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3.52 TBPS HYBRID OFDM WDM PON COVERING 120-KM LONG-REACH DISTANCE USING 4-ARY QAM & DIRECT DETECTION TECHNIQUE FOR BEYOND NG-PON-2 APPLICATIONS

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ABSTRACT

This paper proposes a Wavelength Division Multiplexed, Orthogonal Frequency Division Multiplexed Passive Optical Network (WDM-OFDM-PON) utilizing 4-ary Quadrature Amplitude Modulation (QAM). This paper investigates the system by evaluating the effect on Optical Signal Noise Ratio (OSNR), Error Vector Magnitude (EVM) and Power Loss in both Optical Line terminal (OLT) and Optical Network Unit (ONU). The Direct Detection Technique approach achieves data rate of 55 Gb/s while maintaining sufficiently low Bit Error Rate (BER) securing IEEE standard. Through this endeavour a single feeder PON consisting of 64 channels is designed with unprecedented capacity of 3.52 Tb/s over a transmission distance of 120km. considering the results achieved, the capacity obtained is the most supreme compared to other WDM-OFDM-PON systems so far.

Keywords: OFDM, wavelength division multiplexing (WDM), direct detection, optical fiber communication, QAM.

INTRODUCTION

As we step into the future, applications requiring high data rates are increasing and to make it feasible for production, low-cost is essential and these are some of the important factors that drives the research for future optical networks. For superior performance and cost efficiency, Passive optical networks (PONs) has been considered as the optimum choice for fiber-to-the-home (FTTH). But the increasing complexity of conventional modulation techniques, like quadrature phase shift keying (QPSK) or quadrature amplitude modulation (QAM), at high data rates negates the desirable qualities of the PON [1-3].

As a standard for high capacity PONs, Wavelength Division Multiplexing (WDM) has been preferred due to a significantly less requirement for computation and parallelization [4]. Moreover, WDM-PON is preferable since optical components can be shared between different WDM channels and therefore, bandwidth gets increased over optical fiber by sending several signals concurrently at different wavelengths [5]. Basically, by utilizing multiple lasers operating at numerous frequencies in the L-band of the spectrum and multiplexers, WDM-PONs can transmit data from multiple channels simultaneously through one single mode fiber (SMF). Furthermore, due to its simple structure, higher spectral efficiency [6] and low maintenance cost, it would be a viable and lucrative technique to implement in order to enhance the total performance and capacity of the system [7]

Another candidate to accommodate the demand for higher data rates is orthogonal frequency division multiplexing (OFDM) PON. Apparently, the process of encrypting digital data transmission on various carrier frequencies is called OFDM [8]. It is widely acceptable because of its boisterousness to narrowband interference and frequency selective fading [9]. OFDM is a multicarrier technique in which the high speed data stream is transmitted on a number of different frequency low speed-data channels [10]. This multiplexing technique yields the convenience of electronic equalization and provides robustness against multipath fading of legacy wire-less OFDM systems into the optical domain to attain impairment-sustainable ultra-high-speed optical systems [9]. In addition, it is highly resilient to inter symbol interference (ISI) caused by chromatic dispersion, which makes it highly suitable for such applications [11]. With the addition of a guard interval known as cyclic prefix, the transmitted signal is extremely immune to ISI [12]. Likewise, it buttresses symmetric data rates, dynamic bandwidth allocation and cost-effective implementation [13]. In addition to this, the utilization of inverse fast Fourier transform (IFFT) makes OFDM very efficient in terms of computation. Exploiting the economic benefits of direct detection optical OFDM (DDO-OFDM), the optical network units (ONU) can be made cost effective while providing sufficient performance.

Utilizing the techniques mentioned and discussed previously, we are proposing a high capacity PON, with high data rates per channel. The hybrid WDM-OFDM-PON was incorporated with a higher modulation technique, in the form of a 4-ary QAM. We have taken the DDO-OFDM approach when considering this network, over the coherent optical OFDM (CO-OFDM) approach to make the ONU cost effective. In this paper, the proposed optical network, along with the achieved results, were extensively studied, while considering performance parameters such as signal to noise ratio (SNR), error vector magnitude (EVM) and power loss. In addition, constellation diagrams were inspected to evaluate and compare the quality of the transmitted and retrieved data.

VOL. 13, NO. 23, DECEMBER 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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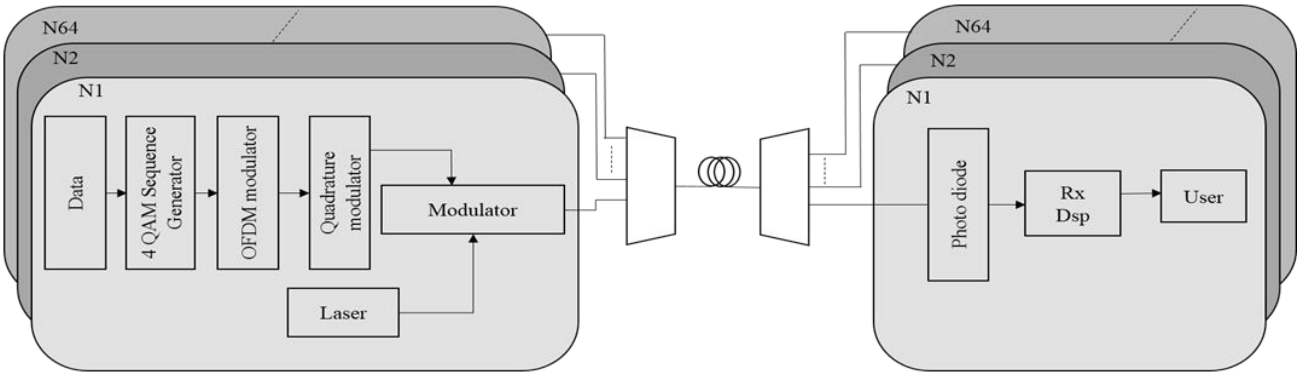

Figure-1. The proposed architecture of the WDM-OFDM-PON.

The results that were obtained are quite an improvement of the previous network design which was developed. In the beginning, we succeeded to achieve a capacity of 2.2Tbps using 40 channels over a length of 120KM where as previously it was only 1.92Tbps using 40 channels over a distance of 100KM. The data speed of each channel was 55Gbps compared to the 48Gbps obtained before. Later on, we have developed the network to its furthest limit and achieved a record unprecedented capacity of 3.52Tbps using 64 channels ensuring each of the channel performing successfully, which was more than 70% improvement than the last results. The entire design of the network was constructed in such a way that the overall complexity was kept to a minimum to ensure that the network is as simple as possible [14], [15].

HYBRID WDM-OFDM-PON ARCHITECTURE CONCEPT

An OFDM-WDM-PON can be interpreted as a passive optical network with point-to-multipoint physical layer architecture with orthogonal frequency division multiplexing and wavelength division multiplexing. Since it is a passive optical network, there are no active elements, which are electrically powered, like amplifiers or repeaters, in optical outside plant (OSP) [16], [17].

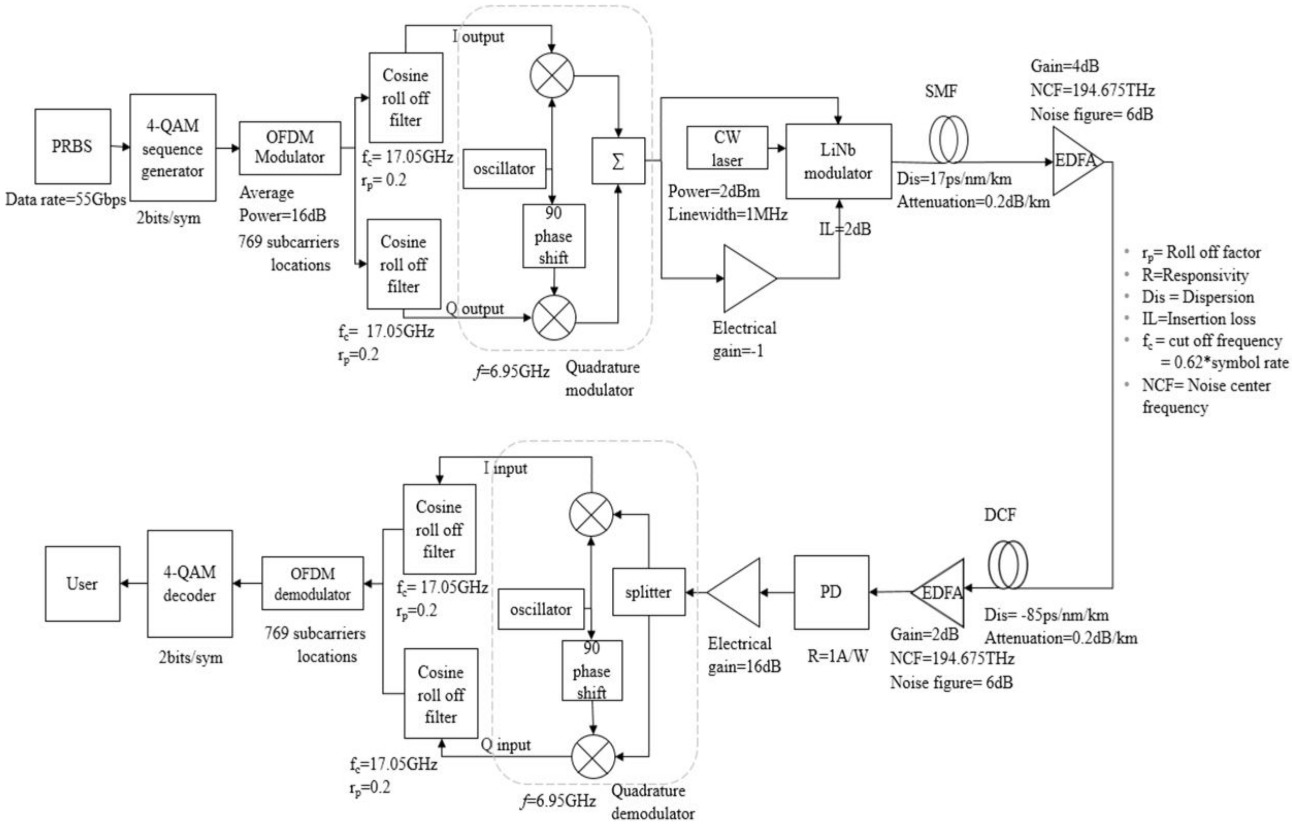

Figure-2. Experimental setup for a single channel WDM-OFDM-PON.

Initially, pseudo random sequence bits, which are actually binary sequence, were generated using Pseudo random binary sequence (PRBS) generator [18]. Basically, the symbols from the QAM sequence generator are then passed through the OFDM modulator where primarily the bits are converted to parallel from serial arrangement. Then they are transformed from frequency domain to time domain using Inverse Fast Fourier Transformation, which is cost effective to implement, and then guard bands are added by incorporating cyclic prefix to it to maintain orthogonality [19] and prevent interference as it abolishes inter-symbol interference (ISI) and inter-frame interference (IFI) [20], [21]. Finally, the bits are rearranged by parallel-to-serial converter and analog signal is sent out using DAC. Next, roll off filters separate the output from OFDM modulator into both in-phase and quadrature components. The Quadrature modulation coalesce two amplitude-modulated (DSB) carrier signals in a way such that the original amplitude modulations are distinguishable, by coherent demodulation, at the receiver [22].

Then, we need a wavelength specific optical source or its equivalent at each premise. For operational simplicity, a wavelength specified laser, a CW laser was used as it can deliver constant power output during long periods of time [23]. A LiNb MZ modulator was used to produce optical signals from electrical (up-conversion). The input waveguide was divided into two waveguide interferometer arms. A phase shift induces for the wave passing over the arm when voltage is applied across that arms. When the two arms are reconstituted, the phase difference between the two waves is transformed to an amplitude modulation.

In addition, optical gain elements are required in the most cases, since the insertion loss and the coupling loss of optical link including the modulator itself [24]. Finally, the resulting signal, including the outputs from other channels, are multiplexed using WDM multiplexer. Since each channel was identified with a different wavelength, since WDM MUX/DMUX was used as an optical branching device [25]. The optical link represents the distance of the communication fiber. SMF and DCF were used. The length of DCF was used according to the dispersion properties of SMF as it compensates for the chromatic dispersion (CD) produce by the SMF during transmission [26], [27]. In fact, CD is a salient hindering factor which limits the maximum reach of this transmission system [28], [29]. Also, optical amplifiers were added as it ensures the signal does not get attenuated for large distances [30].

However, in the receiving side, at the very beginning the transmitted signal is separated by WDM demultiplexer according to their wavelength. Besides, the direct detection technique was used since it necessitates low cost and complexity [31]. Also, it involves no local oscillator in the detection process. Thus, the process requires the transmitter information to be directly associated with the intensity variation of the transmitted field, therefore a PIN photodiode was used. In direct detection, the instantaneous intensity or power of the incident optical signal is detected and the output of the photo detector is proportional to the incoming field [32]. Next in the Quadrature Demodulator, no new frequency is produced when two sinusoids are added as it is a linear operation. Therefore, the bandwidth of the composite signal is analogous to the bandwidth of the DSB components. Using this technique, the spectral redundancy of DSB permits a doubling of the information efficiently [33]. Afterward, filtered I and Q components were fed into OFDM demodulator removes the guard bands first and then using Fast Fourier Transformation convers the signal from time domain to frequency domain. So, lost symbols due to frequency selectivity can be recovered by using interleaving. Thus, it is almost immune to impulsive parasitic noise and co-channel interference [34]. At last, QAM decoder, decrypt the date and deliver them for the user to read.

PERFORMANCE ANALYSIS OF THE WDM-OFDM-PON

A back to back connection was setup to evaluate some of the performance parameters of the simulation model. An additive white Gaussian noise (AWGN) source was added and amount injected into system was varied. Other transmission parameters were kept constant, with the laser input power at 2 dBm and the linewidth at 1 MHz.

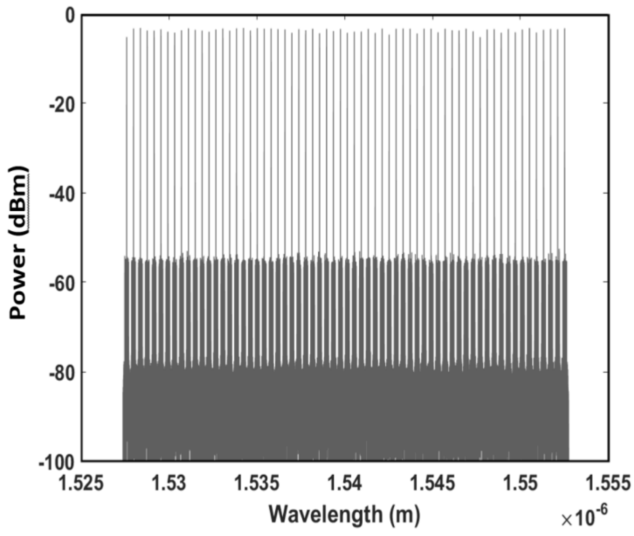

Figure-3. Optical Spectrum of 64 Channel WDM OFDM PON, with laser linewidth of 1 MHz and input power of 2 dBm.

Figure-3 shows the optical spectrum which was obtained from Optical Spectrum Analyzer (OSA) connected forthwith after WDM mux. 64 distinct lines representing 64 different channels from 64 different CW lasers each operating at 64 different frequencies beginning from 193.1 THz to 196.25 THz. Back to back two adjacent channel was set with a spacing of 50 GHz and central line width of 1 MHz. If we observe the figure carefully, we will see the distinct lines are equally spaced and uniformly allocated across the spectrum.

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Transforming the channel frequency to wavelength, we will get the range of wavelength lies between 1528 nm to 1553 nm, which is specified in the figure at x axis whereas the y axis denotes the power of the lasers. The almost equal height of all the distinct lines assures us the equal allocation of power across all the channels. The Side Mode Suppression Ratio (SMSR) was found 50 dBm here and from the spectrum the lowest side mode suppression ratio of 90.40% was calculated. This gives us clear idea about the robustness and fairness of the signal.

The BER performance of the network was observed by plotting it against the Optical Signal to Noise Ratio (OSNR) of the system was plotted and is shown in Figure-4. This graph was prepared from BER test set and WDM analyser connected to the network system. According to the IEEE standards the Forward Error Correction (FEC) limit is 10-3 BER and for our 64 channel WDM OFDM PON system it was corresponding to 25.84 dB OSNR. BER values were converted into log scale and denoted at Y axis whereas OSNR values were denoted at x axis. The Log scale was chosen to reduce numerical complexities of the large values of BER. The FEC limit was used to verify & enhance network performance in later tasks such as transmission distance, signal power strength etc.

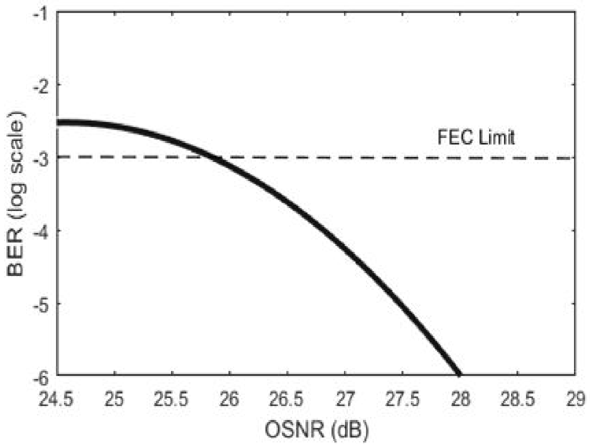


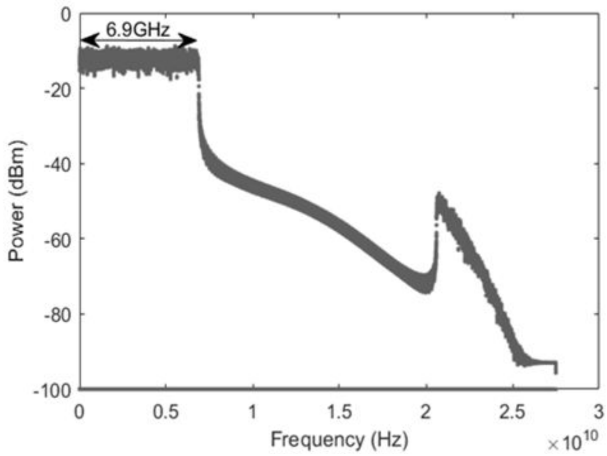
Figure-4. Bit error rate versus optical signal to noise ratio for 64 channels. Forward error correction threshold was seen at OSNR value of 25.84 dB.

To validate the performances of each and individual element of the network, radio frequency spectra of the elements were studied. Figure-5.a. shows the signal of the in-phase branch (I branch) of the OFDM block. The bandwidth of the signal was 6.9 GHz. The figure also showed some aliasing, but was easily removed by using a low pass filter after the signal was passed through the low pass cosine filter. Figure-5.b. shows the signal after it has been up-converted. The signal has a bandwidth of 13.6 GHz after the up-conversion process. Figure-5.c. shows the signal obtained from the photodetector after direct detection. The spectrum clearly shows that the signal does not suffer from ICI. After that the signal is down-converted and the final OFDM signal is seen in Figure-5.d. The figure shows that the original signal is received but with some added noise from the amplification process. But even with the presence of the noise, the operation of the OFDM demodulator remains unaffected because of a large SNR.

The performance study with a back to back connection was done not only to validate the network model, but also to find the threshold values of some parameters, which can be used to validate the performance of the network while transmitting over a large distance.

MAXIMUM TRANSMISSION DISTANCE

In order to evaluate the impact of noise over the signal power, Optical Signal to Noise Ratio (OSNR) was studied. Figure 6 shows the relationship of OSNR over a range of transmission length starting from 24 to 120 km for our 64 Channel Hybrid OFDM WDM PON. OSNR provides us the measurement of the ratio comparing optical signal power and noise power. From these OSNR values we come to know about the impairments in the network while transmitting optical signal. According to the figure, we see that we receive 43.2 dB to 36 dB OSNR values starting from 24 km to 120 km respectively. The OSNR value concluded at 36 dB for transmitting data at 120 km, which is indeed a very healthy ratio.



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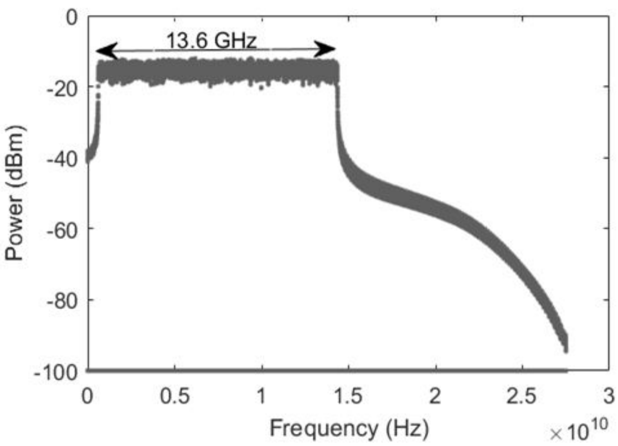

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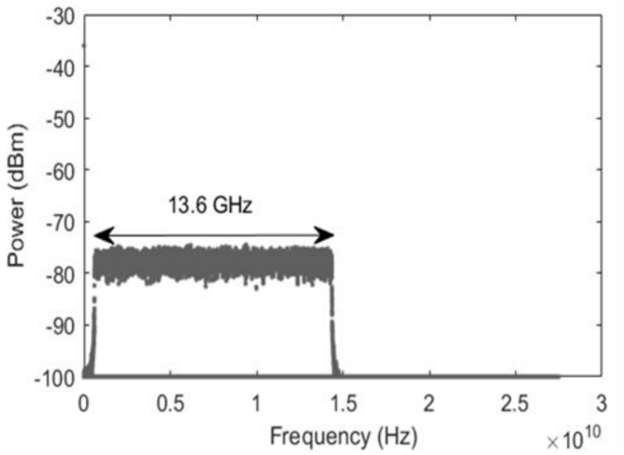

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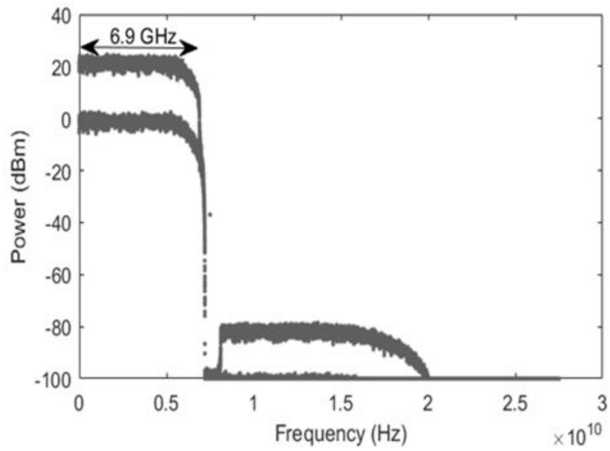


(d)

Figure-5. Radio-Frequency (RF) spectrum of the individual components. (a) OFDM output before up conversion (I-branch). (b) Signal after RF up conversion. (c) Signal after direct detection. (d) Signal after down-conversion.

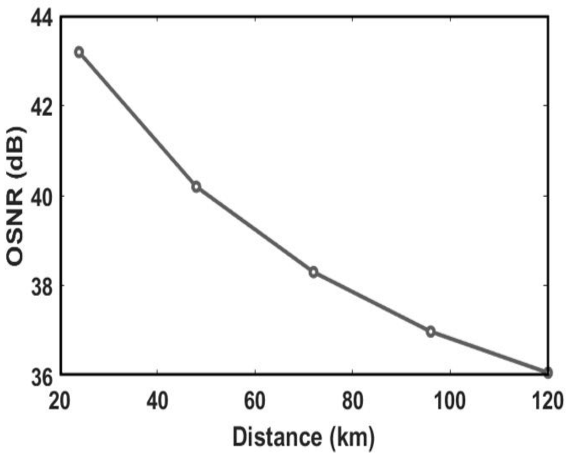


Figure-6. Change of Optical Signal Noise Ratio (OSNR) against the transmission distance of 64 channel OFDM WDM PON network where for up to 120 km its value is 36 dB.

This optical power over noise power ratio is sufficient enough to transmit signals successfully. From the figure, it is also clear that the value of OSNR decreases with the increase of the transmission length. This decrease took place due to the chromatic dispersion generated in the SMF and fiber amplifiers. Besides, attenuation loss also got increased with the escalating fiber length.

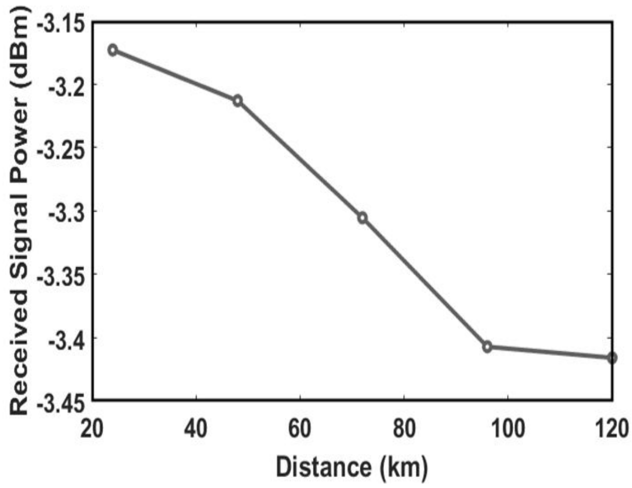


Figure-7. Received signal power with respect to the transmission distance of 64 channel OFDM WDM PON system where the value is found -3.17 dBm for 24 km which ended up at -3.42 dBm for 120 km.

Moreover, Figure-7 illustrates the optical power received at the receiving end with corresponding to different fiber length. The value of optical power at receiving side was found -3.17 dBm for 24 km and with a gradual increase of transmission length up to 120 km the value concluded at -3.42 dBm, which is sufficiently robust. It should be noted that, the power of CW laser at the transmitting side was 2 dBm. Beside the change, we also see that with the progressive transmission distance the value of power decreases gradually. It happens mainly due to the decrement in OSNR the received power gets attenuated as the signal is transferred over longer distances.

Added with that, we have operated EDFA after both SMF and DCF to boost the weakening optical signal as it traverses large distance. This EDFA has some consequences besides boosting and is also accountable for inducing a large amount of the noise observed in the network. Despite these drawbacks, we did not require any signal repeaters and our 64 channel WDM OFDM PON system managed to function successfully up to 120 km.

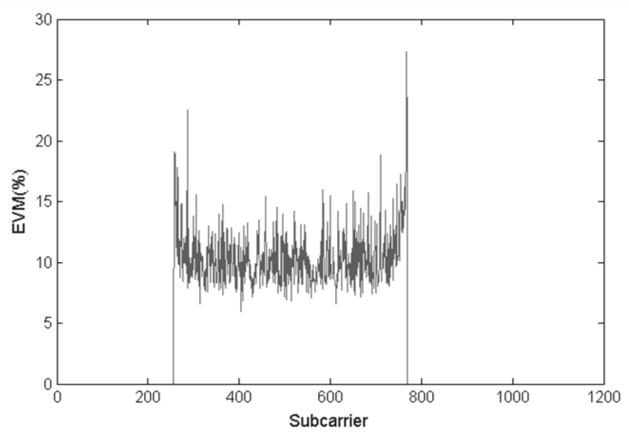
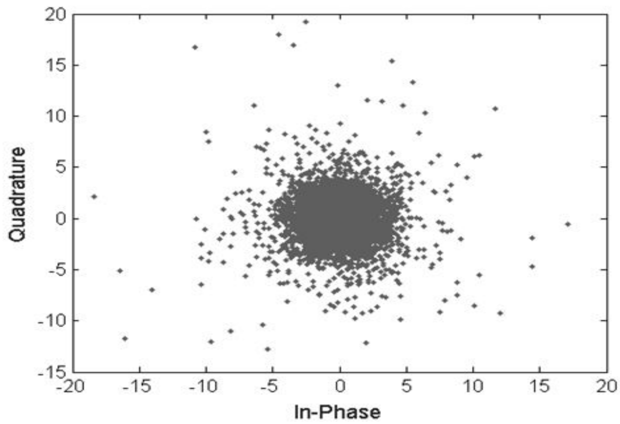


Figure-8. EVM vs. Subcarrier where the range of subcarrier is 512.

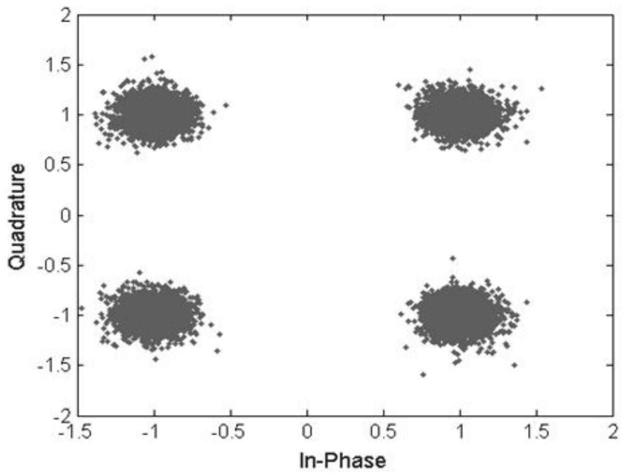
Figure-8 enables us to see the data of Error vector magnitude (EVM) in percentage scale with respect to subcarrier index. For this 64 channel WDM OFDM PON system, the EVM varied between the ranges from 6% to 28%, though the greater part of the subcarriers stayed within 7% to 14%. The range of subcarrier denoted at x axis also indicates our network's subcarrier no. which is 512. The information of EVM was obtained from OFDM Demodulator component and it was observed that with the increment of laser speed and transmission distance it begins to show greater values.

Figure-9(a) shows the constellation diagram before using Dispersion Compensating Fiber (DCF). It is perceptible that the nonlinearity impairments along with chromatic dispersion impact the network system. Therefore, DCF is implemented to ameliorate the signal and eliminate chromatic dispersion that is formed because of the increment in data rate and transmission length. We put DCF immediately after SMF and EDFA. EDFA is used to boost the weakening optical signal after a long distance. After using DCF, EDFA was used in the network system for the second time. The dispersion of SMF was calculated and found 17 ps/nm/km. So, according to its transmission distance and the value of dispersion, the transmission distance of DCF is set one fifth of it and the value of dispersion is set -85 ps/nm/km, which is 5 times than the value of SMF and negative in nature. We also particularized each channel frequency at each related CW laser in the transmission side which then passed through LiNb MZ modulator and forwarded to WDM mux. Beside CW laser, at every OFDM Demodulation component in the receiver side the channel frequency was also specified and at each Photodetector PIN center frequency was specified which is no different than channel wavelength.

Figure-9(b) exhibits the signals constellation diagram after incorporating DCF. In the figure, the



(a)



(b)

Figure-9. Constellation Diagram of 64 channel OFDM WDM PON system (a) before using DCF (b) after using DCF, where Dispersion is set -85 ps/nm/km at the DCF component.

constellation diagram of our full furnished network system is provided. It was observed that, in four area situated at four different quadrants the points got centralized which is due to the exploitation of 4-QAM (Quadrature Amplitude Modulation) system in our network. Deploying amplitude and phase variations in an indistinguishable time QAM technique expands the capacity of a network system. Since 4-QAM architecture was used in our network, the further these four intensity profile belonging to detected constellation points are centralized, the more competent it is for the network. The constellation diagram is never expected to be scattered in more than four different places situated at four quadrants not keeping sound and distinguishable distance to each other. This situation usually take place when the network offers poor BER (Bit Error Rate). This ultimately affects the amount of resistance the system has to offer when subjected to noisy channels. So, a perfect constellation diagram also expresses the BER of that network. From the above two graphs, it is clear that the constellation points became more centralized and the scattering is reduced in four different quadrants due to using of DCF and channel estimation, which ensures us a zero BER valued and a healthy 4-QAM architecture network.

CONCLUSIONS

In this paper, the architecture of WDM-PON was examined and scrutinized by integration of OFDM with direct detection technique. The system was designed by 64 WDM channels with a channel spacing of 50GHz and 512 OFDM signal, each with 55 Gb/s bitrate to create a data rate of 3.52Tb/s. The results achieved clearly validate the reliability of the proposed system. According to the results, a clear constellation diagram of 4-QAM was shown by the system at the receiving side. Moreover, the results reveal that after 120 km long-haul transmission the OSNR which started with 43.2 dB gradually dropped to 36 dB and received signal power got lessened from -3.17 dBm to -3.42 dBm moderately. This decrement of values of OSNR and power with the increment of distance is an obvious phenomenon, but getting worthwhile values for the system till the end was one of the key challenges that were dealt with this research. In addition, higher OSNR is required to retain BER under FEC limit, when the transmission length rises. Nevertheless, non- linearity on the fiber also increases with the increment in OSNR which was also kept in check.

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