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Hybrid compensation of polarization-multiplexed QPSK optical format for high bit rate networks

Omar Y. Shabaan, Omar A. Athab
Department of Information and Communications, College of Al-Khwarizmi Engineering, University of Baghdad, Iraq

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ABSTRACT

Transmitting the highest capacity throughput over the longest possible distance without any regeneration stage is an important goal of any long-haul optical network system. Accordingly, Polarization-Multiplexed Quadrature Phase-Shift-Keying (PM-QPSK) was introduced lately to achieve high bit-rate with relatively high spectral efficiency. Unfortunately, the required broad bandwidth of PM-QPSK increases the linear and nonlinear impairments in the physical layer of the optical fiber network. Increased attention has been spent to compensate for these impairments in the last years. In this paper, Single Mode Fiber (SMF), single channel, PM-QPSK transceiver was simulated, with a mix of optical and electrical (Digital Signal Processing (DSP)) compensation stages to minimize the impairments. The behaviour of the proposed system was investigated under four conditions: without compensation, with only optical compensator, with only DSP compensator and finally with both compensators. An evidence improvement was noticed in the case of hybrid compensation; where the transmission distance was multiplied from (720 km) to more than (3000 km) at 40 Gb/s.

Corresponding Author:

Omar Y. Shabaan,
Department of Information and Communications Engineering,
College of Al-Khwarizmi Engineering, University of Baghdad,
Al-Jadriyah, Baghdad, Iraq.
Email: omar.yousif@kecbu.uobaghdad.edu.iq

1. INTRODUCTION

The enormous bandwidth demand for communication systems has proclaimed fiber-optical lightwave networks as the saving solution, fundamentally in view of the incredibly wide bandwidth related with an optical carrier [1, 2], which can attain (10^{14} Hz) that is more than 10,000 times more than the frequency of a microwave carrier (around 10^{10} Hz) [3]. The mix of Polarization-Multiplexing with QPSK which result in PM-QPSK is developing as one the most encouraging answers for achieving bit rates of 100 Gbps (and higher) and incrementing the limit of lightwave networks [4-6].

There are many reasons for the popularity of PM-QPSK as a modulation format in the physical layer of optical coherent systems; one of them is the simplicity of the transmitter, since it can be implemented with binary driving signals. Moreover, the DSP calculations, particularly phase tracking can be performed with sensible sophistication. In addition, the affectability of QPSK is reasonable for long-haul networks, for example, transoceanic connections. Furthermore, because both in-phase and quadrature-phase components are independently modulated when Gray coding is utilized then PM-QPSK can be considered as 1-D modulation, which implies less synchronization troubles in detection with more noise tolerance [7-9].

In such high-speed systems, linear and nonlinear influences become severest. Polarization Mode Dispersion (PMD) and Chromatic Dispersion (CD) incorporate linear deficiencies [10, 11]; while Self-Phase

Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM) are the nonlinear impairments. Moreover , another factor that influences the performance of long-haul networks, is added by the erbium-doped fiber amplifiers (EDFAs) as a type of noise called Amplified Spontaneous Emission (ASE) noise [12].

Different compensation techniques have been proposed and investigated to reduce the influence of the linear and the nonlinear deficiencies over the physical layer of the optical path. Among them, S. J. Savory, et al. [13] who presented outcomes of a 42.8 Gb/s bit-rate practical transmission, using PM-QPSK. The maximum attained compensation for chromatic dispersion obtained after using a DSP stage with coherent receiver reached 107,424 ps/nm over 6400 km of standard SMF (SSMF). Marco and Mussolin [14], tested a digital back-propagation (DBP) method for fixing the nonlinearities of a PM-QPSK 112 Gb/s communication across a 20 multi-spool link (each of 80 km) without compensation. A serious reduction of approximately 80% was reported, when compared to the standard BP process in order to achieve nonlinear compensation. In 2012, Zhang, Xu, et al. [15] combined a DSP channel estimation adaptively with an equalizer. Their experimental work illustrated a 112-Gb/s PM-QPSK high spectrum narrowing tolerance. They recommended a technique capable to distinguish strict narrow-band signal for bandwidths approaching 20 GHz.

S. Gupta, et. al. [16], used an optical DCF stage to compensate nonlinearities in both an RZ and NRZ modulation through an SMF. The in-line amplification separation was improved up to 140 km in RZ using duty cycle calibration, while for NRZ, they cannot exceed 80 km. R. S. Asha [17] improved the Q factor, RF output power, and extinction ratio by 21 dB, 3.5 dB, and 20 dB respectively using chirped fiber Bragg grating (CFBG), without a DCF; as compared to the same system when both DCF and FBG were implemented. The modulation format was set to an optical single sideband with 10 Gb/s through the comparision. N. Kathpal and A. K. Garg [18] proposed a novel reparation technique to mitigate dispersion degradation in Radio over Fiber (RoF) system named Alternate Mark Inversion–Symmetrical–Symmetrical-Post (AMI–SSP). It was tested at 100 Gb/s for 700 km optical link achieving a 11.93 Q-factor with very low BER of approximately $3.46*10^{-33}$. A. Sharma, et al [19], compared dispersion compensator composed of DCF and FBG for a 120 km optical link at 100 Gb/s. Results indicates that optical pre-compensation scheme using only DCF has bigger Q-factor corresponding to the DCF and FBG combination.

As listed above, some researchers used various DSP techniques to compensate for the impairments whereas others utilized the passive optical components to achieve the same goal [20-22]. Consequently, in this work, a combination of optical & electrical compensation stages was proposed and added to the physical layer of the PM-QPSK system to minimize the unwanted impairments.

2. ELECTRICAL AND OPTICAL COMPENSATION CONSIDERATIONS

The main goal of a wideband optical fiber system is to avoid signal regeneration for the lengthiest attainable distance with uppermost possible data throughput. To attain this characteristic, two compensation techniques may be used; electrical, using DSP method, or optical, using passive fiber devices.

2.1. Optical Compensation

Main dispersion compensation techniques that are used today in optical fiber communication systems are FBG and DCF, planar waveguide technology and imaged phased array [8]. DCF based on FBG is widely used in the dispersion compensation scheme. The positive dispersion of transmission fiber can be compensated by the negative dispersion of DCFs (-70 to -90 ps/nm.km). Pre, post and symmetrical schemes are basically the three dispersion compensating schemes that use DCF. The net dispersion after using DCF is designed to be zero using [23]:

$$D_{SMF}*L_{SMF} = -D_{DCF}*L_{DCF} \tag{1}$$

D is dispersion parameter and L is the fiber length.

Working as a reflective device, the FBG reflects light propagating through at a specific wavelength corresponding to the grating modulation periodicity. The mathematical relationship that represents the finishing appearance of the optical signal to be reflected through a Fiber Bragg Grating [16], is given by:

$$\lambda_B=2n_{eff}\Lambda \tag{2}$$

where λ_B represents the reflected wavelength and n_{eff} is the effective refractive index that has the influence of the directed mode in the core's fiber, and Λ is the grating length area.

2.2. Electrical Compensation

After demodulation, a digitization and distortion compensation are carried out for the received signals. The performance amelioration and design constraints reduction provided by DSP stage certifies an attractive proposition for optical communications. For some modulation formats, the DSP follows the blocks in Figure 1. Depending on a certain format different algorithms are implemented to the different blocks [24].

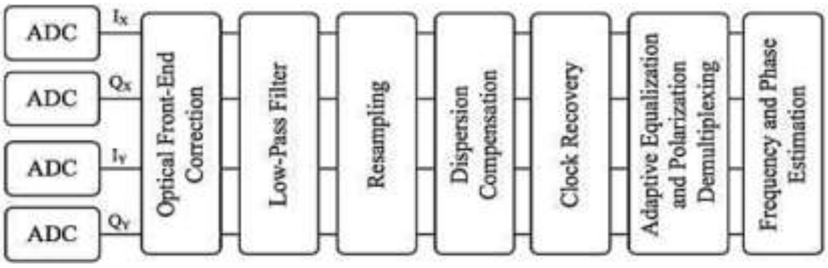

Figure 1. DSP stage processes

3. SIMULATION MODEL

An optical PM-QPSK transmitter/receiver structure separated by the optical fiber channel, is shown in Figure 2. The bit rate was set to 40 Gb/s. The transmission window was simulated using a laser with 1550 nm and 0.1 MHz line-width. The IQ modulator is preceded by a polarization beam splitter (PBS). The optical beam is splitted and sent into four separate Mach Zehnder modulators (MZMs). Each two MZMs are arranged together to process one polarization component, each one is driven by a PSK sequence generator with 2 bits/sym. An ideal polarization beam combiner (PBC) is then used to combine the two polarization components resulting in a 40 Gb/s PM-QPSK that is sent over the transmission link. The link is composed of fiber span’s loop (number of spans to be determined during the simulation) comprising of a standard SMF (SSMF) followed by an EDFA. The attenuation factor (α) corresponding to the utilized window is 0.2 dB/km. The other link parameters are listed in Table 1. The EDFAs gain and noise figure were set to 14 dB and 4 dB, respectively.

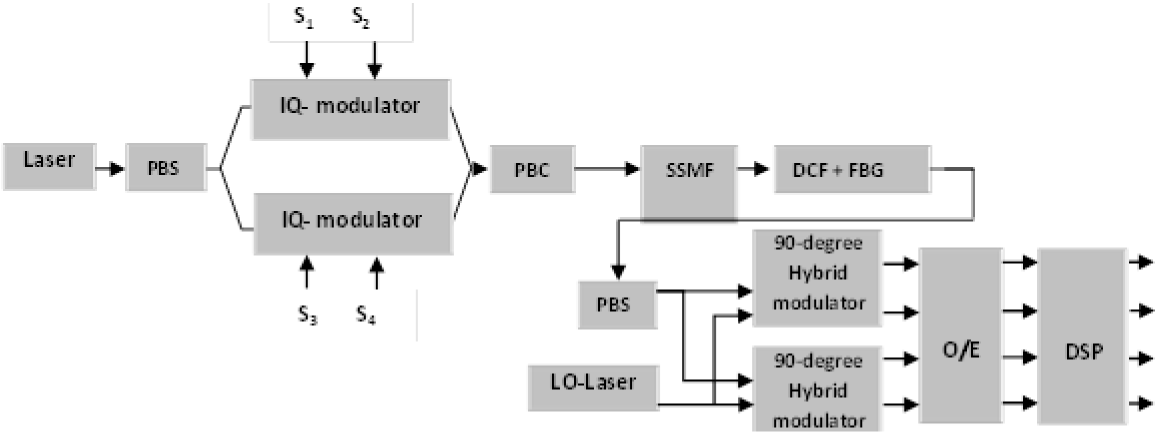

Figure 2. Single carrier PM-QPSK communication system

Table 1. Simulation parameters for optical compensation stage

Component	Parameter	Value
SMF	Length	100 km
	Dispersion	16 ps/nm.km
DCF	Length	21 km
	Dispersion	-80 ps/nm.km
FBG	Length	2 mm
	Bragg wavelength (λ_B)	1552 nm
	effective refractive index (n_{eff})	1.45

The SSMF is followed by an optical compensation stage composed of a DCF with attenuation (α) of 0.3 dB/km, and an EDFA with 12.4 dB gain and 4 dB noise figure. An FBG is present after the last DCF section. The other simulation parameters of the optical compensation stage are mentioned in Table 1. A 1st order, 50 GHz Gaussian optical band-pass filter was used to filter the received signal. A coherent detection was designed to detect the received optical information. This was performed by a heterodyne receiver followed by a low pass filter. The components (inphase/quadrature) of each polarization are used to rebuild the digital field. After that, an electrical digital processing was applied. Then, a DBP algorithm is carried out to mitigate the system nonlinearities as described in [14]. The system analysis was accomplished under Optisystem 13 environment.

4. RESULTS AND ANALYSIS

The simulation parameters for the SMF and the optical compensation stage are illustrated in Table 1. The analysis was performed for 4 different cases to compare the effect of different compensation scenarios. During all simulations the bit rate was fixed to 40 Gb/s. The main measurement test was the constellation diagram captured at selected fiber propagation lengths. The objective direction of the analysis was to compare the individual effect of each compensation technique (optical, electrical) with the free transmission state, then testing our proposed combination of the two types to distinguish the improvement amount that is obtained.

The first case shown in Figure 3, is the free transmission (without any compensation). The maximum length before serious degradation was 5 km. This is the expected result because the chromatic dispersion is directly proportional to the transmission length of the fiber [25], which is multiplied by the dispersion parameter of the SMF given (Table 1). Although the laser linewidth was fixed to 0.1 MHz.

The second case is illustrated in Figure 4. After adding the DSP component (i.e. only electrical compensation stage), an amelioration of (5km - 600km) was obtained. Although, a propagation of 720 km was attained but with a remarkable error in the constellation points. The remarkable improvement is obtained due to dispersion compensation part in the DSP stage which uses a digital back-propagation algorithm [24] which estimates the total dispersion accumulated throughout the propagated path, then reverse it effect after the optical detection of the signal.

Third simulation case shown in Figure 5 was performed after adding a suitable combination of optical compensation stages only. This DCF stage compensates only the resulting impairment from the chromatic dispersion (CD) effect, and imposes a high negative dispersion amount (Table 1) opposing the cumulated dispersion present from signal propagation through SMF. Thus the obtained constellation was approximately similar to the one obtained in the second case. Increasing the propagation length to more than (1000 km) distorted seriously the received signal.

Figure 6 shows the simulation results of our proposed fourth scenario where both electrical and optical compensation stages were connected together. In this dual compensation technique, the main goal was to split the impairment correction function such that the DCF compensate for the CD mainly, while DSP component (i.e. electrical compensation stage) deals with other correction functions whilst the CD compensation was disabled here. This last scenario imported the best improvement to the system. When applying the proposed technique, the transmission length was augmented dramatically to reach (**3570 Km**) with an acceptable constellation diagram. The main function of the DSP stage was set to solve problems imposed by frequency and phase disorders and clock recovery (Figure 1). It is clear from the analysis that the maximum attainable roof of an optical or an electrical compensation stage apart cannot exceed the (**1000km**) transmission length. While, in a dual mixing of the two techniques, a threefold propagation length was reached and an acceptable constellation diagram was remarked.

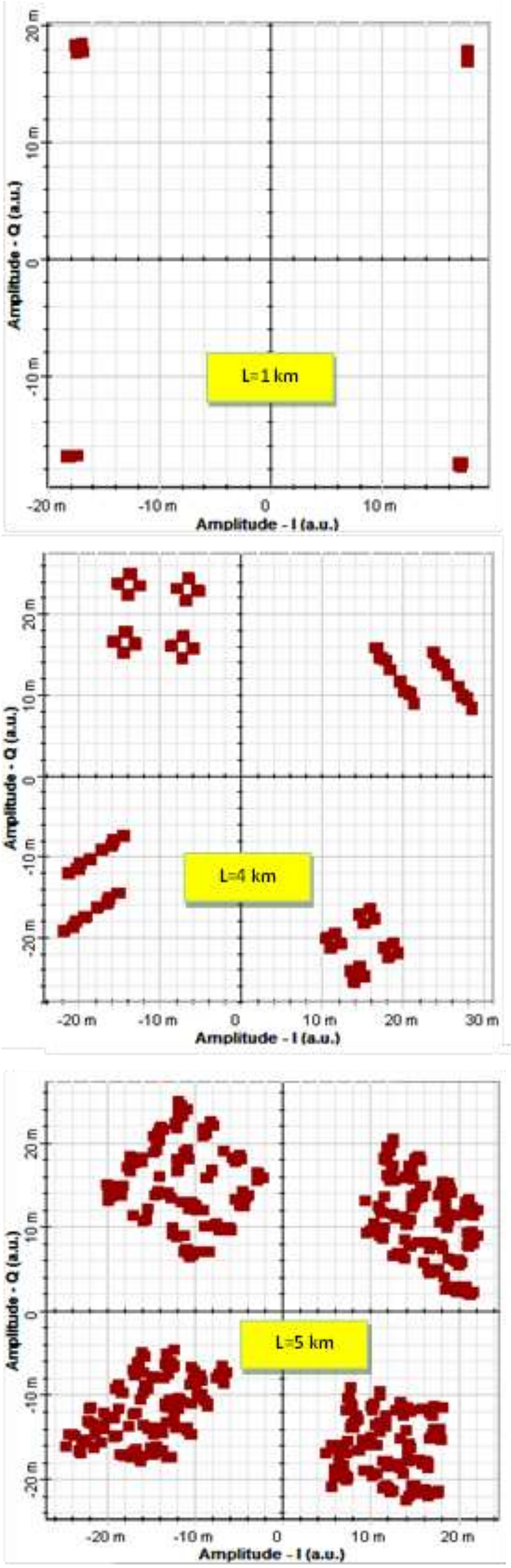

Figure 3. Constelation of PM-QPSK without compensation (40 GB/s)

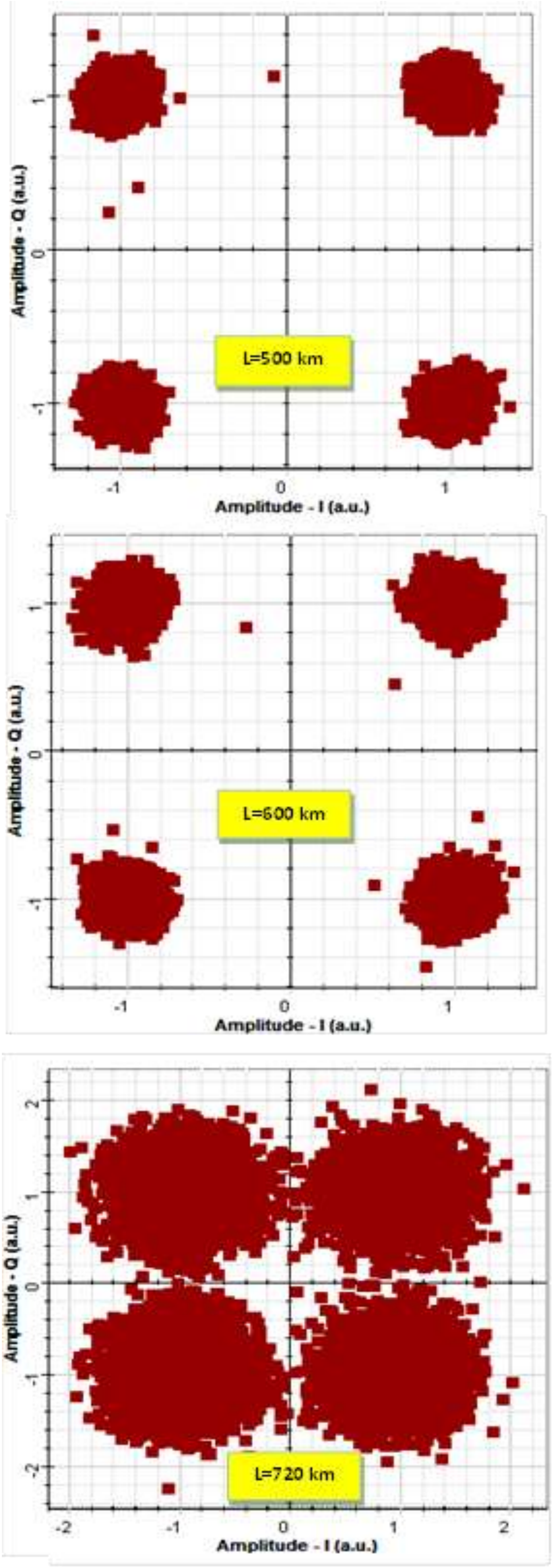

Figure 4. Constelation of PM-QSK with DSP compensation (40 GB/s)

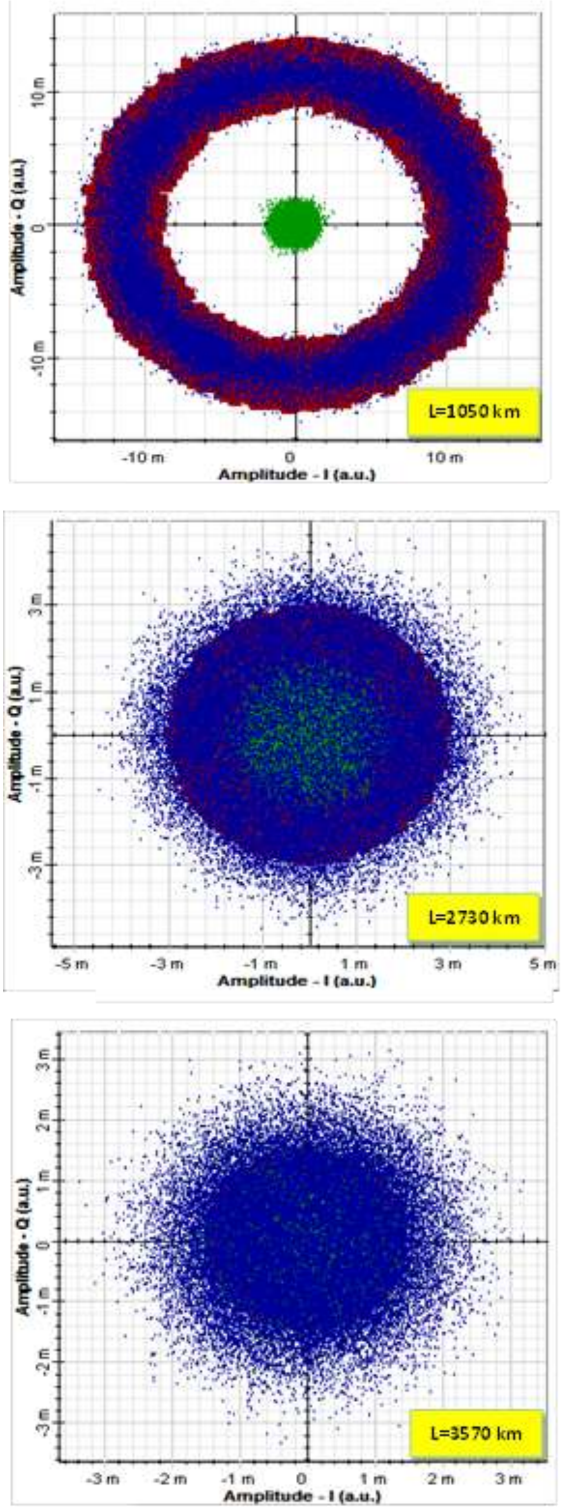

Figure 5. Constelation of PM-QSK with DCF, FBG (40 GB/s)

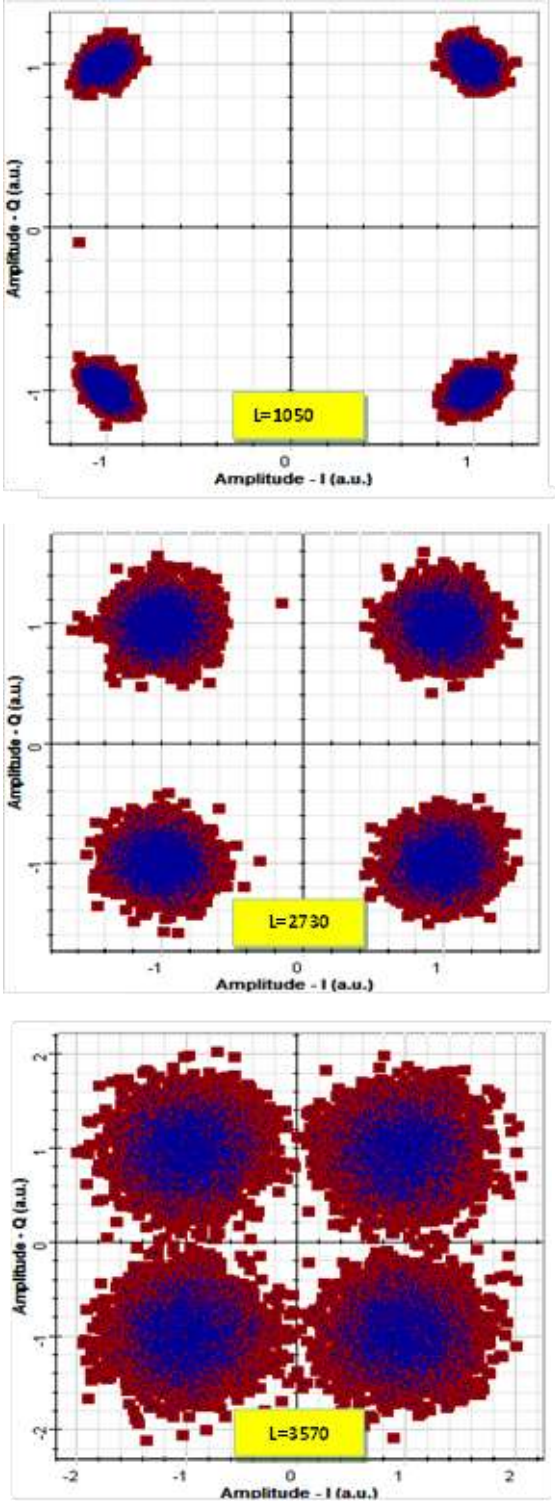

Figure 6. Constelation of PM-QSK with DSP and DCF, FBG (40 GB/s)

5. CONCLUSION

The correction obtained after adding optical or electrical compensation stages each one apart gave close results (~700 km of acceptable propagation length). Our proposed technique suggest to benefit from the additional correction functions present in the DSP stage and adding it to the CD compensation of the optical stage. This dual combination shows a very big improvement to the transmission length for a

PM-QPSK system up to (**3570 Km**), which was more than three times higher than each stage apart. The tested bit rate in this work was 40 Gb/s, which is compatible with the newest optical transmission systems used today. This result opens the scope to investigate the higher bit rates with this new technique.

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