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Empirical Analysis of the SAC-OCDMA-WDM System by Leveraging the AND Subtraction Technique

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***Abstract*—This study utilized C-band carrier frequency to evaluate Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) systems, employing Fiber Bragg Gratings (FBG) as encoders and decoders and implementing the AND subtraction detection technique. The system's performance is influenced by various factors, including optical transmission distance, optical power, channel bandwidth, data rate, and the number of channels. Extensive simulations were conducted to examine the impact of these parameters on system performance. The proposed SAC-OCDMA system was integrated with a Wavelength Division Multiplexing (WDM) system to increase the number of active channels. The network was designed and analyzed using commercially available Optisystem software. The proposed SAC-OCDMA system architecture with two channels maintained operational limits up to unrepeated transmission over 336 km at a data rate of 1.6 Gbit/s, achieving results within the pre-FEC threshold. Additionally, the SAC-OCDMA system was simulated with up to ten channels, considering the pre-FEC bit error rate threshold. The results were compared with recent technical articles and were found to be superior in terms of the number of channels and transmission distance. The proposed model achieved a superior data rate of 6.4 Gbps and a maximum transmission distance of 24 km for a 10-channel architecture.**

***Index Terms*—SAC-OCDMA, Unique Signature Code, FBG, WDM, Optisystem.**

I. Introduction

THE massive need for bandwidth in telecommunications is being caused by the quick expansion of high-definition video, cloud-based services, and machine-to-machine communication. Growing demand for telecommunication services with vast bandwidths, quick data rates, and premium customer service has spiked over the last 20 years. To mitigate the growing demand for user data exchange, various methods have been implemented in access networks. Any transmission between users mostly depends on the physical constraints of transmission networks and the strategies used for resource allocation among consumers. New multiple-access solutions that enable multiple channels to utilize the same network bandwidth have been launched as a result[1], [2].

Among all the multiple-access solutions, In the field of telecommunications, optical code division multiple access, sometimes known as OCDMA, is an intriguing multiple-access option. OCDMA, or optical code-division multiple access, is a transmission technique that spreads the power of a signal across a wide range of frequencies, making it appear like noise to unintended receivers. This noise-like quality makes it difficult for eavesdroppers or unauthorized users to intercept or decipher the signal, enhancing the security of the communication. Diminishing the transmission distance's sensitivity to specific spectrum fluctuations ultimately results in greater data security. This technique also has the significant benefit of simultaneously using every nanometer of accessible bandwidth, which enables more effective use of the resources that are accessible[3], [4].

SAC-OCDMA, formerly known as Spectral Amplitude Coding Optical Code Division Multiple Access, is a new method for reducing bandwidth demand that also has a high-security benefit. Additionally, channels' interferences influencing the operation of a SAC-OCDMA system are decreased by the code sequences' orthogonality. SAC-OCDMA provides the potential for designing all-optical networks based on optical coding and decoding devices by allowing the conveyed data to be sent concurrently. Each of the codes in the SAC-OCDMA optical communication channel is distinguished by a particular channel's identity. SAC-OCDMA enables the transmission of data using various wavelengths, allowing several users to utilize the same optical cable simultaneously without any disruption, hence providing fast and secure communication. This technology is especially advantageous in fiber-to-the-home

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(FTTH) networks, local area networks (LANs), and metropolitan area networks (MANs), as it enables high data speeds and minimizes crosstalk. The practical uses of this technology encompass secure military communications, broadband internet services, and high-speed data transfer in smart cities and IoT ecosystems.[5], [6].

Combining SAC-OCDMA with WDM technology unlocks significant potential for scaling channel capacity within the system. This optimization of wavelength usage unlocks more efficient data transmission and resource utilization. The positive aspect of WDM is to leverage the maximum capacity of the fiber-optic cable by allowing several beams of light at various wavelengths to be sent on the same fiber-optic cable. Another key benefit of wavelength division multiplexing is that it provides an upsurge in data flow capacity despite altering the fundamental design of the existing network. Consequently, the bandwidth utilization of an optical transmission medium is enhanced significantly more than that of an individual wavelength[7], [8].

Numerous studies have delved into exploring various coding schemes within SACOCDMA systems, each showcasing different performance benchmarks. For instance, Sokaina demonstrated a data rate of 100 Mbit/s across 13 channels over a 5 km transmission distance using SAC-OCDMA with m-sequence and Hadamard codes. In a separate study, Sokaina achieved data rates of 600 Mbit/s for 3 channels over a 25 km distance and 1.6 Gbit/s for 8 channels over a 5 km distance using Narrowband Bragg Filter and SMF. Mohanad reported achieving data rates of 1.24 Gbit/s for 2 channels over a 54.5 km distance and 2.48 Gbit/s for 4 channels using 2D-CS coding. Meftah achieved a data rate of 662 Mbit/s for 4 channels over a 63 km distance using SAC-OCDMA, while Suresh obtained similar rates over a 60 km distance for 3 channels using EDW and MDW coding techniques. Liu Yan demonstrated a data rate of 4.8 Gbit/s for 4 channels over a 25 km distance using WZCCLS coding. However, no research has been done on implementing WDM with SAC-OCDMA which could effectively increase the number of channels by optimizing different parameters. The Multichannel of SAC-OCDMA was not investigated thoroughly with the effect of it on transmission distance and data speed. Fiber optics used in transmission distance faces dispersion for which no researcher has used DCF to minimize it and the effect of it on this system architecture can be a topic of interest for a researcher. No research was made on the effect of the filter at the final end of the system which could filter out the spectrum effectively as per our knowledge. A more detailed comparison is texted in the comparison part of this paper.

In this research, SAC-OCDMA was implemented by using FBGs as an encoder and decoder, which has lessened multiple access interference (MAI). This study also signifies the effect of BER, Q-factor, and OSNR on the quantity of channels. BER is the primary indicator to assess the performance of the proposed system architecture.

The paper is structured as follows: In Section II, the novelty of the work is detailed, providing insights into the approach employed. Following that, Section III delves into the research methodology. Moving on to Section IV, the system design of a dual channel along with parameters. Section V signifies the simulation results and discussion, In Section VI, comparisons are presented, offering a comprehensive analysis. Lastly, Section VII encapsulates the study, summarizing key findings and drawing conclusions.

II. NOVELTY OF THE WORK

Inspired by the research gap identified and presented above the proposed system network was designed using narrowband Fiber Bragg Grating (FBG). The main goal is to optimize the system in such a way that the spectrum could travel at most distances with larger bandwidth by maintaining a pre-FEC BER threshold. In light of this existing research landscape, our proposed SAC-OCDMA system architecture stands out, particularly in crucial performance metrics by effectively harnessing the optical spectrum, our system facilitates higher user capacity compared to conventional methods. A cosine roll-off filter is being used at the receiving end which has effectively filtered out our desired spectrum. Moreover, it achieves notably extended signal transmission distances, evidenced by reliable data transfer rates of 1.6 Gbit/s over 24 km and 6.4 Gbit/s over an impressive 336 km using standard single-mode fiber (SMF) with dispersion compensation fiber (DCF). This enhancement translates into both expanded reach and heightened network potential. Furthermore, our architecture accommodates a larger number of concurrent user channels compared to existing SAC-OCDMA systems, thus signaling greater network capacity by implementing WDM. Notably, our system maintains an exceptional average bit error rate (BER) of less than 10^{-9} using SMF and DCF, outperforming the majority of existing networks in both transmission distance and bit rate capabilities. Considering both factors concurrently, our proposed method demonstrates a clear advantage over prior similar studies, positioning it as a promising solution for real-world applications that demand both extensive reach and high-speed data transmission capabilities.

III. RESEARCH METHODOLOGY

A. System Design of the proposed architecture

The proposed hybrid SAC-OCDMA system having 10 channels is displayed in Figure 01. Three building pieces make up the SAC-OCDMA system design: a transmitter subsystem, a fiber section, and a receiver subsystem. Ten data channels are multiplexed across five Wavelength Division Multiplexing (WDM) channels with wavelengths of 1535.32 nm, 1540.32 nm, 1545.32 nm, 1550.32 nm, and 1555.32 nm, each accommodating two data channels. The proposed SAC-OCDMA system has been simulated to find out the optimum transmission distance by monitoring several parameters, such as the bit rate, bandwidth, and optical power. An inexpensive simple white light source has been deployed as a broadband optical source. The internal construction of the WDM channel consisting of two user channels is described in Figure 01. To evaluate system performance different parameters have been calculated including the Q factor. The Q-factor enables the estimation of the bit error rate for channels. The numerical determination of the Bit Error Rate (BER) ($P_{e(SAC-OCDMA)}$) can be derived from the Q-factor, as illustrated in equation (1)[9], [10]:

$$P_{e(SAC-OCDMA)} = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \quad (1)$$

Here $erfc$ is the complementary error function, and Q is the Q-factor. where the Q Factor can be calculated as equation (2):

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 - \sigma_0} \quad (2)$$

Here μ_1 and μ_0 are the means of the two distributions, typically representing the mean signal and mean noise respectively. σ_1 and σ_0 the standard deviations of the two distributions, representing the spread or variability of the signal and noise, respectively. In the realm of optical communication, a range of filters has been explored, with Fiber Bragg Grating (FBG) emerging as a frequently employed choice. Notably, FBG has been instrumental in the implementation of spectral amplitude coding within the context of the Optical Code Division Multiple Access (OCDMA) system, commonly recognized as the SAC-OCDMA system. In the proximity of an emitted light source, FBG, characterized by its repetitive structure, predominantly reflects periodic alterations in the refractive index. This utilization of FBG holds particular significance in the broader context of our research on optimizing optical communication systems. Bragg wavelength refers to a certain wavelength of which the Bragg grating reflects a frequency band around it and can be calculated by the following equation (3)[11], [12]:

$$2n_{eff}\Lambda = m\lambda_B \quad (3)$$

In the equation, Λ signifies the Bragg grating period, m signifies the Bragg's order, and n_{eff} signifies the effective index. The optical fiber's attenuation and dispersion parameters have been set as 0.2 dB/km and 16.75 ps/nm/km following the ITU-TG.652 standard. For generating diverse wavelengths, a noncoherent and low-cost optical source is used. In an optical communication system, signals pass through fibers, which can be subject to different forms of noise and distortion. Higher OSNR implies a higher quality signal, as the signal is stronger relative to the noise. In optical communication systems, OSNR is a critical parameter because OSNR directly impacts the system's bit error rate (BER). In this study, OSNR is calculated and plotted against transmission distance to illustrate the effect of it. OSNR can be calculated by equation (4) [13], [14]:

$$OSNR = \frac{log_{10}(BER) + 10.7}{1.45} \quad (4)$$

When signals coming from numerous transmitters overlap, it becomes nearly impossible for the receiver to recognize differences between them. This is known as multiple-access interference (MAI). The following describes how MAI may be calculated equation (5) [15], [16]:

$$Z_{AND} = \theta_{ab}(k) - \theta_{(a\&b)b}(k) = 0 \quad (5)$$

Where, $\theta_{(a\&b)}$ symbolizes the AND execution between a sequence and b sequence, θ_{ab} signifies cross-correlation sequence and for any integer k, 0 < k < N–1. a and b are the two SAC-OCDMA code sequences.

IV. System Design of a Dual Channel Along with Parameters

The SAC-OCDMA system has been meticulously devised to incorporate two channels, each characterized by distinct parameters, which have been systematically evaluated across varying transmission distances. Figure 02 illustrates the system architecture, clearly showing the placement of the two

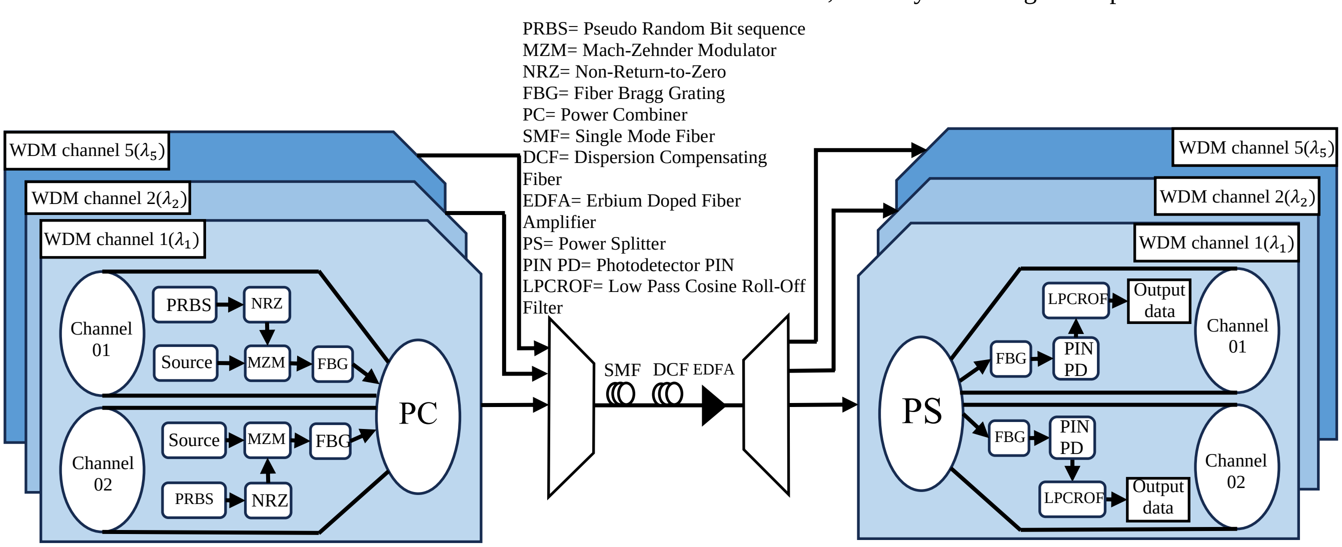

Fig 01 The proposed technique for 10 channels of the SAC-OCDMA system

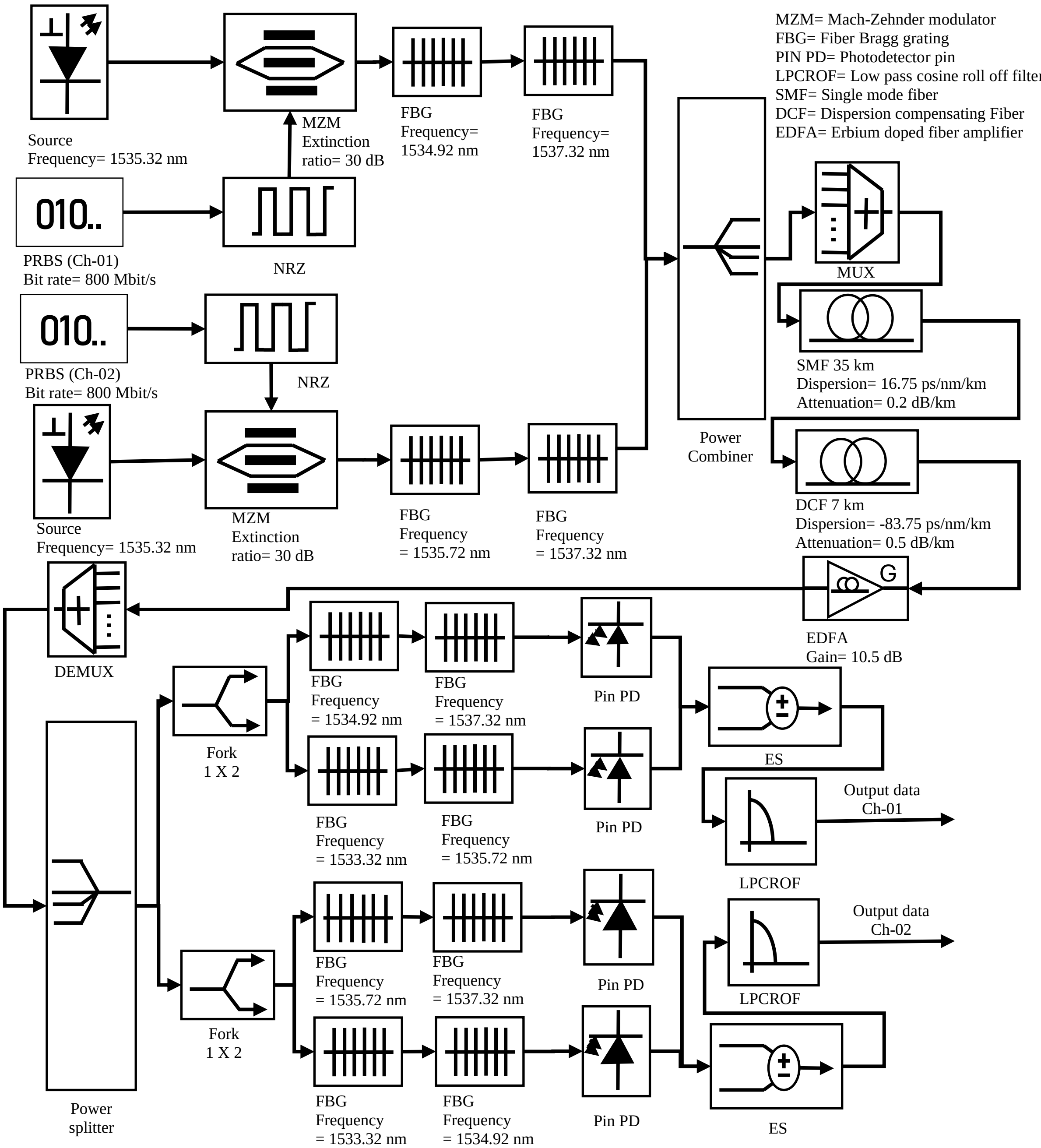

Fig 02 The proposed Architecture with two channels.

channels. The optical spectrum emitted by the source is directed towards the Mach-Zehnder Modulator (MZM). A Pseudorandom Bit Sequence (PRBS) is generated to produce random bit sequences, which are subsequently transferred to a Non-Return-to-Zero (NRZ) generator. The resultant signal is modulated by the MZM, and the modulated signal is subsequently directed to two Fiber Bragg Gratings (FBGs), with each FBG being linked to a unique signature code. This procedural sequence is replicated for the lower channel. The signals from the two channels are then merged using a power combiner before entering the Wavelength Division Multiplexing (WDM) Multiplexer[17], [18]. The combined signal is sent by fiber optics and reaches the receiver. At the receiving end, the received signal undergoes separation via a power splitter. The signal from the splitter is further divided through a fork, directing the signals to two sets of FBGs. Within each set, there are two FBGs, positioned in both the top and lower parts. Subsequently, the signals from the two sets of FBGs are routed to an electrical subtractor. The output from the electrical subtractor is then directed to a photodetector known as a Positive-Intrinsic-Negative (PIN) diode[19], [20]. Finally, the signal from the PIN diode undergoes filtration through a low-pass cosine roll-off filter, resulting in the extraction of the desired output. Table 01 signifies different optimized parameters used in the system architecture.

Table 01
Optimized Simulation parameters

Parameter	Values
Data Rate of the Proposed System	6.4 Gbit/s
WDM channels	5
Channel Spacing	1 nm
White light Source	Center wavelength = 1535.32 nm
Signal format	Non-return to zero code (NRZ)
Photodetectors	PIN

A. Transmitter End

Number In this system architecture, two white light sources have been used as the broadband optical source. The white light source is connected to the MZM. In this system, MZM has been used to control the amplitude of the optical wave of the system. Two PRBS generators were used to generate random bit sequences in the system connected to two different NRZs. NRZs then connected to MZM. These two distinct MZM are connected to two pairs of FBGs which is one pair each to the system. In the system architecture, the FBG provides a signature code at its output and the signature code of every channel is unique[17], [18]. This is the mention-worthy reason for implementing FBGs as an encoder whose function is to generate a special signature code for every individual to establish a distinction between every signal at the resulting end. This same operation is also applicable to the lower part of the transmitting part. Then the signal from two sets of FBGs is combined in the power combiner and then sent to the fiber section of the proposed system architecture. For WDM operation, 5 WDM channels are combined in WDM MUX at the transmitting end to send the signal to the fiber section. The PRBS in this model produces an N-bit sequence[19], [20]:
When,

$$N = T_w B_r \quad (6)$$

$$N_G = N - n_1 - n_t \quad (7)$$

N is the length of the generated pseudo-random sequence. It represents the number of bits in the sequence before it repeats. T is the bit period or duration of one bit in the PRBS sequence. It is the time taken for one bit to be transmitted. w is the pulse width or width of the individual pulses in the PRBS sequence. B is the bit rate or the rate at which bits are transmitted in the sequence. r is the repetition rate or the rate at which the PRBS sequence repeats. N_G represents the total number of bits in the generated PRBS sequence. N is the length of the PRBS sequence, which is the total number of bits in the sequence before it repeats. n_1 is the number of "1" bits in the PRBS sequence. n_ts the number of transitions (changes from "0" to "1" or from "1" to "0") in the PRBS sequence. A sequence with a period of (2^k-1) is created using the PRBS generator with order k. Here $k = log_2(length\ of\ PRBS\ sequence + 1)$

Depending on the Rectangle form parameter, this model may generate pulses with varying edge shapes at NRZ[21], [22]:

$$E(t) = \begin{cases} 1 - e^{\left(\frac{t}{c_r}\right)}, 0 \leq t < t_1 \\ 1,\ t_1 \leq t < t_2 \\ e^{-\left(\frac{t}{c_f}\right)}, t_2 \leq t < T \end{cases} \quad (8)$$

The fall time coefficient is denoted by *"c_f"* , the rising time coefficient by *"c_r"*, and the bit period by *"T"*. To produce pulses with precise values for the parameters Rise time and Fall time, *"t_1"* and *"t_2"*, along with *"c_r"* and *"c_f"*, numerical computations are performed. The following equations represent how the MZ modulator behaves[23], [24]:

$$E_{out}(t) = E_{in}(t) \cdot \cos(\Delta\theta(t)) \cdot \exp\,(j \cdot \Delta\varphi(t)) \quad (9)$$

where the phase difference between the two branches is:

$$\Delta\theta(t) = \frac{\pi}{2} \cdot (0.5 - ER \cdot (Modulation(t) - 0.5)) \quad (10)$$

Where: $$ER = 1 - \frac{4}{\pi} \cdot arctan\left(\frac{1}{\sqrt{extrat}}\right) \quad (11)$$

and the signal phase change "$\Delta\varphi$" is as follows:

$$\Delta\varphi(t) = SC \cdot \Delta\theta(t) \cdot (1 + SF)/(1 - SF) \quad (12)$$

where the value of the parameter *SC* is either 1 or -1 depending on whether the negative signal chirp is true or false. The electrical input signal is modulation *(t)*, the symmetry factor is *SF*, and the extinction ratio is extracted. Normalization of the electrical input signal is done between 0 and 1. The average power is computed using the following formula for parameterized and noise bin signals. At the power combiner, the signal output for each port is attenuated by[25], [26]:

$$E_{outX,Y}(t) = \frac{10^{\frac{-\alpha}{20}}}{\sqrt{N}} \sum_1^N E_1 N_{XY}(t) \quad (13)$$

$E_{outX,Y}(t)$ represents the overall output error at time "t" for the process related to *X* and *Y*. α is a parameter, that values the attenuation or loss in decibels. *"N"* is the number of terms in the summation. $\sum_1^N E_1 N_{XY}(t)$ is the summation of *N* terms, where $E_1 N_{XY}(t)$ likely represents individual errors at time *t* between *X* and *Y*. The index *i* ranges from 1 to *N*, indicating the summation of errors for each term. $\frac{10^{\frac{-\alpha}{20}}}{\sqrt{N}}$ This is a scaling factor applied to the summation. It involves the parameter α and the square root of *N*. Table 02 signifies different optimized parameters used in the transmitting end of the system architecture.

Table 02
Optimized Simulation parameters for transmitting end.

Parameter	Values
PRBS generator	
Bit rate	6.4 Gbit/s
Order	2^k-1
Mark probability	0.5
NRZ generator	
Rectangle shape	Exponential
Amplitude (wrt DC)	1 a.u
Sample rate	$6.4\text{x}10^{11}$ Hz
White light source	
Center frequency	1535.32 nm, 1540.32 nm, 1545.32 nm, 1550.32 nm, 1555.32 nm
Average power	-115 dBm
Power spectral density	-60 dBm/Hz
Sample rate	$6.4\text{x}10^{11}$ Hz
Noise bins spacing	10 GHz
Mach-Zehnder Modulator	
Extinction ratio	30 dB
Symmetry factor	-1
Fiber Bragg Grating	
Bandwidth	0.3 nm
Reflectivity	0.9998
Sample rate	500 GHz
Noise threshold	-100 dB
Noise dynamic	5 dB
Noise calculation bandwidth	1 THz

B. Fiber Section

With the increase in population, the demand for bandwidth has also increased in optical networks. To mitigate the problem the installation of new optical fiber would be expensive, rather effectively using the current optical fiber would be a wise decision. However, attenuation and dispersion in the signal's transmission line are the primary problems faced by the fiber optical network. So, using an efficient system network architecture could solve the problem. The proposed system architecture has shown that SMF or single-mode fiber could be used in wavelength division multiplexing. SMF is utilized as the transmission fiber because it has a small core diameter, which provides for the effective single-mode propagation of light. It also has low dispersion, which means that multiple wavelengths of light propagate at the same speed, eliminating pulse broadening and enabling high-speed data transmission over great distances. DCF is utilized as a compensating fiber to compensate for the dispersion introduced by the SMF[27], [28]. Dispersion is a phenomenon where distinct wavelengths of light travel at different speeds, generating pulse spreading and distortion. DCF has a strong negative dispersion coefficient that can be utilized to compensate for the positive dispersion created by the SMF, canceling out the dispersion and allowing for high-quality signal transmission. In SAC-OCDMA systems, the synergy of SMF and DCF ensures effective signal transmission, minimizing distortion and pulse broadening[29], [30], [31]. The combination of SMF with DCF provides a good balance between efficient signal transmission and excellent dispersion compensation, making it an attractive choice for high-performance optical communication systems. Post compensation model is being used to calculate the length of SMF and DCF in the proposed system architecture. That is[32], [33]:

$$D_{SMF} \times L_{SMF} = -D_{DCF} \times L_{DCF} \tag{14}$$

Where D_{SMF} and L_{SMF} signify the dispersion and length of SMF, likewise, $-D_{DCF}$ and L_{DCF} indicate the dispersion and length of SMF. The single-mode fiber has been selected for the abovementioned recommended design. 16.75 ps/nm/km is taken into account as the SMF's dispersion and 0.2 dB/km is taken into account as its attenuation. DCF or Dispersion Compensation Fiber is used to adjust this parameter. The dispersion and attenuation value of DCF are taken -85ps/nm/km and 0.5 dB/km respectively. No problem was found during the synchronization of both signals and the proposed signal runs perfectly without interference. EDFA is being used to amplify the signal. Erbium-Doped Fiber Amplifiers (EDFAs) are used in optical fiber communication to boost signals by efficiently amplifying light signals in the erbium-doped core, enabling long-distance transmission without the need for frequent signal regeneration[33], [34], [35]. The gain factor of EDFA is calculated based on SMF and DCF. Table 03 signifies different optimized parameters used in the system architecture's fiber section.

Table 03
Optimized Simulation parameters for fiber section.

Parameter	Values
Single Mode Fiber (SMF)	
Length	10 km
Dispersion	16.749 ps/nm.km
Dispersion slop	0.075 ps/nm^2.km
Differential group delay	0.2 ps/km
Effective area	80 um^2
Fract. Raman contribution	0.18
Attenuation	0.2 dB
Dispersion Compensating Fiber (DCF)	
Length	2 km
Dispersion	-83.748 ps/nm.km
Dispersion slop	0.075 ps/nm^2.km
Differential group delay	0.2 ps/km
Effective area	80 um^2
Fract. Raman contribution	0.18
Attenuation	0.5 dB
Erbium Doped Fiber Amplifier (EDFA)	
Gain	3 dB
Noise figure	5 dB

C. Receiving End

The received signal from the optical fiber is distributed into two portions using a 1x2 optical splitter corresponding to two channels of the system at the receiving end. For increasing the number of channels, the signals are multiplexed by WDM and then demultiplexed by the WDM demultiplexer. To split the signal into two segments for dual channels, a 1x2 optical splitter has been employed. In the simulated FBG encoding system of this research, a complementary decoder is employed both at the transmitter end and the decoder's end to filter out the lower segment of the signal. Simultaneously, a direct decoder is utilized at the transmitter after the signal passes through FBGs to filter out the higher segment, and this direct decoder is also employed at the decoder's end. Two photodetector diodes are utilized to detect the optical signal output of the component. [36], [37]. A low-pass Cosine roll-off filter has been employed to eliminate the unwanted spectrum from the desired signal spectrum. To ensure the accuracy of the preliminary results of this research, the proposed SAC-OCDMA architecture has been simulated with commercially accessible Optisystem software.

This proposed SAC-OCDMA system architecture utilizes the AND subtraction detection approach. This process entails calculating the data's product from various sequences. The approach enables several channels to use a single optical channel without interfering. The receiver uses the technique to decode the channel's output[38], [39]. Using multiple replicas of the data, this procedure entails calculating the product of the data. The "AND subtraction" method's output effectively reassembles the channel's original data signal while canceling out the data signals from other channels. At the power splitter end the signal output for each port can be calculated as[40], [41]:

$$E_{OutX,Y}(t) = \frac{E_{1n_{xy}}(t)10^{\frac{-\alpha}{20}}}{\sqrt{N}} \tag{15}$$

$E_{1n_{xy}}(t)$ represents the individual error at time t between X and Y. $1n_{xy}$ indicates that the error is associated with the first term in a sum involving N terms. α is a parameter, and its value is the attenuation or loss in decibels. N is the number of terms in the summation. $\frac{10^{\frac{-\alpha}{20}}}{\sqrt{N}}$ This is a scaling factor applied to the summation. It involves the parameter α and the square root of N.

The Cosine Roll Off Filter has the following transfer function:

$$H(f) = \left\{ \frac{\alpha}{\sqrt{0.5 \cdot \alpha^2 \cdot \left[1 + \cos\left(\frac{|f| - f_1}{r_p \cdot \Delta f_{FWHM}} \cdot \pi\right)\right]}} \right\} \left\{ \begin{array}{c} |f| < f_1 \\ f_1 \leq |f| < f_2 \\ f_2 \leq |f| \end{array} \right. \tag{16}$$

where f_c is the filter cutoff frequency, r_p is the roll-off factor, and α is the value for Insertion loss.

Here are the values of f_1 and f_2:

$$f_1 = \left(1 - r_p\right) f_c \quad 0 \leq r_p \leq 1 \tag{17}$$

$$f_2 = \left(1 + r_p\right) f_c \quad 0 \leq r_p \leq 1 \tag{18}$$

Table 04 signifies different optimized parameters used in the receiving end of the system architecture.

Table 04
Optimized Simulation parameters for the receiving end.

Parameter	Values
Photodetector PIN	
Responsivity	1 A/W
Dark current	10 nA
Thermal power density	$10x10^{-24}$
Absolute temperature	298 K
Load resistance	50 Ohm
Shot noise distribution	Gaussian
Junction capacitance	3 pF
Modulation bandwidth	2 GHz
Sample rate	$3.2x10^{12}$
Central frequency	1535.32 nm, 1540.32 nm, 1545.32 nm, 1550.32 nm, 1555.32 nm
Low pass cosine roll-off filter	
Depth	100 dB
Roll-off factor	0.5
Electrical Subtractor	
Bit rate	$1x10^{10}$ Bits/s
Sequence length	128 bits
Samples per bit	64
Number of samples	8192
Sensitivity	-100 dBm
Resolution	0.1 nm

V. Simulation Result and Discussion

A. Performance evaluation of SAC-OCDMA with different fiber lengths using optimized parameters.

The simulation is conducted using a data rate of 1.6 Gbit/s, FBG bandwidth of 0.3 nm, and a transmission distance of 336 km to evaluate the impact of the bit error rate (BER) and quality factor (Q-factor) on the transmission distance. The simulation is performed using 10 channels, resulting in a Q-factor of 6.09249 and a BER of less than 10^{-9}. Figure 03 displays the variation in minimum logarithmic bit error rate (BER) with respect to transmission distance for different channels. The proposed method remains efficient for transmitting data at a rate of 6.4 Gbit/s across 10 channels. Subsequently, the obtained value of Bit Error Rate (BER) is no longer deemed satisfactory. Figure 03 demonstrates that the minimum logarithmic bit error rate (BER) is influenced by both the bit rate and transmission distance. The minimum logarithmic bit error rate (BER) worsens as the distance between the transmitter and receiver increases and the bit rate increases.

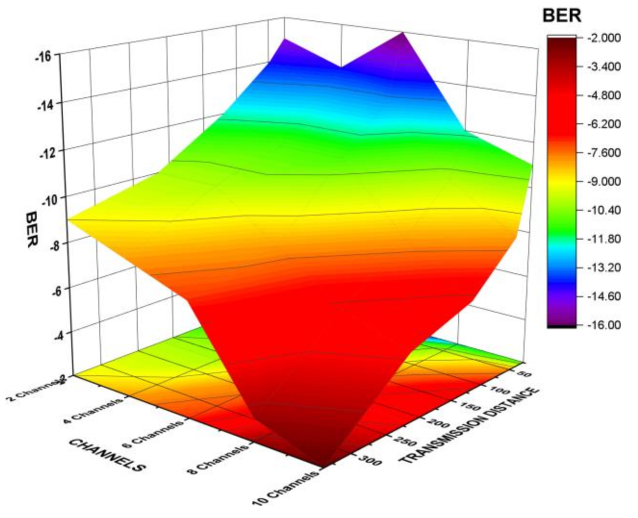

Fig 03 Min log BER vs Transmission distance for 5 WDM channels

B. Simulation of the performance of a SAC-OCDMA system of 10 channels

The proposed SAC-OCDMA system could accommodate up to 10 channels or 5 WDM channels due to the new orthogonal code. By employing WDM, the system allows multiple data streams to be carried by different wavelengths of light, effectively maximizing the channel capacity. Five unique light wavelengths, spaced apart to avoid interference, make up the WDM channels in the C-band region of the spectrum. The wavelength of the channels are channel 01 = 1535.32nm (Range: 1533.32nm-1537.32nm), channel 02 = 1540.32nm(Range: 1538.32nm-1542.32nm), channel 03 = 1545.32nm (Range: 1543.32m-1547.32nm), channel 04 = 1550.32nm (Range: 1548.32nm-1552.32nm) and channel 05 = 1555.32nm (Range: 1553.32nm-1557.32nm. A 1 nm channel spacing is employed to achieve inter-channel isolation, effectively mitigating spectral overlap. To assess the system's scalability, simulations were conducted for varying channel counts (2, 4, 6, 8, and 10) with a constant FBG bandwidth of 0.3 nm and data rate of 6.4 Gbit/s. The ability to distinguish individual channels through their unique optical signatures enables the encoding system to validate the correct assignment of distinct signature codes by the FBG for each channel. Figure 04 depicts the Q-factor's relationship with the distance of transmission and channel count. Figure 05 depicts how the Q-factor decreases as the number of channels rises. As a result of a transmission distance of 24 km, the average Q-factor of 6.7307 is still enough for up to 10 channels. The value of the Q factor declines gradually as distance increases and falls below an acceptable level from the BER analyzer, it can also observe an eye diagram. With the increase of channels and the length of the fiber, the eye-opening was deteriorating. Figure 05 depicts the observed degradation of the eye diagram (transition from 'a' to 'd') with increasing channel count and fiber length. Notably, both 2-channel ('a' and 'b') and 10-channel ('c' and 'd') configurations demonstrate a decline in eye quality as channels and fiber length are increased. By optimizing for minimum log BER and Q-factor, the system achieved a maintained bit rate of 6.4 Gbit/s over a 24 km transmission distance with up to 10 channels, demonstrating its effectiveness under these operating conditions.

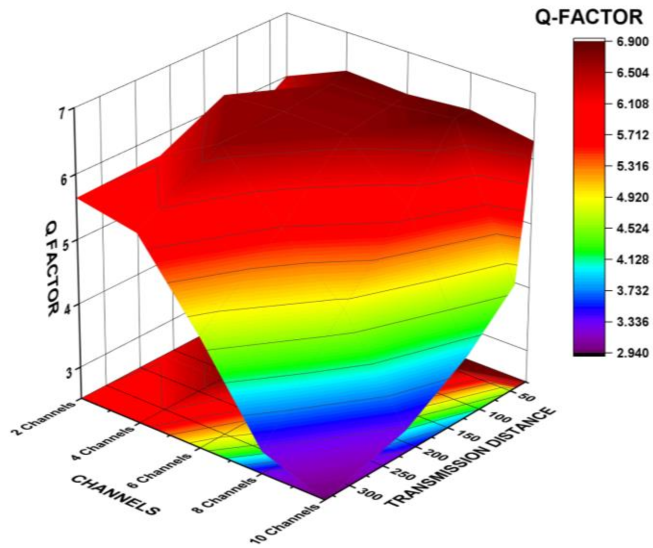

Fig 04 Effect of Q factor on the number of WDM-channels and transmission distance up to 336 km

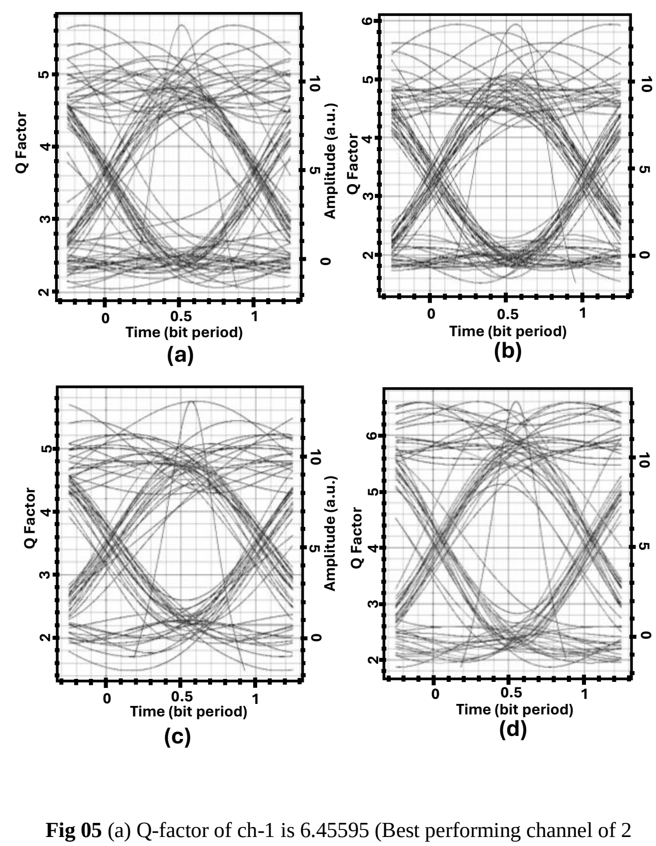

Fig 05 (a) Q-factor of ch-1 is 6.45595 (Best performing channel of 2 channel configuration) (b) Q-factor of ch-2 is 6.09249 (Worse performing channel of 2 channel configuration) (c) Q-factor of ch-1 is 6.7307 (Best performing channel of 10 channel configuration) (d) Q-factor of ch-10 is 2.95421 (Worse performing channel of 10 channel configuration)

C. Performance evaluation of SAC-OCDMA by WDM from optical spectrum analyzer (OSA) for 10 channels over a 24 km distance using optimized simulation parameters.

Figure 6 shows the optical spectrum captured by a dual-port OSA, representing the output of a WDM-MUX and WDM-DEMUX system. Five distinct lines are visible, corresponding to five individual channel sets extracted from a white light source. These channels operate within the C-band frequency range, spanning wavelengths from 1535.32 nm to 1555.32 nm. This confirms the successful operation and individual channel integrity within the designed communication band. The variation of minimum Optical signal-to-noise ratio (OSNR) across different transmission distances for various channels serves as a crucial metric in optical communication systems. It provides insights into the

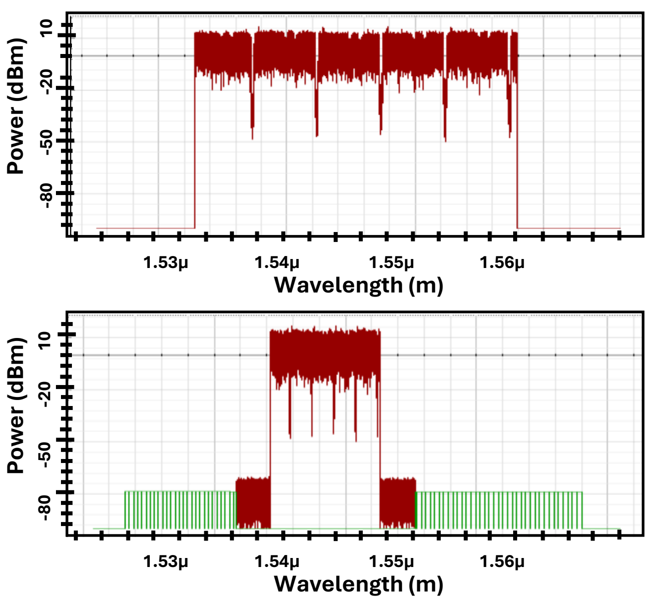

Fig 06 Optical spectrum from dual port OSA connected to WDM MUX and WDM DEMUX over a transmission distance of 24 km.

signal quality degradation as the distance increases, helping to assess the system's performance across diverse communication scenarios. Monitoring this variation aids in optimizing network design and ensuring reliable data transmission across varying transmission distances. Figure 07 illustrates how the minimal OSNR varies for transmission spans ranging from 24 to 336 kilometers. Additionally, analyzing the minimum log BER (bit error rate) versus OSNR for these distances, provides insights into the signal robustness, demonstrating how the bit error rate varies with optical signal strength and noise levels are essential for optimizing performance in different communication scenarios. The network's BER performance is portrayed in Figure 08 by exhibiting the minimum log BER versus the minimum OSNR.

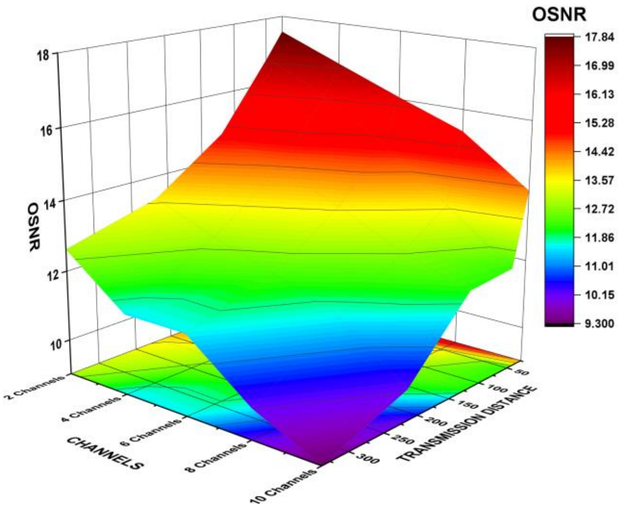

Fig 07 Variation of minimum OSNR over different transmission distances up to 336 km for different WDM channels.

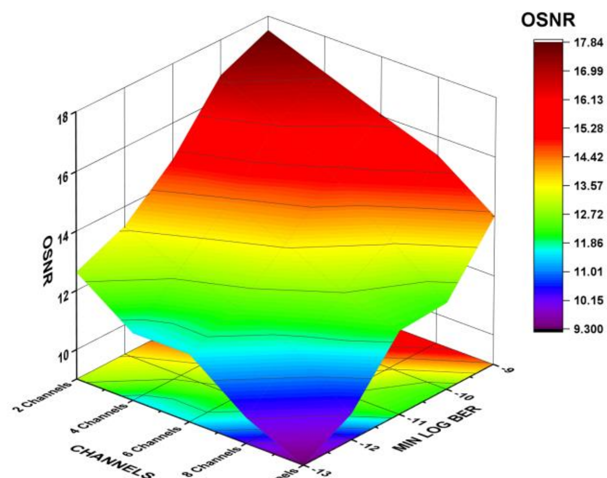

Fig 08 Min log BER vs OSNR for different WDM channels.

VI. COMPARISON WITH SIMILAR RESEARCH OUTPUT

Multiple studies have examined the efficacy of various coding methods in SAC-OCDMA systems. Sokaina successfully achieved a data throughput of 100 Mbit/s for 13 channels across a transmission distance of 5 km utilizing Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) using m-sequence and Hadamard codes. Multiple studies have examined the efficacy of various coding methods in SAC-OCDMA systems. Sokaina successfully achieved a data throughput of 100 Mbit/s for 13 channels across a transmission distance of 5 km utilizing Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) using m-sequence and Hadamard codes[37]. She also achieved 600 Mbit/s for 3 channels over a 25 km transmission distance and 1.6 Gbit/s for 8 channels over a 5 km transmission distance using a Narrowband Bragg Filter and SMF[16]. Mohanad achieved a data rate of 1.24 Gbit/s for 2 channels over a 54.5 km transmission distance and 2.48 Gbit/s for 4 channels using 2D-CS coding[4]. Meftah achieved a data

TABLE 5.
PERFORMANCE COMPARISON OF THE PROPOSED SYSTEM WITH THE PREVIOUS WORKS

Researchers	Coding Technique	Net Data rate	Transmission range	Number of channels	Transmission medium
Sokaina[16], [37]	m-Sequence and Hadamard Code	100 Mbit/s	5km	13	SMF
			45km	8	
	Narrowband Bragg filter	600 Mbit/s	25km	3	SMF
		1.6 Gbit/s	5km	8	
Mohanad [4]	2D-CS	2.48 Gbit/s	20km	4	SMF
		1.24 Gbit/s	54.5km	2	
Meftah [42]	2D cycle shift code	662 Mbit/s	63km	4	SMF
Suresh [39]	EDW and MDW	662 Mbit/s	60km	3	SMF
Liu Yan [10]	WZCCLS code	4.8 Gbit/s	25km	4	SMF
Proposed Architecture for two channels	Narrowband Bragg filter	1.6 Gbit/s	336km	2	SMF + DCF
Proposed Architecture for ten channels	Narrowband Bragg filter	6.4 Gbit/s	24km	10	SMF + DCF

rate of 662 Mbit/s for 4 channels over a 63 km transmission distance using SAC-OCDMA[42]. Suresh achieved similar data rates using EDW and MDW coding techniques over a 60 km transmission distance for 3 channels[39]. Liu Yan achieved a data rate of 4.8 Gbit/s for 4 channels over a 25 km transmission distance using WZCCLS coding[10]. Our proposed SAC-OCDMA system architecture surpasses existing hybrid techniques in key performance areas, as detailed in Table 5. By efficiently utilizing the optical spectrum, the system enables higher user capacity compared to conventional approaches. Additionally, it achieves significantly longer signal transmission, demonstrated by reliable data transmission at 1.6 Gbit/s over 24 km and 6.4 Gbit/s over a remarkable 336 km using standard single-mode fiber (SMF) with dispersion compensation fiber (DCF). This translates to both extended reach and increased network potential. Furthermore, the architecture supports a larger number of concurrent user channels compared to existing SAC-OCDMA systems, signifying greater network capacity. While achieving an excellent average bit error rate (BER) of less than 10^{-9} using SMF and DCF, our system outperforms most existing networks in both transmission distance and bit rate capabilities. When considering both factors simultaneously, the proposed method offers a clear advantage over previous similar studies, making it a promising candidate for real-world applications demanding both reach and speed.

VII. CONCLUSION

This research investigated the performance of a proposed SAC-OCDMA system architecture through extensive simulations. The results show that the system maintains efficiency across various data rates, channel counts, and transmission distances. Notably, the system effectively transmits data at 2 channels over 336 km and scales up to 10 channels at 6.4 Gbit/s over 24 km, demonstrating its adaptability. This trade-off between channel count and transmission distance suggests the system's potential for various applications. Furthermore, the use of narrowband filters promises improved data speeds, faster services, and enhanced security for telecommunication users, highlighting the significant value of this proposed SAC-OCDMA system. The practical consequences of utilizing SAC-OCDMA in real-world scenarios involve substantial enhancements in data rates and longer transmission distances, hence improving the efficiency and scalability of fiber optic networks. By combining SAC-OCDMA with Wavelength Division Multiplexing (WDM), it is possible to significantly expand the number of active channels, hence enabling high-capacity communications. This feature is very advantageous for sophisticated network infrastructures in telecommunications, data centers, and broadband services. Moreover, the system's resistance to interference and exceptional performance over extended distances make it a practical solution for safeguarding networks against future challenges, guaranteeing their ability to handle increasing data requirements and facilitate the adoption of new technologies.

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