Experimental Analysis of Receiver Performance of Optical CDMA System Using DPSK and OOK Modulation Through Balanced Detection and Optical Thresholding Techniques

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Summary

In this paper, the performance of optical code division multiple access (OCDMA) system is studied using differential phase shift keying (DPSK) with balanced detection (BD) and optical thresholding. For the OCDMA- DPSK receiver, the performance parameters (i) bit error rate (BER), (ii) receiver sensitivity and (iii) spectral efficiency for asynchronous multiple access network are evaluated and compared with on off keying (OOK) modulation. Analysis of the system performance limiting issues such as multiple access interference (MAI) and signal interference beat noise (BN) are carried out and genuine approximation model is derived for the comparison. The optical signal to noise ratio (OSNR) is measured for various lengths of the fiber with dispersion compensated erbium doped fiber amplifier (DC-EDFA). The numerical results shows (i) 3dB receiver sensitivity improvement for BD (ii) better tolerance of 6dB to MAI and BN of DPSK over OOK – OCDMA and (iii) additional system gain and network security through OCDMA encoding / decoding (E/D) technique.

Key words:

Optical code division multiple access (OCDMA), differential phase shift keying (DPSK), balanced detection (BD), multiple access interference (MAI), beat noise (BN), bit error rate (BER), optical signal to noise ratio (OSNR)

1. Introduction

Optical code division multiple access (OCDMA) is much suitable technique for the next generation broadband access networks where number of users are connected through a star coupler in passive optical network(PON) and the users are assigned with different optical code for encoding at the transmitter. Optical orthogonal codes are the techniques used for encoding and decoding as in [1] and [2]. Encoding and decoding schemes for asynchronous OCDMA system with arrayed waveguide grating (AWG) was effectively used in [5] for code-based photonics routers. At the receiver, the decoder recognizes the code via matched filtering or through the detection process to enhance the autocorrelation of the target user and minimizes the cross correlation for the undesired users. Due to the optical domain encoding /decoding process the OCDMA system is suitable for high speed, large capacity supporting different bit rates and enhanced privacy. OCDMA system does not require bandwidth reservation like WDM system and any user at any time can access the network without prior permission in asynchronous operation. Thus the OCDMA system has the advantage of flexibility of user allocation in asynchronous mode and secured transmission with different signature codes. Asynchronous incoherent OCDMA systems should be able to operate in the worst case scenario without any timing coordination. The key challenge in realizing viable OCDMA network lies in overcoming interference from many simultaneous users. Nonlinear optical thresholding is used to suppress the multiple access interferences in asynchronous system through highly nonlinear fiber (HNLF). In [11] a holy fiber based nonlinear thresholding is used to enhance the performance of OCDMA receiver and demonstrated for 255 chip 320 Gchip/s super structured fiber bragg grating (SSFBG). Optical codes provide the large number of codes with desirable cross-correlation characteristics but employing longer length codes are not a viable solution. Time gating and optical thresholding cannot work for truly asynchronous approach which is used in synchronous OCDMA using chip level or slot level timing coordination. Using an encoding/decoding (E/D) technique MAI can be eliminated effectively. In OOK-OCDMA an interference level is studied to be more and also requires high power level to maintain the desired BER for the given number of users with direct detection (power). Even after employing the optimum fixed decision threshold or adoptively varying the decision threshold with the number of users, the performance of the asynchronous OOK-

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OCDMA system does not meet the performance level of DPSK-OCDMA (i.e. DPSK with decision threshold equal to 0). Optical thresholding can eliminate MAI to the extent as that of DPSK encoder/decoder in the system without sacrificing the BER and OSNR required for proper operation of the receiver. Maximization of number of users and spectral efficiency was carried out in [12] for multi-wavelength OCDMA in high speed optical local area networks using multiple pulse per row (MPR) with optimum threshold detection

The OCDMA system is flexible to user allocation and support varying bit rates. Its performance is limited by the system beat noise in the presence of laser and photodetector noises and interferences. Beat noise occurs due to square-law detection of the optical signal. The important property of the beat noise is that its variance is proportional to the square of the light intensity. The spreading codes used to overcome the interference should have low cross correlation and high autocorrelation peak only at 0.Hence to overcome the interference (MAI and BN) and to maintain low BER, longer spreading codes or error-correcting codes can be used.

DPSK has favorable transmission properties which includes the requirements of ~3dB lesser OSNR compared to OOK and minimizes interference effect due to the fiber nonlinearity. DPSK encoding/decoding is used to suppress the interference. Advantages of developing DPSK techniques are to increase the receiver sensitivity approaching that of coherent detection. The behavior is similar to the traditional error correction code. At the end of transmitter, data are encoded into pseudorandom optical codes (OC) where users are assigned different OC in the OCDMA system. At the receiver, the decoder recognizes the target OC corresponding to the high level output of autocorrelation and low level output of cross correlation. For this asynchronous system works without any timing co-ordination provided long optical code (for DPSK short OC) and E/D with very high power contrast ratio (PCR) between autocorrelation and cross correlation is used. DPSK data format in OCDMA has been proposed and investigated theoretically and experimentally to combat noise in OCDMA system in [8].

DPSK provides many advantages i) signal to noise interference ratio increase because symbol 0 and 1 provides additional energy and eye opening in factor of two. The eye after the differential detection provides symmetrical positive and negative values for 0 and 1 symbols leading into an optimum threshold detection level equal to zero and independence of the average power incoming to the receiver. It reduces the complexity for threshold determination, but on other hand it requires additional devices like differential detection and optical Mach-Zehnder interferometer with one bit delay between arms. As a result the overall increase in complexity remains the same in either case, but balanced detection is preferred.

2. Theoretical Consideration

Incoherent system of our proposed model uses 2-D coding schemes to provide better correlation performance and improved power and bandwidth efficiency in the asynchronous mode of operation. The received optical field as in [3] at the photodetector of the desired user with m interfering signal (0 < m < 8) is

$$E(t) = T_C \Re\{P_d + \sum_{i=1}^{m} P_i + 2\sqrt{P_i P_d}\cos(\Delta\phi_i)$$

$$+ 2\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}\sqrt{P_i P_j}\cos(\Delta\phi_{ij})\} \rightarrow (1)$$

= Data + MAI + PBN + SBN

where P_d and P_i are data decoded and interfering power respectively, P_i terms will not have fixed value, but a random variable fluctuating around its average P_i leading to MAI. First term is the data signal, second term is MAI, third term is primary beat noise (PBN) and the fourth term is secondary beat noise (SBN); T_c is the Chip duration and $\Re$ is the responsivity of the photo detector. Assuming the bandwidth of photo detector is larger than the frequency difference between the incoming signals and for smaller numbers of users the interference

$\xi = \langle P_i \rangle / P_d$, ξ is such that $m\sqrt{\xi} << 1$,

then SBN can be neglected. Also for the incoherent system the BN is a random process uniformly distributed over [-π, π] during T_c and therefore the BN can be ignored by averaging throughout the detection, approximating the system to MAI noise dominant.

The received signal is

$$Z = T_C \Re\{P_d + \sum_{i}^{m} P_i.\} + \int_{0}^{T_C} n(t) \rightarrow (2)$$

and n(t) is the photo detector noise included for the completeness of analysis and the average received signal $\langle z \rangle$ is scaled and approximated as

$$\frac{\langle Z \rangle}{(T_C \Re)} = (1 + m\xi)P_d \rightarrow (3)$$

Assuming that the MAI and receiver noise both have Gaussian distributions, the error probabilities can be derived**.** Time-wavelength two dimensional (2-D) coding is explained to minimize interference and spectral phase encoding/decoding in [6] with or without time speeding was also used. The total number of users in the OCDMA network can be increased using 2-D codes which divides the bit into a number of pulses (chips) on different wavelength. Spectrally phase coded OCDMA systems [6] are susceptible to coherent beat noise and MAI to the required extent. Phase coding scheme require additional components and system complexity is also increased due to laser diode phase noise and coherence problems. Sensitivity at high data rates (>1Gb/s) is affected by spectral amplitude coding (SAC) OCDMA by the noise of the source and interference level of the system.

Arbitrary codes with orthogonal property so as to increase the autocorrelation peak of the signal and minimize the cross correlation noise of interferers are presented. In [7], Prime sequences with code of length equal to P^2 are used, where P is the prime number. Multiple pulse per row (MPR) codes are family of 2-D OCDMA codes which span the time and wavelength domains as in [8], the 5x7 MPR code with 2 pulses per row and 5 wavelengths were used. Also the detection threshold value is set to the code weight for error free operation. 64 codes set Walsh code, m sequence and prime codes were the other E/D schemes followed in various applications of OCDMA

3. Optical Transmitter

Laser diode operating at 1552.5244 nm corresponding to 193.1 THz with output power of 1dBm, line width of 10 MHz, without polarization reference and with zero phase generates the optical signal. The output spectrum of laser is shown in Fig.1 (a). The data is generated using an user defined code generator and precoded using one bit delay precoder to get the DPSK data and applied to the LiNb Mach-Zehnder modulator (MZM), and the modulated spectrum is shown in Fig.1 (b).The modulated signal is then encoded with a defined code in the encoder, for the signature of the user which is an 8 bit code of run length 2. This encoded output corresponds to the desired user. Other 7 such users operating at 1554.4564 to 1549.8522 nm with channel spacing of 0.645 nm (0.08 THz spacing).The 8 user encoded outputs are combined through a star coupler then to the fiber. The fiber lengths are varied from 50 kms to 600 kms to study the OSNR obtained at the input of the photodetector.The general parameters of the system are i) sample rate = 1.3648 THz, ii) number of samples = 4096, iii) samples per bit = 32, with a sequence length = 128 bits

Encoded signal from the star coupler has the following characteristics and are shown in the Table.1. Single mode optical fiber (SMF) of length 100 kms with attenuation of 0.22 dB/km, dispersion of 4.46 ps/nm/km and dispersion slope of 0.09 ps/nm^2/km operating within the performance limit at 1200 nm to1700 nm is used in our experiments. Group velocity dispersion and third order dispersion are considered.

4. Optical Thresholder

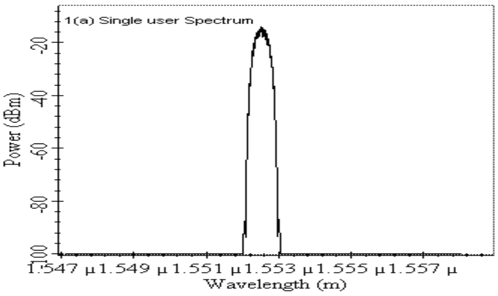
Optical thresholder consists of a short length of one km of highly nonlinear characteristics offering very high attenuation of 11dB/km and dispersion of minus 346 ps/nm/km and erbium doped fiber amplifier (EDFA) to compensate for the losses. The EDFAs are gain controlled each with a noise figure of 6 dB and noise bandwidth of 10 THz; the gains of the EDFAs in cascade are 22dB and 11dB respectively. These are connected in nonlinear optical loop mirror (NOLM) with multiple looping operations to get the minimum BER at the receiver output. The input optical spectrum to the receiver is shown in Fig.1 (c), which is similar to that at input end of the fiber due to compensation carried out by optical thresholding but attenuated ~ 15 dB. This is achieved by properly selecting the parameters of the dispersion compensating fiber (DCF) and EDFAs in the thresholder. Additionally, (i) DCF with length of 1km and attenuation of 11dB/km and negative dispersion of 410ps/nm/km to compensate for the dispersion of the single mode fiber (SMF) link is also used to ensure complete compensation and (ii) the EDFA with short length at the end of the fiber. The eye diagram with thresholding (i.e. with NOLM) and without thresholding are shown in Fig.1 (d) (also Fig.1 (g)) and Fig.1 (e) respectively.The eye diagram for 8 channels DPSK and 8 channels OOK are compared in the Table 2, DPSK OCDMA system has the advantage of better BER and sensitivity. The eye diagram for OOK OCDMA is not given which has only 10 % of eye opening, asymmetric structure, and minimum BER of only 170.1e-5; whereas the DPSK OCDMA has 90 % of eye opening, symmetrical and BER of 1.94 e-5. Therefore for DPSK OCDMA the electrical decision threshold level of 0 (i.e. no threshold setting is required**)**

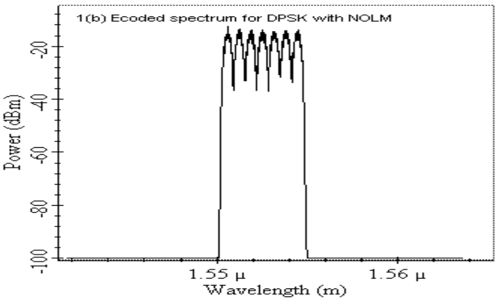
Table 2: Encoded Signal and Noise

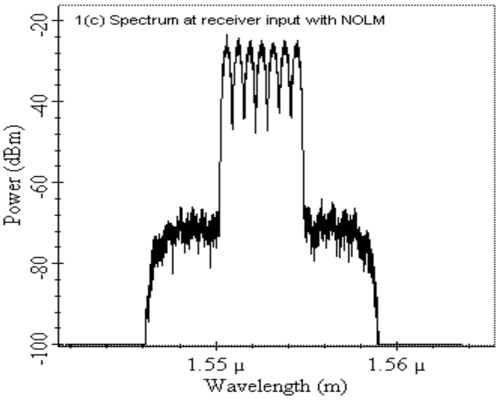
Characteristics	Signal power (dBm)	Noise power (dBm)	OSNR (dB)
Minimum Value	-6.7996392	-12.03328	2.0042
Maximum value	-6.2082046	-8.7438653	5.5679
Ratio of Max/min	0.5314346	3.2893425	3.2893
	(nm)	(nm)	(nm)
Wavelength at minimum	1553.1678	1550.5972	1553.1678
Wavelength at maximum	1551.8814	1553.1678	1550.5972

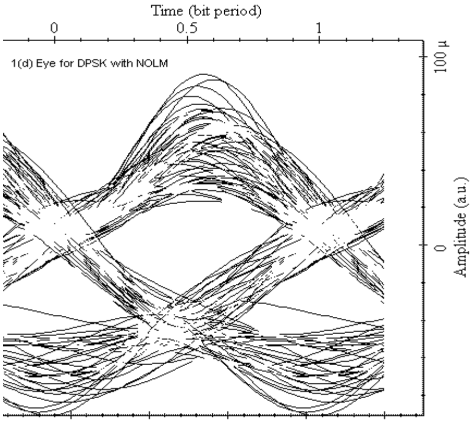
Table 2: Eye Comparison

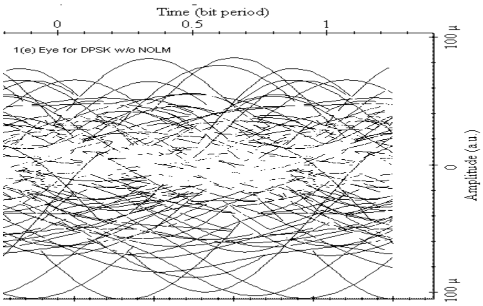
Parameters	Eye Characteristics for DPSK OCDMA (a.u)	Eye Characteristics for OOK OCDMA (a.u)
Maximum Q factor	3.838	2.871
Minimum BER	5.943e-5	170.1e-5
Eye height	0.1982e-6	- 1.824e-6
Threshold level	- 9.103e-6	14.60e-6
Decision instant	0.458	0.703











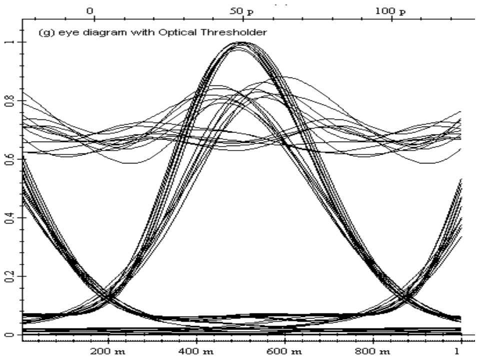
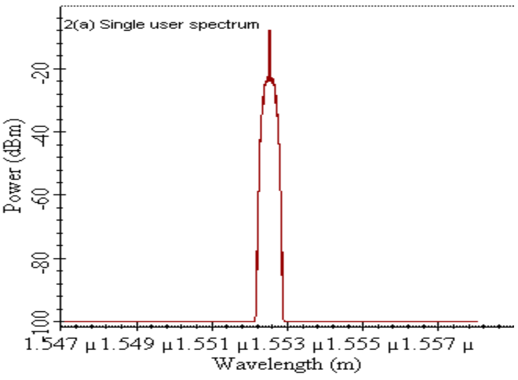


Fig.1 Spectrum and eye diagrams for DPSK system (a) Single user spectrum, (b) Encoded spectrum, (c) Spectrum at the receiver input with NOLM, (d) Eye for DPSK with NOLM, (e) Eye for DPSK without NOLM, (g) Eye with optical thresholder and without encoder (NOLM: Nonlinear optical loop mirror DPSK: Differential phase shift keying)

5. OCDMA Receiver

The front end of the receiver is the DPSK OCDMA decoder, to decode a particular desired user. The corresponding signature code used in the transmitter for encoding is used to decode the modulated signal which is an 8 bit code of run length 2. The Mach-Zehnder delay interferometer (MZI) with delay of 1 bit ((1/bit rate) = 2.345s) and coupling coefficient of 0.5 is used in the detection process. The MZI is followed by the balanced detection configuration. Two parallel branches, one consisting of pin photodiode and another with 1 bit delay plus identical pin photodiode. The electrical output signals are combined and further processed through filter. The electrical output for the desired user is minus 57.864 dBm corresponding to the receiver input signal of minus 4.144 dBm. The process is repeated with direct detection also. The same arrangement is followed for the OOK OCDMA but with direct detection. Receiver sensitivity of 6 dB improvement for DPSK OCDMA over OOK OCDMA is reported. Additional 1.2 dB improvement in receiver sensitivity for balanced detection of DPSK OCDMA over direct detection at the cost of additional complexity introduced. An extended reach up to 500 km with only 2-dB optical signal-to-noise ratio penalty is found feasible for a 10.7-Gb/s NRZ-DPSK link with the chirped fiber Bragg grating (CFBG) as a narrowband optical filter demodulator and a maximum likelihood sequence estimation combination as in [10].

The time domain signal as in Fig.2 (e) is distorted much compared the DPSK due to OOK and the power level is merely modified. As in Fig.2 (d), a very small eye opening and ambiguity in decision instant as 0.25 or 0.703 times the bit duration, clearly indicates the poor BER performance of the OOK OCDMA system. The decision instant 0.703 times the bit duration is mentioned in the Table 2. This occurs even after the approximately undistorted signal as in Fig. 2(b) and receiver input spectrum is given in Fig 2(c).



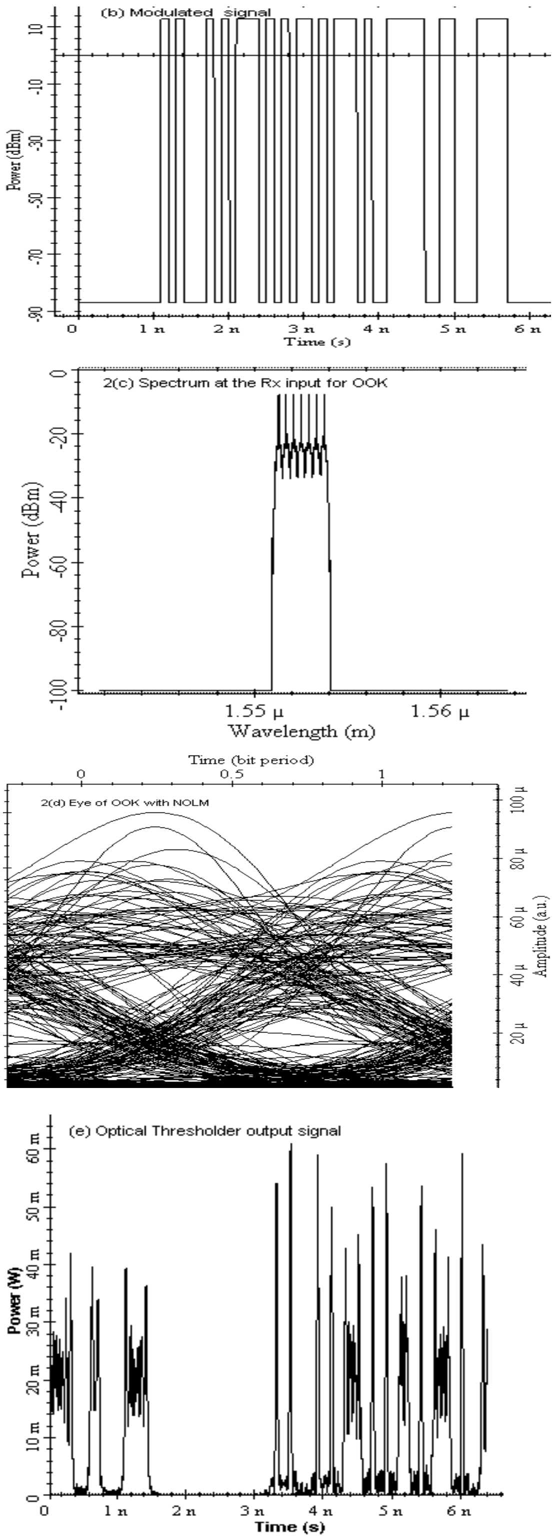


Fig. 2 Spectrum, signal and eye diagrams for OOK system (a) Single user spectrum, (b) Modulated signal, (c) Spectrum at the receiver input with NOLM,(d) Eye for OOK with NOLM, (e) optical thresholder output signal

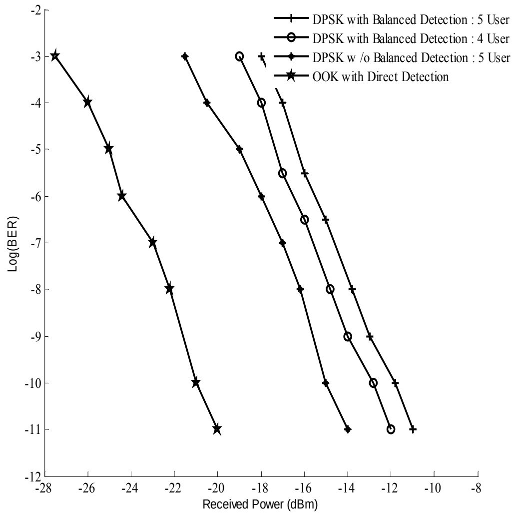


Fig.3. Log(BER) vs received power at minus 10 dB interference. Results are with optical thresholding

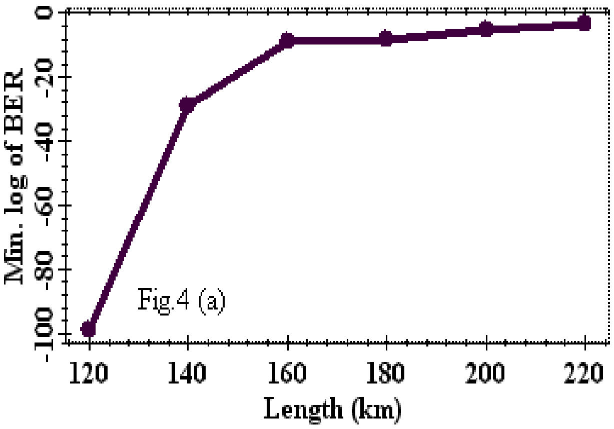
6. Results and Discussion

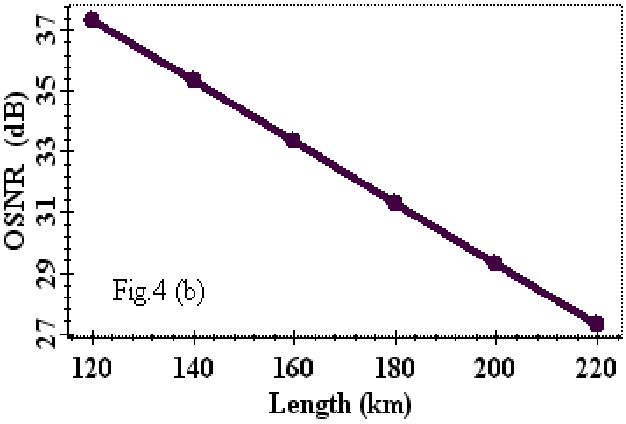
From the results obtained the average power penalty for one user is ~ 1.2 dB as in Fig.3, presented for 4 and 5 users.

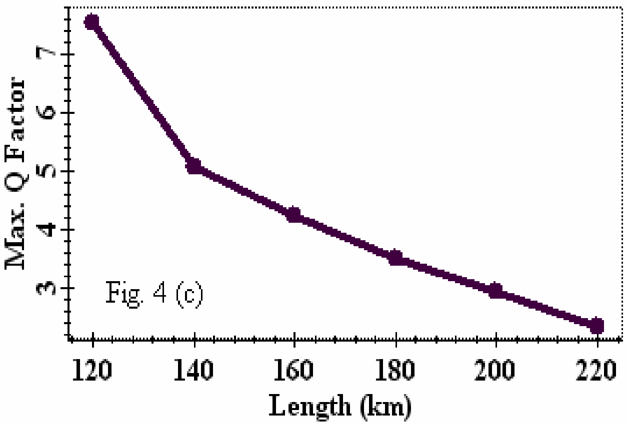
The performance has been significantly improved with optical threshold. The received interference power level at the input of the thresholder increases with the number of users. For large number of users (> 8) and for larger fiber span (>100km), the in line EDFA and DCF; and source power (from 1dBm) should be adjusted to reduce the per user power penalty to be less than 0.5 dB from 1.2 dB in our 8 user case. It is obvious that OCDMA system with optical thresholding performs better than the optimum fixed decision thresholding. The optimum decision threshold may be varied dynamically according to the number of users to meet the performance of optical threshold receiver, but at the cost of increased receiver complexity to generate the threshold control signal. The adaptive decision threshold receiver may outperform the optical threshold receiver at the cost of further increased receiver complexity. The balanced detection (BD) alone for DPSK OCDMA can improve the receiver sensitivity by ~ 3 dB as in Fig.3 given for only 5 users case. Comparing DPSK OCDMA with BD and OOK OCDMA with direct detection, the receiver sensitivity of 9 dB is reported in Fig.3. BER performance is degraded with increasing number of users, and the degree of degradation may be reduced by properly adjusting the each user power and better encoding / decoding technique such as (64 code set) Walsh code to minimize MAI and coherent detection techniques. It is demonstrated in [9], that differential phase shift keying (DPSK), can tolerate higher in-band crosstalk-noise levels compared to amplitude shift keying (i.e. OOK).

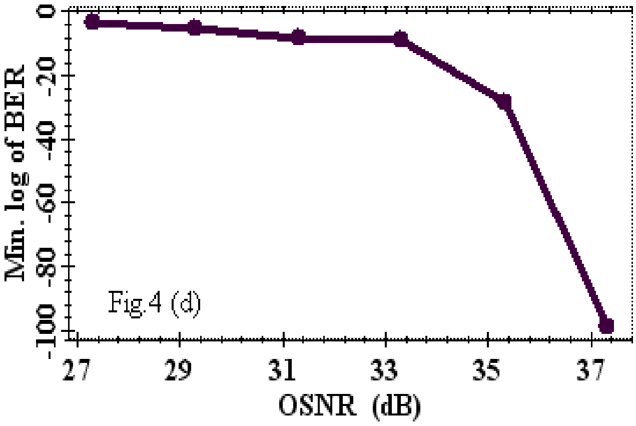
7. Optical Fiber link for OOK

The optical fiber used in the system is single mode fiber (SMF) and the performance is optimized for 120 kms of SMF. With the variations of the length the fiber the system characteristics changes. As inFig.4 (a),the BER performance is degraded exponentially. OSNR in Fig.4 (b) and Q factor in Fig.4(c) decreases linearly with the fiber length. Therefore by properly adjusting the gain of DC-EDFA to provide an OSNR to be always greater than 37 dB it can be shown to get considerable improvement on BER performance, as highlighted in Fig.4(d) and Fig4(e).









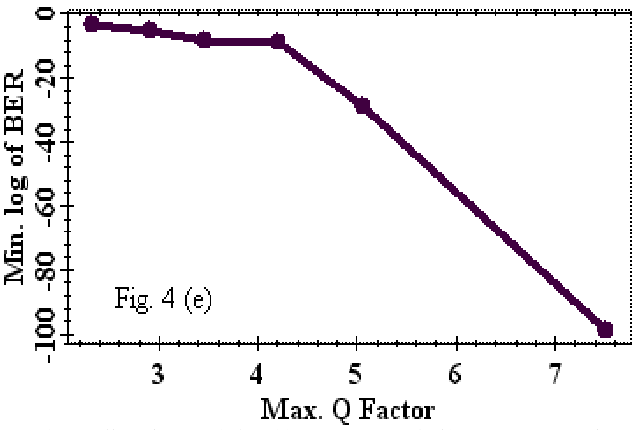


Fig. 4. Fiber characteristics. (a) BER vs Length (b) OSNR vs Length (c) Q vs Length (d) BER vs OSNR and (e) BER vs Q factor

The capacity of asynchronous multi-user access is of key importance for practical applications. Optical coding provides the large number of codes with desirable cross-correlation characteristics. The key challenge in realizing viable OCDMA network lies in overcoming interference from many simultaneous users. Nonlinear optical thresholding was used to suppress the multiple access interference in asynchronous system through highly nonlinear fiber (HNLF). Using an effective encoding/decoding (E/D) technique, MAI can be eliminated effectively. In OOK-OCDMA, an interference level is studied to be more and also requires high power level to maintain the desired BER for the given number of users as seen from Fig.4 (d).

8. Conclusion

The BER and receiver sensitivity improvements over the standard OCDMA with direct detection system is presented. Comparing DPSK OCDMA with BD and OOK OCDMA with direct detection, the receiver sensitivity of 9 dB is reported. Two approaches (i) optical thresholding and (ii) balanced detection were used to minimize the effect of BN and MAI. The incoherent asynchronous OCDMA system is MAI dominant, but for coherent systems mitigation of BN is critical. The numerical results reveal that applying optical thresholding leads to improved BER system performance in the presence of MAI and receiver sensitivity. The system performance can further be compared if optical nonlinear thresholding is replaced with adaptively varying (dynamic) the optimum decision threshold in accordance with number of active users in the OCDMA systems.

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