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Enhanced Performance of Spectral Amplitude Coding Optical Code Division Multiple Access System Using Zero Cross-Correlation Code through Wired and Wireless Optical Channels

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Abstract: *Spectral amplitude coding-optical code division multiple access (SAC-OCDMA) is an outstanding flexible system for optical access networks. However, the major drawbacks of SAC-OCDMA system are users' interference, intensity noise, thermal noise, dispersion etc. In this paper, different performance enhancing techniques for wired and wireless SAC-OCDMA system using zero cross-correlation (ZCC) code are proposed. It is found that the wired optical channel along with dispersion compensation fibre (DCF) and in-line erbium doped fibre amplifier (EDFA) gives better performance than without DCF and EDFA. Also, it has been observed that the performance of optical wireless channels (OWC) can be improved by using transmitters and receivers with larger aperture diameters (up to 40cm) and higher input power (22dBm). Further, it is reported that 10×10Gbps SAC-OCDMA wireless system gives a faithful transmission distance of 12000 km.*

Keywords: *DCF, EDFA, OWC, SAC-OCDMA, ZCC*

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I. Introduction

During the last two decades, optical wired and wireless communication has been blossomed effectively in indoor and outdoor optical networks. The attractive optical code division multiple access (OCDMA) is an all-optical, compact and secure optical system. OCDMA provides a larger transmission distance, high bandwidth, low cost etc. This system depends on the concept of transmission of the unique code sequences over a single optical medium [1-3]. Nevertheless, multiple access interface (MAI) and phase-induced intensity noise (PIIN) deteriorate its performance, which restricts the transmission from the simultaneous active users and produce the bottleneck for desired bit error rate (BER) of 10^{-9} [4-7]. The MAI can be eliminated in OCDMA system using SAC scheme which consists of several code families such as maximal-length sequence (M-sequence) codes, Walsh–Hadamard codes, modified quadratic congruence (MQC) code, modified double weight (MDW) code etc. But, the ZCC code in the SAC-OCDMA system is the most efficient code owing to its simple design, zero cross-correlation and high autocorrelation properties. Also, ZCC code and non-return to zero (NRZ) data format provides less complexity as compared to other codes in SAC-OCDMA system [8].But the presence of chromatic dispersion (CD) produces the major hindrance for long-range optical communication.

Kaler et. al [9] analyzed 10Gb/s NRZ links with pre-, post- and symmetrical-dispersion compensation methods with dispersion compensated fibre over 6-30km. Also, EDFA power (0-12dBm**)** was optimised for varying length (30-150km) of the single mode fibre (SMF). They showed that symmetrical-dispersion compensation scheme gave better performance as compared to pre- and post-compensation. Also, by increasing EDFA power, the transmission distance increases due to reduction in the nonlinear effects at BER of 10^{-12}.

Sharma et. al [10] studied the FSO/WSO technology using the next generation inter-satellite optical wireless channel (IsOWC) application between two satellites over 1000km at 2.5Gb/s with and without square root (SM) module. These channels have numerous advantages over microwave communication such as wireless security, larger distance, less cost, no electromagnetic interference etc. These channels can be used for low, medium, geosynchronous earth orbits and for highly secure military applications. It is shown that the acceptable BER can be obtained at 1550nm wavelength where SNR reduces from 44dB to 4dB over 100–1000km distance between two satellites by using SM module.

From the available literature it has been found that up till now, the SAC-OCDMA system is used with ZCC code for medium haul applications only and at bit rate < 10Gbps . Hence, for greater scalability and reliability SAC-OCDMA system can be realized using optical wireless channel (OWC) instead of optical wired channel. Here, SAC-OCDMA system has been examined for wired and wireless optical channel at different bit rates for 10 users simultaneously. In this paper, performance of SAC-OCDMA system using ZCC code is evaluated with and without DCF and EDFA in optical wired channel. Also, 10×10Gbps system is analyzed for varying input power (16 to 22dBm) over 12000km distance. Section 2 describes the mathematical description of the ZCC code used in SAC-OCDMA system. Section 3 explains the model of SAC-OCDMA system for wired channel (with and without DCF, EDFA) and wireless channel. In section 4, analysis of the transmission performance of proposed schemes for 5 and 10 users is done and finally, in section 5, conclusions are made.

II. Mathematical Description Of ZCC Code

The enhanced performance of SAC-OCDMA system is based on the choice of efficient code for encoding. For this code should follow the two important properties i.e. minimum cross correlation between two different code sequences and maximum autocorrelation between two same code sequences. There are several codes in SAC-OCDMA system such as Haramard, MCQ, random diagonal (RD) etc. But the ZCC code is a simple design, zero cross-correlation and high autocorrelation code which reduces the MAI. For ZCC code zero cross-correlation and maximum autocorrelation is computed as [8]:

$$\sum_{j=1}^{N} C(j)D(j)=\begin{cases} w, & \text{for } C=D \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where C and D denotes the ZCC code sequences and w is the weight.

The ZCC code is a represented in matrix L×K where L represent the users and K represents the code length. For basic weight (w = 1) the ZCC code is defined as [8]:

$$Z(w=1) = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{2}$$

For higher weight (w>1), the ZCC code is defined as:

$$Z(w>1) = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \tag{3}$$

where A represents the (1,w(w-1)) matrix of zero.

B represents the w repetition of matrix $\sum_{j=1}^{w} j[01]$.

C represents the duplicate matrix from w-1.

D represents the diagonal matrix of pattern [m×n] with alternative zero column matrix.

For w = 2, the ZCC code is defined as:

$$Z(w = 2) = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

Here, users are three (L=3) and code length is six (K=6).Similarly, for w = 3,4,…. the code can be designed. The relation between users, code length and code weight is given as:

$$L = w+1 \tag{5}$$

$$K = w\,(w+1) \tag{6}$$

The signal to noise ratio is given as following [8,11]

$$SNR= \frac{\frac{2P_{sr}^2 R^2 w^2}{L^2}}{\frac{P_{sr} e B R}{K}\left(\left(L-1+w\right)w\right)+\frac{4BT_n K_b}{R_L}} \tag{7}$$

where P_{sr} = effective power of broadband source,

R = responsivity of photodiode

L = numbers of active users.

B = optical bandwidth

e = electron charge,

K = code length

T_n = noise temperature of the receiver

R_L = load resistor of receiver.

The BER expression is given as [8,11]:

$$BER=\frac{1}{2}\,erfc\left(\frac{\sqrt{SNR}}{2}\right) \tag{8}$$

where erfc = complementary error function

$$erfc\,(y)=1- erf\,(y) = \frac{2}{\sqrt{\pi}}\int_{y}^{\infty} e^{-t^2}\,dt \tag{9}$$

III. Modelling Of SAC-OCDMA System

The schematic diagram of the SAC-OCDMA system using ZCC code consists of a wired optical channel for 5 users, as illustrated in Fig. 1.

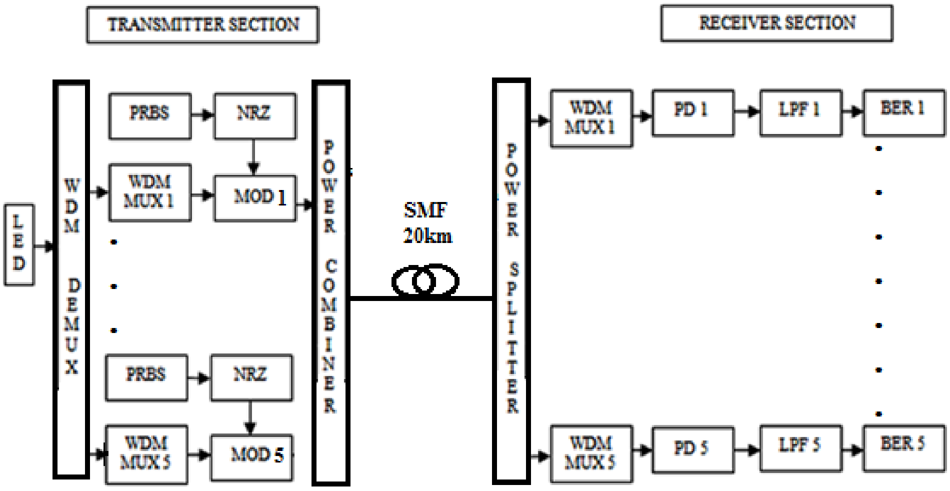

Figure 1 Schematic diagram of 10Gb/s SAC-OCDMA system using ZCC code over optical fibre link for 5 users

The standard SMF is used as an optical wired channel with spectral width = 0.8nm, attenuation = 0.2dB/km, dispersion = 16ps/nm/km. The performance of SAC-OCDMA system using ZCC code is characterised by referring BER and eye diagrams. The transmitter consists of incoherent light source light emitting diode (LED) with input power of 16dBm, encoder and power combiner for combining the power in a SMF at 155Mbps bit rate over 20km distance. Each encoder consists of a pseudo-random bit sequence (PRBS) generator, NRZ signal generator, wavelength division multiplexer (WDM) for different ZCC code sequences and Mach-Zehnder modulator. At the receiver, a power splitter is used for delivering signal power to each code user with decoders. Only the intended decoder is capable of correctly demodulating the optical code signal. Here, each decoder consists of wavelength division multiplexer, PIN photodiode for converting optical signal to electrical signal (with responsivity = 1A/W, thermal noise = 2×10^{-44} W/Hz and dark current = 10nA), low pass Bessel filter (cut off frequency = 0.65×bit rate), 3R regenerator for regenerating the distorted signal and BER analyzer for analyzing output with BER , quality factor, eye diagram and eye height [8,11].
In Fig. 2 and Fig. 3, LASER (input power = 20dBm) is used instead of LED as an input light source.

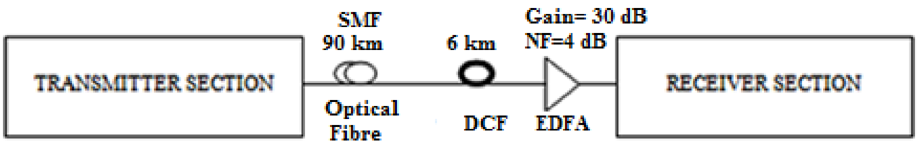

Figure 2 Schematic diagram of 10Gb/s SAC-OCDMA system using ZCC code over optical fibre link with DCF and EDFA

Fig. 2 shows the compressed schematic diagram of Fig. 1 by applying DCF (with length = 6km, dispersion = -85ps/nm.km) and EDFA (with gain = 30dB, noise figure (NF) = 4dB) along with the SMF for 10Gbps SAC-OCDMA system.

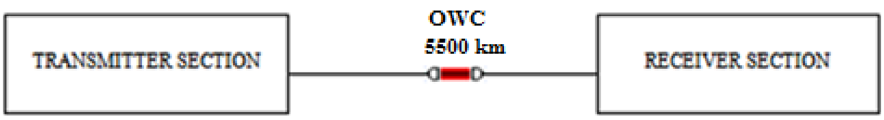

Figure 3 Schematic diagram of SAC-OCDMA system using ZCC code over wireless optical channel

Also, Fig. 3 shows the 10Gbps SAC-OCDMA using ZCC code with an optical wireless channel instead of the optical wired channel. The OWC can be extended to 10 multiple channels. These OWCs are used by 10 simultaneous users for long haul transmission (from 5500 to 12000km) at different bit rate from 25 to 45Gbps (4, 9, 10).

IV. Results And Discussion

The proposed schemes have been analyzed for multiple users (5 and 10 users) at different bit rates (from 155Mbps to 40Gbps) in SAC-OCDMA system using ZCC code The various parameters considered for optical wired and wireless channels are shown in Table 1.

Table 1: Parameters of optical wired and wireless channels.

S. No.	Components used	Parameters	Parameters values
1	DCF	Dispersion	-85 ps/(nm.km)
2	DCF	Length	6 km
3	Low Pass Bessel Filter	Cut off frequency	0.65 × Bit rate
4	Optical Fibre cable	Reference wavelength	1550 nm
5	Optical Fibre cable	Length	12,000 km
6	Optical Fibre cable	Bit Rate	40 Gbps
7	OWCs	Distance	5500 km
8	Photodiode	Dark current	10 nA
9	OWC Receiver	Aperture Diameter	40 cm
10	OWC Transmitter	Aperture Diameter	20 cm

4.1 Performance improvement in optical wired channels

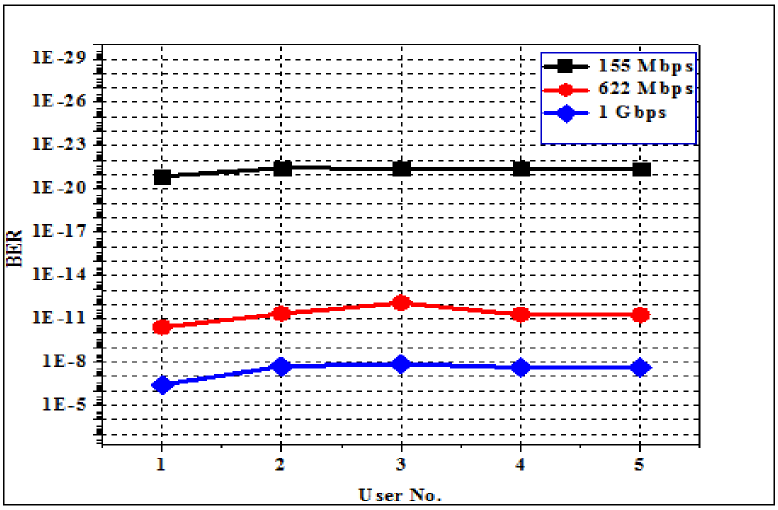

Figure 4(a) BER performance of SAC-OCDMA system using ZCC code for 5 users at different data rates with LED input source over 20km

Fig. 4(a) shows the BER performance for 5 users at 155Mbps, 622Mbps and 1Gb/s over 20km SMF. It can be seen that for 155Mbps, 622Mbps and 1Gbps SAC-OCDMA system, the BER ranges from 10^{-22}-10^{-19},10^{-13}-10^{-10} and 10^{-8}-10^{-5} respectively. The acceptable BER threshold for reliable SAC-OCDMA communication is 10^{-9}. At 1Gb/s, the SAC-OCDMA system performance degrades due to the presence of dispersion and incoherent input source LED.So, the coherent LASER (10dBm input power) can be used instead of LED at high bit rate (>1 Gbps).

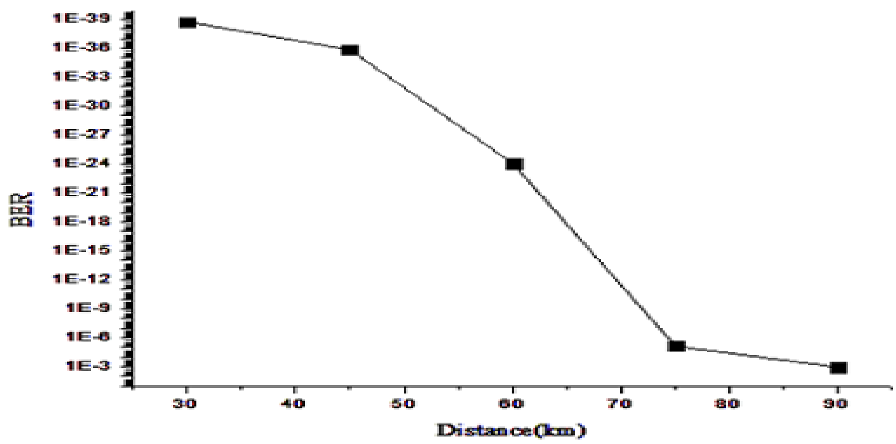

Figure 4(b) BER performance of SAC-OCDMA system using ZCC code for 5 users for varying distance (km) with LASER input source

Fig. 4(b) shows the BER performance of 10Gb/s SAC-OCDMA system using ZCC code with LASER over 70km long optical fibre. It can be seen that BER values are 2.08×10^{-39} and 1.0×10^{-9} at 30km and 70km respectively. After 70km, the system performance degrades due to presence of chromatic dispersion. The system performance can be enhanced by using EDFA and DCF along with the SMF to mitigate the effect of dispersion.

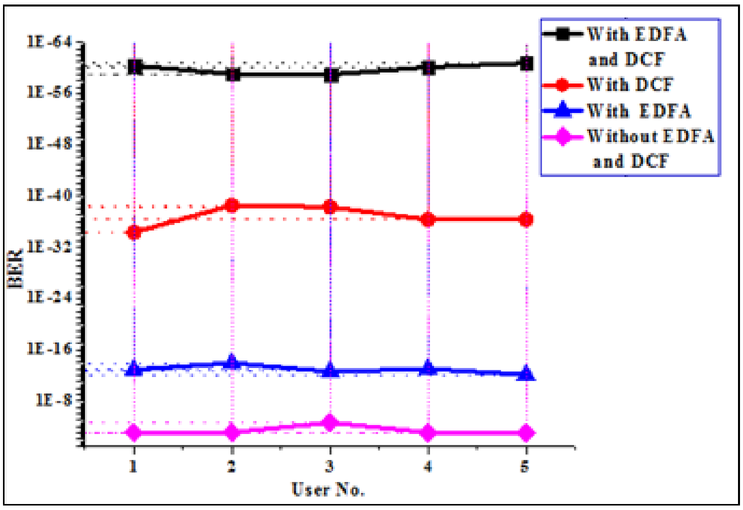

Figure 5: Comparative performance of 10Gb/s SAC-OCDMA system using ZCC code with EDFA and DCF, with DCF, with EDFA and without DCF and EDFA over 90km

Fig. 5 shows BER performance of system with and without using DCF and EDFA over 90 km. It can be seen that the OCDMA system performs better when EDFA and DCF are used along with the SMF (BER of 10^{-64} to 10^{-56}) than otherwise. This is due to the compensation of dispersion and distortion of the signal over long optical fibre link. The observed BER values are shown in Table 2.

Table 2 BER for optical wired channel for 5 users with P_{in} = 20dBm.

BER (Bit Rate= 1Gbps, Distance= 20 km)	**BER (Bit Rate= 10Gbps, Distance= 90 km)**			
Without DCF and EDFA	Without DCF and EDFA	With EDFA	With DCF	With both EDFA and DCF
5.38×10^{-8}	3.02×10^{-5}	1.21×10^{-14}	1.42×10^{-40}	1.73×10^{-61}

4.2 Performance enhancement in optical wireless channels

The limited performance of SAC-OCDMA system using ZCC code optical wired channel can be further enhanced by using OWCs over long distance (>90km) and at high bit rate (>10 Gb/s). Fig. 6(a) shows the BER performance of system with respect to receiver aperture diameter (cm) at 10Gbps.

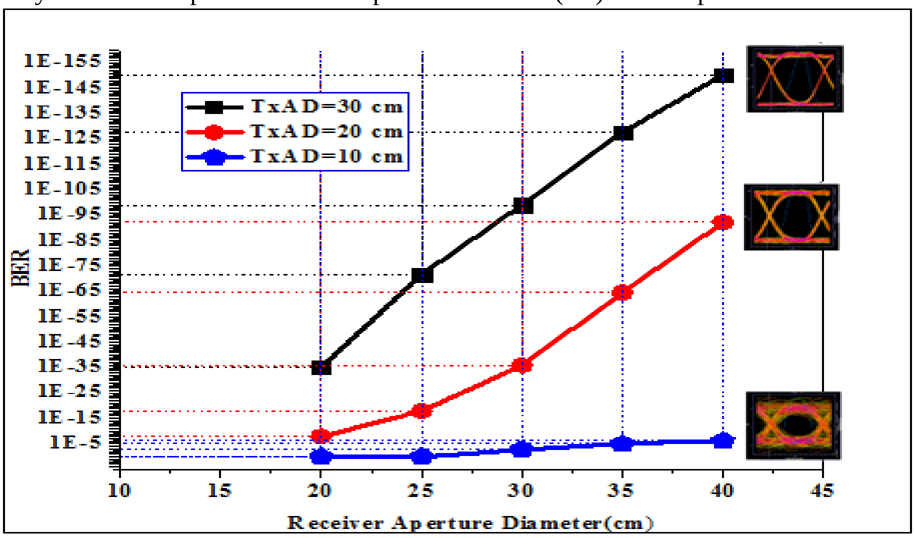

Figure 6(a): BER performance of 10Gbps wireless SAC-OCDMA system using ZCC code for 10 users over 5500 km at different receiver and transmitter aperture diameters (cm)

Here, 10 OWCs are used simultaneously for 10 active users over 5500km wireless channel under thermal noise. This is due to the fact that wireless channels can accommodate multiple users and thus promote the high bandwidth over large coverage distance. The larger aperture diameters of transmitter and receiver facilitate better transmission and reception of the multiple coded signals. Thus, the 30cm transmitter and 40cm receiver aperture diameter of OWC provides high BER value (i.e.1.52×10^{-155}) as compared to other lower diameter values. This implies that larger the aperture diameter better is the wireless system performance.

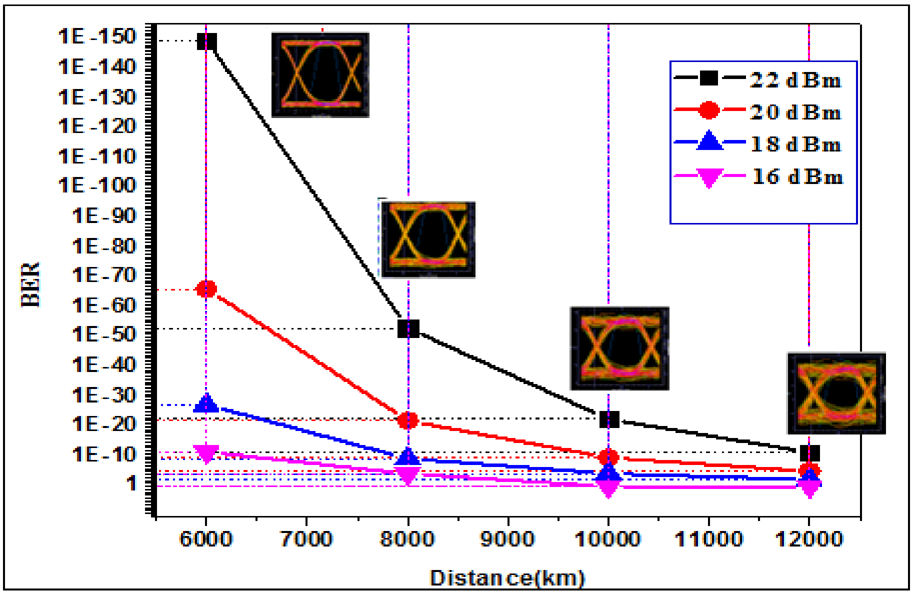

Figure 6(b): BER performance of 10Gbps wireless SAC-OCDMA system using ZCC code for 10 users over 5500 km over varying transmission distance with different input power

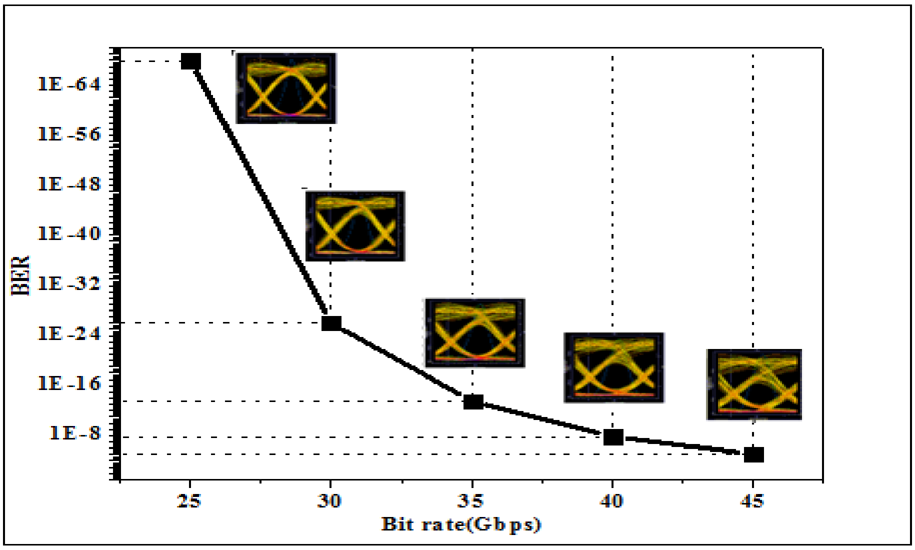

Figure 6(c): BER performance of wireless SAC-OCDMA system using ZCC code for 10 users over 5500 km for varying bit rates

Fig. 6(b) shows a wireless SAC-OCDMA system with different input powers and distances. It is clear that the increase the input power of the LASER source, enhances the transmission distance (>6000km) simultaneously. At 22dBm input power, the faithful transmission distance increases up to 12000km with an acceptable BER value. Further, the system performance can be improved for higher bit rate (up to 40Gbps) with multiple OWCs as shown in Fig. 6(c). The respective eye diagrams are also shown in Fig. 6(a)-(c) which supports the above results. The larger and clear eye opening shows less distortion and high quality. Table 3 shows the BER performance of SAC-OCDMA system with OWCs.

Table 3 BER for optical wireless channels for 10 users.

BER (Bit Rate= 10Gb/s, Distance= 5500 km, RxAD=40cm)			**BER (Bit Rate= 10Gb/s, Distance =10000 km, TxAD =30 cm, RxAD=40cm)**			**BER (Distance= 5500 km, TxAD =30 cm, RxAD=40cm, P_{in} =22 dBm)**		
TxAD =10cm	TxAD =20cm	TxAD = 30 cm	P_{in} = 18dBm	P_{in} = 20dBm	P_{in} = 22dBm	Bit Rate= 25 Gb/s	Bit Rate= 35 Gb/s	Bit Rate= 45 Gb/s
2.7×10^{-4}	6.7×10^{-90}	1.52×10^{-155}	3.7×10^{-10}	4.4×10^{-21}	8.1×10^{-35}	2.7×10^{-69}	5.8×10^{-27}	1.7×10^{-7}

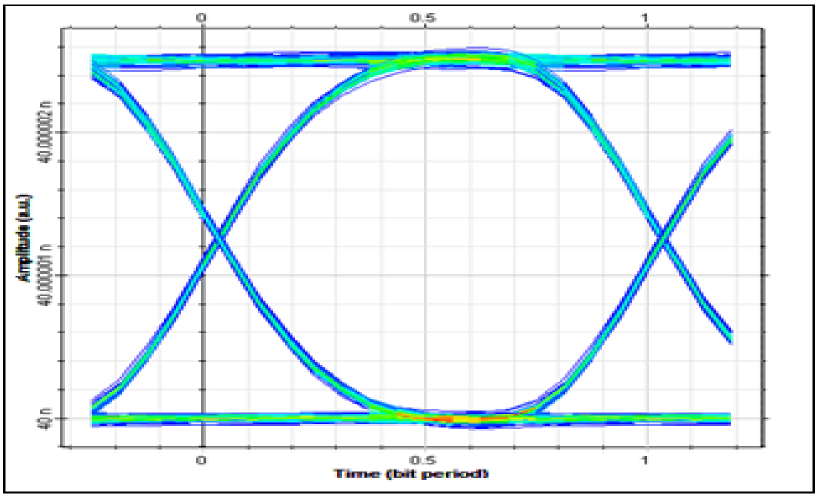

Figure 7(a): Eye diagrams of 10 user wireless SAC-OCDMA system using ZCC code for P_{in} = 22dBm, Tx AD = 30cm , RxAD = 40cm over 5500km at 10Gb/s bit rate

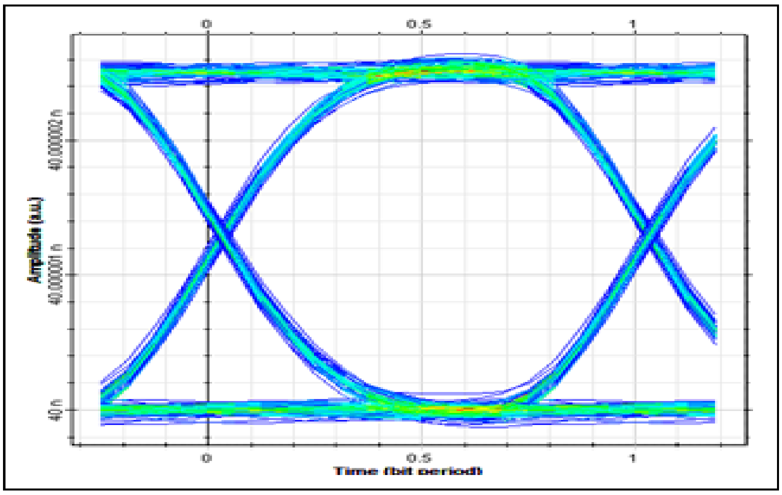

Figure 7(b) Eye diagrams of 10 user wireless SAC-OCDMA system using ZCC code for P_{in} = 22dBm, TxAD = 30cm , RxAD = 40cm over 5500km at 40Gb/s bit rate

Fig. 7(a) and 7(b) shows the larger eye-opening and high quality eye diagrams SAC-OCDMA using ZCC system for 10 OWCs at 10Gbps and 40Gbps respectively and hence, provides the improved system.

V. Conclusion

The different performance enhancing schemes in SAC-OCDMA system using ZCC code has been proposed in wired and wireless optical channels. The better performance has been observed using LASER input source, when EDFA and DCF are used along with the SMF to compensate for the dispersion and distortion of the signal in optical wired SAC-OCDMA system. It is found that optical wired system can be used at 10Gbps over 90km distance with BER less than 10^{-9}. However, by using multiple OWCs in SAC-OCDMA system the performance improves by 133% increment in faithful transmission distance (up to 12000km) and 4% enhancement in bit rate (up to 40Gbps) as compared to a wired optical channels. This SAC-OCDMA system can be effectively used for security applications in future generation ground and satellite communication.

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