performance can be clearly noticed as the power penalty which grows with increasing number of simultaneous users and causes the shift of the BER curve to the right with every additional active user coming on the network. This "forces" transmitter Tx-D to transmit more and more power in order to maintain the same BER performance. This results in power consumption increases and system performance degradation.
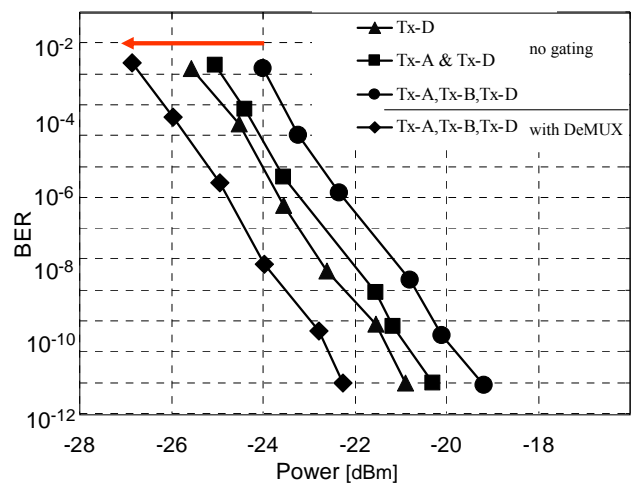

Fig. 4. BER measurements. Rx-D no time gating: Tx-D only (triangles); Tx-A + Tx-B (squares); Tx-A + Tx-B + Tx-D (circles); Rx-D with 2ps-time gate: Rx-A + Tx-B + Tx-D (diamonds).

Now for a comparison, new BER measurements - see Fig. 4 (diamonds), were taken using the same Rx-D receiver but coupled with a 2ps-TOAD-based all-optical DeMUX while keeping transmitters Tx-A, Tx-B, and Tx-

D present on the network. Obtained experimental data confirmed that this new receiver successfully suppresses MAI noise (seen Fig. 2b) and by doing so introduces a *negative* power 'penalty' of approximately -3dB (note the left shift of the BER curve (diamonds) in Fig. 4. This resulted in the overall system budget improvement and secondly, contributed to the already discussed increase of a system scalability.

4. Conclusion

The demonstrated 1.25Gbit/s incoherent CDMA system has superior scalability and a significantly improved power budget.

The increase in the system scalability offers significant improvements in number of simultaneous users and was achieved by elimination of MAI noise by using all-optical signal processing in conjunction with traditional OCDMA receiver.

The theoretical performance analyses of the system with implemented two dimensional frequency-hopping time-spreading incoherent coding scheme was carried out. Two cases were examined. First, with data detection done by a conventional OCDMA receiver and the second, when a 2ps-TOAD-based all-optical demultiplexing technique was implemented in conjunction with the conventional OCDMA receiver. Error-free operation with a BER less than 10^{-12} was demonstrated.

Obtained experimental results show that such an advanced receiver could not only eliminated the MAI noise but at the same time improved overall system power budget by as much as 3dB. The use of this receiver significantly increases number of simultaneous users (by nearly tree times) all without any degradation of BER performance. In addition, if a Forward Error Correction (FEC) technique to improve 10^{-4} raw BER is implemented to achieve targeted level of BER say 10^{-9}, then number of simultaneous user will further increase nearly three times -- from eleven to thirty.

By comparing these results to a DWDM approach, this increase in number of simultaneous users does *not* required any additional wavelength laser sources and could be achieved by using only *three* communication wavelengths.

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