Simultaneous Distribution of OFDM with IR-UWB Signals using Radio over Fiber

Belkacem Anes, Borsali Ahmed Riad

Abstract – **The main purpose of this paper is to study a seamless converged transmission between wireline and wireless services delivering multi-channel Polarization Division Multiplexing Coherent Optical Orthogonal Frequency Division Multiplexing (PDM CO-OFDM) integrated with both single and dual-polarization Impulse Radio Ultra-Wide Band (IR-UWB) signals over an existing reconfigurable Add/Drop Wavelength Division Multiplexing Optical Distribution Network (Add/Drop WDM ODN) infrastructure. All the transmitted channels are distributed using optimum low optical powers, and the performance of the proposed system is evaluated based on Bit Error Rate (BER) and constellations diagrams for the DP CO-OFDM channels that reached a 720 Gbps over fiber link of 420 km. While, the IR-UWB signals are analyzed in terms of BER and eye diagrams achieved high quality transmission over 60 km and 120 km for 1 Gbps single and 5 Gbps dual-polarization IR-UWB signals, respectively, under the adopted Forward Error Correction (FEC) BER limit of 10^{-9}.**

Keywords – **Radio over fiber, IR-UWB over fiber, PDM CO-OFDM, Add/Drop WDM, Optical distribution Network (ODN).**

I. Introduction

The overall target of the future next generation optical fiber access networks is to deliver high multi-data rate services, support multi-standards, multi-band technologies and serve a huge number of users at low cost employing high spectral efficiency modulation formats, advanced multiplexing techniques and more flexibility [1]. One of the key enabling solutions to assure these requirements over a single unified communication system is the Radio Over Fiber (RoF), which it is the technology that could transport any kind of information services (data, video, real-time applications…etc) seamlessly over the same fiber link to the both mobile and fixed users. Generally, the RoF system has many Base Stations (BSs) physically connected with a centralized Central Office (CO) via optical fiber links [2]. This centralized architecture is greatly reduces the implementation, maintenance costs, and decreases the power consumption of the whole optical infrastructure. Concerning short-range wireless access communications that offering high data rate connectivity at low complexity using wide band unlicensed frequencies, ultra-wideband is a great choice that can coexist with other radio communication systems [3]. Due to the low Power Spectral Density (PSD) less than -41.3 dBm/MHz over the spectral range of [3.1-10.6] GHz regulated by the Federal Communications Commission (FCC), the typical communication distance of a UWB wireless system is limited to only a few to tens of meters [4].

The efficient solution to extend the coverage area of the UWB communication is to combine it into the current and future Optical Distribution Networks (ODNs) [5]. In literature, many techniques have been used in this regard; which are proposed effective heterogeneous networks that host both wired and UWB wireless services using an existing Wavelength Division Multiplexing Passive Optical Network (WDM-PON) infrastructure as in [6] for the first time. These converged networks must be adopting and exploiting high Spectral Efficiency (SE) and high capacity due to the exponential growth of data communications traffic. The conventional modulation schemes that using serial transmission or single carrier frequency modulation such as Non-Return to Zero (NRZ) and Quadrature Amplitude Modulation (QAM) doesn't scale to the demand of next generation access networks. A multi-carrier modulation namely optical OFDM is considered as a very promising technology to satisfy the increasing demand of bandwidth offering an exceptional error-free transmission with high data rate over long distances; this is mainly due to its capability to overcome linear channel impairments such as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD). OFDM is a special form of multicarrier modulation which distributes data stream over a huge number of lower rate orthogonal subcarriers [7]. Furthermore, optical OFDM and its spectrum characteristics make it a flexible technique for networks with many Reconfigurable Optical Add And Drop Multiplexers (ROADMs) [8]. On the other hand, to further increase the system capacity and throughput of the Next Generation (NG) optical networks; it should be to incorporate PDM with the WDM coherent optical OFDM systems without increasing the cost and the complexity of the system. In [9], the authors were confirmed after calculation that the spectral efficiency of the PDM 64-QAM CO-OFDM WDM system is 12.5 bit/s/Hz better than PDM 64-QAM WDM systems that have 9.375 bit/s/Hz. The basic idea behind PDM is transmitting two baseband signals by the same wavelength independently over orthogonal polarizations states [10], this indicates that the PDM is a very effective and promising solution to doubling the spectrum efficiency and permits to double the user capacity [11]. For the ultra-high-speed optical fiber networks over long-haul links; losses, dispersion, and non-linearity effects are the main limiting factors that affects the maximum distances that could be achieved, especially; multiple high data rates are needed in these systems. In recent years, a lot of techniques in both electrical and optical domains have been developed to counteract the Kerr

Article history: Received February 09, 2021; Accepted June 25, 2021

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nonlinearity and dispersion effects through several compensation techniques. The authors in [12] were used a midway Optical Phase Conjugation (OPC) to mitigate the effect of both dispersion and the fiber nonlinearity for a data rate of 10x100 Gb/s in WDM 4 QAM PDM CO-OFDM system. In this regard that serves our research scope in this work the authors in [13] were studied three dispersion compensation configurations using Dispersion Compensation Fiber (DCF) for 8×40 Gb/s Differential Phase Shift Keying (DPSK) WDM system where the simulation results show that the performance of the mix-compensation system is better than the post compensation for long-distance high-speed WDM systems and can greatly reduce the fiber nonlinearities effects and increase the transmission distance. The distribution of 50 Gbps single polarization CO-OFDM channels with IR-UWB signals was proposed by [14] and the results of this study revealed that the performance of CO-OFDM signals is not affected with slightly degradation of the UWB signals when the optical coherent OFDM channels were increased.

To the best of our knowledge, all the previous works up to date don't study and investigate the transport of SP and DP IR-UWB signals with multi-channel DP CO-OFDM over long distances. This paper focuses on the design, implementation and performance analysis of high data rate WDM DP coherent optical 4 QAM OFDM for long-haul transmission using 60 Gb/s data rate per polarization combined with single and dual-polarization IR-UWB wireless signals. The proposed system proved its feasibility and reliability to be used in the future ultra-high data rate optical communication system to handle multi-broadband wired and wireless services.

The rest of this paper is organized as follow; the section 2 describes in detail the proposed system under investigation, while in section 3; we will list the simulation setups, and in section 4 we will present the simulation results and discussion. Finally, section 5 reports the conclusion and some future works.

II. The proposed RoF system

This section describes the whole proposed system that is illustrated schematically in Fig. 1. At the transmitter side, a 1 Gbps Single Polarization (SP) 5^{th} derivative Gaussian IR-UWB signal based on Bi-Phase Modulation (BPM) format is generated and multiplexed with multi-channel Dual Polarization (DP) CO-OFDM signals using WDM multiplexer. The resultant multiplexed signals are passed through short, medium, and long reach optical fiber links that are constructed using Single Mode Fibers (SMFs) connected with Dispersion Compensating Fibers (DCFs), and their optical amplifiers. After the short-reach (60 km), an Add/drop multiplexer operate at a particular wavelength is used to drop and add the IR-UWB signals (drop 1 Gbps SP IR-UWB under bi-phase modulation and add 5 Gbps DP IR-UWB monocycle Gaussian signals under On-Off Keying (OOK) modulation). The added DP IR-UWB signals are transmitted with DP CO-OFDM channels over the medium link (120 km) until to reach a drop demultiplexer, where the DP IR-UWB signals are extracted. Then, the WDM DP 4 QAM CO-OFDM channels continues to propagate through long haul reach fiber link up to 240 km (last mile) toward WDM demultiplexer and coherent optical OFDM receivers.

A. Dual Polarization CO-OFDM Transmitter and Receiver

Here we describe a single coherent detection OFDM transceiver, as shown in the blocks (a), (b), (c), and (d) in Fig. 1. Dual polarization CO-OFDM transmitter consists of two users, user 1 and user 2 where each one of them transmits an OFDM signal. Each OFDM signal is generated independently using a Pseudo Random Bit Sequence (PRBS) generator that produces input binary sequences that mapped into QAM symbols by a 4 QAM mapper. The generated QAM sequence is fed the OFDM modulator that modulates these data symbols by performing successive operations such as serial to parallel (S/P) conversion, Inverse Fast Fourier Transform (IFFT) calculations, adds cyclic prefix, parallel to serial (P/S) and Digital To Analog Conversion (DAC) to transform the signal from digital to analog. Furthermore, the baseband OFDM signal is processed by a pair of electrical Low-Pass Filters (LPFs) to avoid the antialiasing effect. To up-convert the baseband RF OFDM signal from the electrical to the optical domain, an optical in-phase (I) quadrature (Q) modulator is used. A Continuous Wave (CW) laser with pair of MZM modulators is used to map the I and Q waveforms of the RF OFDM signal onto an optical carrier. The output signals from these two MZMs are combined by an optical power combiner to form the complex optical OFDM signal. The complete CO-OFDM transmitter of each user is depicted in Fig. 2.

The up-converted optical OFDM signal is combined with the signal coming from other CO-OFDM transmitter using a Power Beam Combiner (PBC) to perform the concept of dual-polarization multiplexing. The two multiplexed signals form a DP optical OFDM signal which is then amplified, filtered, and transmitted through the optical fiber channel.

The received composite DP CO-OFDM signal coming from the Beam Power Splitter (BPS) with Local Oscillator (LO) signal are applied to the Optical-To-Radio (OTR) down-converter that is built up using four X-couplers, a 90^{o} phase shifter, four PIN photodetectors, and two electrical subtractors, as shown in Fig. 3.

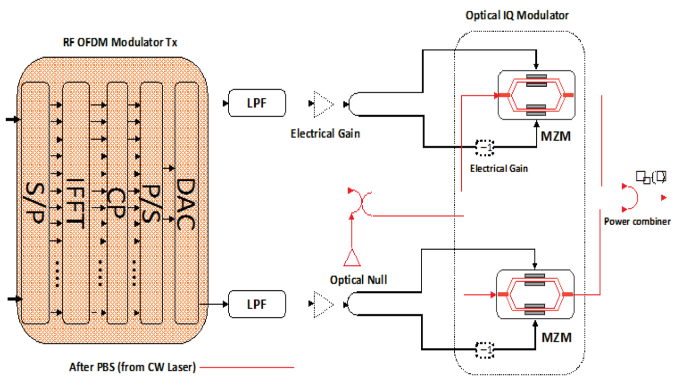


Fig. 2. The CO-OFDM transmitter

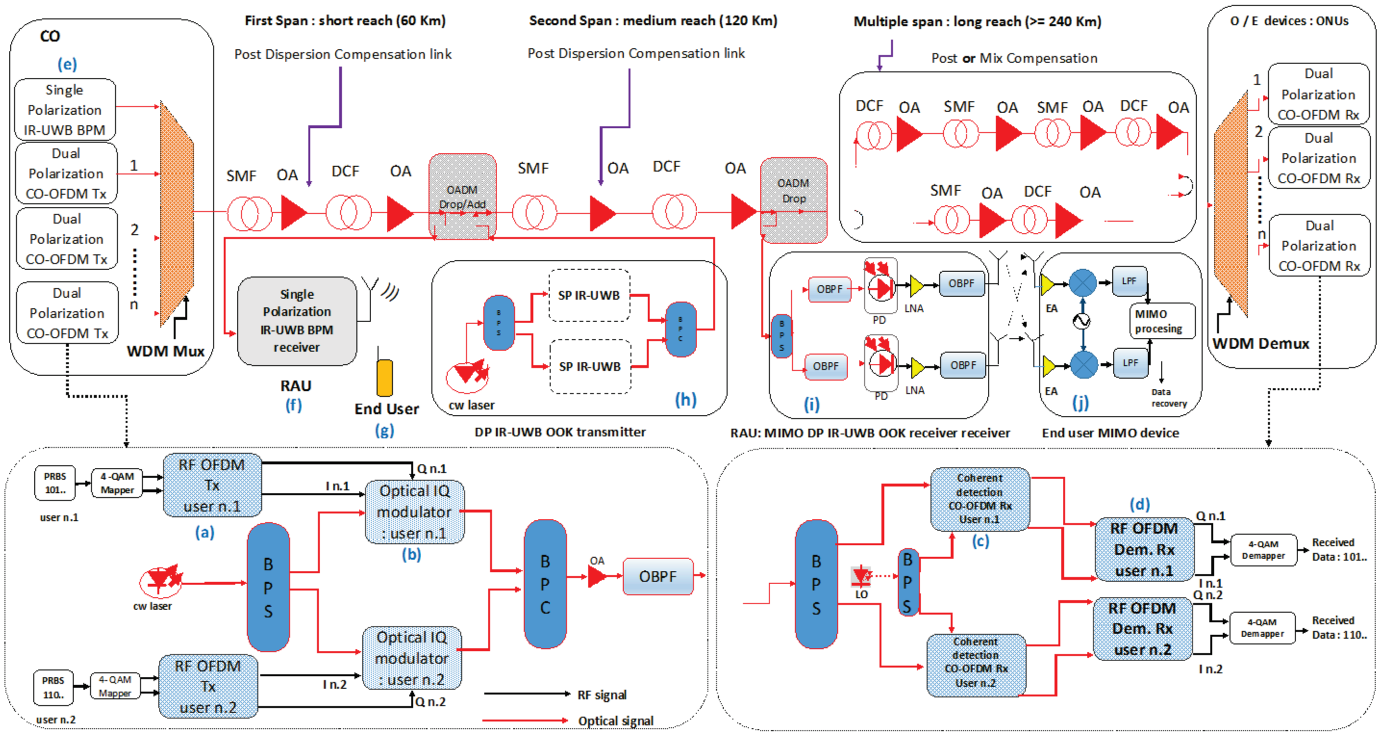


Fig. 1. Schematic diagram of the proposed RoF system

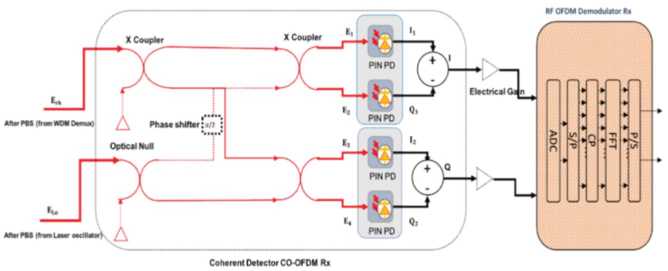


Fig. 3. The CO-OFDM receiver

The OFDM demodulator gives M-ary components at its outputs by adopting reversed processing that performed in the OFDM modulator such as Analog-to-Digital Converter (ADC) sampling, removes the cyclic prefixes, Fast Fourier Transform (FFT) calculations, and parallel to serial conversion. Finally, the outputs of the OFDM demodulator are driven a QAM sequence decoder to recover the transmitted binary data. Fig. 3 shows the structure of the coherent detector connected with the RF OFDM receiver demodulator for each end user device.

B. IR-UWB Transmitter and Receiver

Gaussian pulses are used to generate the IR-UWB signals, which are then modulated using both OOK and BPM formats. At the Central Office (CO), an Intensity Modulation (IM) is performed to modulate the intensity of a CW semiconductor laser by the baseband electrical SP IR-UWB signal using external Mach-Zehnder modulator, as shown in Fig. 4.

The single Gaussian pulse equation is written as:

$$g_0(t) = e^{\left(\frac{-2t^2}{\sigma^2}\right)}, \tag{1}$$

where σ represented as the full width of the Gaussian pulse.

A sequence of pulses generated at the output of the Gaussian pulse generator is presented mathematically by:

$$g_1(t) = \sum_{-\infty}^{+\infty} g(t - KT_0)\,. \tag{2}$$

Then, an electrical differentiator is used to generate the Gaussian pulse, and its derivatives are described as:

$$g_2(t) = \sum_{-\infty}^{+\infty} \frac{d^n}{dt^n} g_1(t)\,. \tag{3}$$

In the case of a conventional modulation format, the IR-UWB signal $S_{IR-UWB}(t)$ is generated by the multiplication of a pulse waveform $g_2(t)$ with the binary data $d(t) \in \{0,1\}$ for OOK, and $d(t) \in \{-1,1\}$ for BPM. As depicted in Fig. 4, the electrical IR-UWB signal before the intensity modulation is represented by:

$$S_{IR-UWB}(t) = d(t) \times g_2(t)\,. \tag{4}$$

At the RAU, the received optical signal is filtered using an Optical Bandpass Filter (OBPF) located in the front of the IR-UWB receiver detector to remove the Amplified Spontaneous Emission (ASE) noise generated by optical amplifiers. After that, a Direct Detection (DD) is performed by a Photodiode (PD) to generate the Radio Frequency (RF) photocurrent.

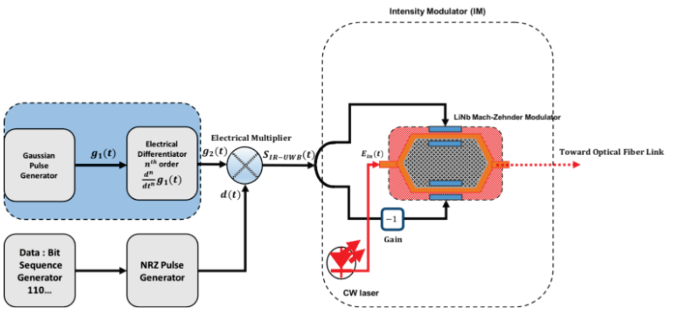


Fig. 4. The SP IR-UWB transmitter (inset in the block (e) at Fig. 1)

The generated photocurrent is then passed through a Low Noise Amplifier (LNA), and an Electrical Bandpass Filter (BPF) to fix the Power Spectral Density (PSD) of the transmitted IR-UWB wireless signals to better comply with the FCC mask before driving the IR-UWB transmission antenna, as depicted in Fig. 5(a). The bandpass Butterworth filter was selected which offers a maximally flat frequency response over the wide spectral band, the filter transfer function is [15]:

$$H(f)=\alpha\times\frac{\left(B/2\right)^{N}}{\prod_{k=0}^{N-1}\left(j(f-f_c)-p_k\right)}, \qquad (5)$$

with

$$p_k=\frac{B}{2}\times e^{j\frac{\pi}{2}\left(1+\frac{2k+1}{N}\right)}, \qquad (6)$$

α is the insertion loss, f_c is the center frequency, B is the bandwidth, and N is the order of the filter.

The radiated RF signal in the air will be detected by the UWB receiving antenna (2x2 MIMO UWB antennas for DP IR-UWB case) of the mobile user device, at the output of the receiver antenna; the modulated RF signal is amplified by a wideband electrical amplifier and then down-converted using an electrical RF mixer with a Local Oscillator (LO), and then followed by a Low-Pass Filter (LPF) to reject unwanted frequencies. The filtered signal in the last step is applied to a data binary recovery unit to get the original information, as depicted in Fig. 5 (b).

C. Optical Fiber Links

The continuous wavelength lasers at the CO are emitting in the C-band region with 50 GHz-channel spacing according to International Union-Telecommunication (IUT-T) grid. So, high Group Velocity Dispersion (GVD) of the SMF at this band limits the maximum allowable transmission reach at high bit rates. To compensate the effect of GVD, a Dispersion Compensation Fiber (DCF) has a high negative GVD is connected at the end of the SMF section.

The length of the DCF is chosen to yield a negligible total GVD over the fiber link. In our proposed system, both post and mix dispersion compensation configurations are used to compensate the accumulated dispersion. The short and medium links consist of SMF and DCF to deploy the concept

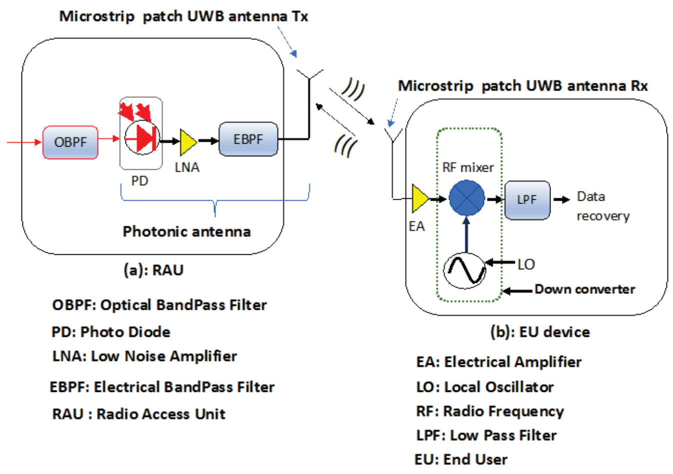


Fig. 5. The SP IR-UWB receiver with the end user device (inset in the block (f) and (g) at Fig. 1)

of post dispersion compensation, while for the long reach a post or mix compensation configuration is used to pursuing conveying multi-DP CO-OFDM channels over the last mile link toward its intended destination, as clearly indicated in Fig. 1.

The length of the DCF that added at the end of a SMF length is calculated using the following formula:

$$L_{DCF} = -\left(\frac{D_{SMF}}{D_{DCF}}\right)\times L_{SMF}, \qquad (7)$$

where: L_{DCF} is the length of the dispersion compensation fiber, L_{SMF} is the length of the single mode fiber, D_{SMF} is the chromatic dispersion single mode fiber, and D_{DCF} is the negative chromatic dispersion of the dispersion compensation fiber.

The gain in decibel G(dB) of optical amplifiers is calculated by:

For SMF: $\alpha_{SMF}\times L_{SMF}$, (8)

For DCF: $\alpha_{DCF}\times L_{DCF}$, (9)

where α is fiber attenuation measured in dB/km and L is the length of fiber in km.

III. System Specifications

The proposed RoF system was designed, simulated and analysed using OptiSystem software package V.15.2. All parameters values of the CO-OFDM, fiber channel links besides IR-UWB transceivers used in the simulation are listed in Tables I, II and III, respectively.

Each CO-OFDM polarization branch is modulated using a QPSK modulator with 2 bits/symbol and mapped onto 512 subcarriers through a serial-to-parallel (S/P) converter. An Inverse Fast Fourier Transformation (IFFT) with 1024 IFFT size is utilized to generate a time domain signal. Acyclic prefix as a symbol extension is added to avoidsubcarriers overlapping. The obtained time domain signal is serialized using a parallel-to-serial (P/S) converter which is further converted into an analog signal using digital to analog (D/A) converters. The 4-QAM OFDM I and Q signals are driven low pass filters having 0.2 roll-off factor. An optical IQ modulator based on two parallel MZMs of 60 dB extinction ratio are used to translate the IQ OFDM signal into optical domain, that will be amplifier by an optical bandpass filter has a 10 dB gain in order to compensate the optical IQ modulation losses.

In the whole system, six 120 Gbps PDM OFDM signals were modulated by using the C-band wavelengths based on International Telecommunication Union (ITU-T) standard (193.15, 193.20, 193.25, 193.30, 193.35 and 193.40 THz), respectively, they are multiplexed with an optical modulated IR-UWB signals at 193.1 THz via a WDM MUX has a frequency spacing of 50 GHz with rectangular transfer function.

Each coherent detector consists of a Local Oscillator (LO) with 0.1 MHz line width, 90^o optical hybrid and balanced photodetectors with a responsivity of 1 A/W and dark current equal to 10 nA for optical to baseband demodulation. The electrical I and Q signals are converted to parallel and followed by the removal of cyclic prefix, and hence, pass through FFT process and demodulated by QPSK demodulator to retrieve the original signal.

TABLE I
TRANSCEIVER PARAMETER VALUES OF THE CO-OFDM CHANNELS

Component	Parameters
QAM mapper	2 bits/symbol
OFDM modulator/demodulator	Number of subcarriers N_{sc} = 512 FFT/IFFT points = 1024 Cyclic prefix length = Symbol The extension (25%)
CW laser	193.15 to 193.40 THz
Bit rate1	60 Gbps per polarization
Low pass filter	0.6×Bit rate1 Roll-off factor = 0.2
LiNb Mach-Zehnder Modulator	Extinction ratio = 60 dB
Optical amplifier	10 dB
WDM Mux/Demux	Frequency spacing = 50 GHz Filter type: Rectangle
Local oscillator	Line width = 0.1 MHz
Balanced photodetectors	Responsivity = 1A/W Dark current = 10 nA

The multiplexed signals are then transmitted to the its corresponding destination over a cascaded SMF-DCF link. The DCF with a specific length as demonstrate the Eq. (7) has a negative dispersion in order to compensate the positive dispersion of SMF. The SMF and DCF link parameters' specifications are employed in accordance with the common communication industry standards used on the field deployments in order to simulate the real environment as much as possible.Table II below illustrates the SMF and DCF parameters used in the system model in the presence of linear and non-linear effects.

TABLE II
PARAMETER VALUES OF THE OPTICAL FIBER LINKS

Parameter	Value	
	SMF	DCF
Attenuation α	0.2 dB/km	0.6 dB/km
Group velocity dispersion D	16 ps/(ns.nm)	-80 ps/(ns.nm)
Dispersion slop S	0.075 ps/ nm^2 /km	-0.3 ps/ nm^2 /km
Differential group delay	0.2 ps/km	0.2 ps/km
Effective area Aeff	80 μm^2	22 μm^2
Nonlinear refractive index	26×10^{-21} m^2 /W	26×10^{-21} m^2 /W

The IR-UWB signalsare transmitted to its RAUs over different SMF up to 120 km.

At the IR-UWB RAUs, an optical band pass filter is placed to enhance the receiver performance, which is optimized in term of bandwidth to 12 GHz for SP IR-UWB signals, whereas; a 15 GHz is required for DP IR-UWB ones. Then, the received signalsare detected by a photodetector (PD) with a responsivity of 1A/W, and then amplified by low noise amplifier with a gain of 25 dB to drive a band pass Butterworth filter centred at 6.85 GHz frequency, and has a 7.5 GHz bandwidth to cover all the IR-UWB signal (3.1-10.6) GHz with filter order equal 5.

After wireless transmission, the received IR-UWB signals are again amplified by an electrical amplifier of 25 dB gain, and then coherently demodulated using synchronized local oscillator and an electrical mixer. Finally, the demodulated baseband signal passes through LPF with a cut off frequency of 0.75 times the bitrate for binary data recovery.

TABLE III
PARAMETER VALUES OF THE IR-UWB SIGNALS

Parameter	SP	DP
Bit rate2	1 Gbps	2×2.5 Gbps
Gaussian pulse order	5^{th} order	Monocycle
Modulation format	BPM	OOK
CW laser	193.1 THz	193.1 THz
Band pass filter	12 GHz	15 GHz
Photodiode responsivity	1 A/W	1 A/W
Low noise amplifier (LNA)	25 dB	25 dB
Butterworth filter	f_c =6.85 GHz B=7.5 GHz order = 5	f_c =6.85 GHz B=7.5 GHz order = 5
Spatial streams	SISO (Single-Input Single-Output)	MIMO (Multiple-Input Multiple-Output)
Electrical amplifier (EA)	25 dB	25 dB
Local oscillator	Synchronized	Synchronized
Low pass filter (LPF)	0.75×Bit rate2	0.75×Bit rate2

IV. RESULTS AND DISCUSSION

The performance of the proposed system is analyzed under three different scenarios which are organized as follow; the study starts with the transmission of one DP CO-OFDM channel without IR-UWB signals, where post and mix compensation techniques will be tested for the last mile transmission (long reach). After that, the simulation is modeled by integrating the IR-UWB signals with the earlier transmitted single DP CO-OFDM channel. The last part is mainly dedicated to multiplexing two, four, and six PDM CO-OFDM channels with the add/drop IR-UWB signals, which both of these wired and wireless signals are transmitted using the optimum parameters values that are extracted from the two previous analysis findings.

A. Performance of Single DP CO-OFDM Channel without IR-UWB Signals

As a first step, we transmit one channel DP 4 QAM CO-OFDM of 60 Gbps per polarization to reach a data rate of 120 Gbps over the proposed system without fiber link (Back-To-Back configuration), and then it is transmitted over three optical fiber links portions (short, medium, and long reach) they separated by two optical add/drop multiplexers OADMs. Fig. 6(a) shows the optical spectrum of the transmitted downstream DP 4-QAM OFDM channel at the CO. While, the received constellation diagrams for both X and Y polarizations are depicted in Fig. 6(b) to use them for reference purposes for all the rest investigations in this work.

In the next step, the optical fiber links are added; where in the short and medium links a post compensation technique is used. While, for the last mile; both post and mix compensation are tested to select the best one to be employed in our last mile WDM transmission system. The simulations results are evaluated in terms of BER and constellation diagrams for each polarization. The configured design is simulated based on different transmitted optical powers (T-o-P) which are -4, -2, 0, 2, and 4 dBm; and adjusted optical launch powers -4, -2, and 0 dBm coming from a local oscillator (LO) at the receiver. All these hybridization T-o-P/LO power variations permit us to fetch the optimum optical launch power that gives good performance. The simulations results are showed in Figs. 7 and 8, respectively. Each figure mentions the correspondent BER value of each polarization channel (in the below), and the transmitted optical power for each transmitted DP channel (in the top).

From the simulations results obtained above and compared with the Back-to-Back constellation diagrams; we can see that the mix compensation is better than post configuration. For post compensation, the circumference of the constellation points is largely scattered for low launched power (-4 dBm and -2 dBm for T-o-P, with -4, -2 and 0 dBm for the LO) and the symbols are very close to each other due to the high channel effects such as the accumulated noises added by the EDFA amplifiers and the chromatic dispersion. In contrast to this, mix compensation offered free error transmission (BER=0) for all input optical powers and was given good constellation diagrams quite similar that observed in B-t-B transmission especially for 0 dBm LO despite a 120 Gbps data rate was transmitted over 420 km in the presence of the fiber nonlinearity. More importantly, post compensation needs high transmitted optical power (0, 2 and 4 dBm) to give similar results that offered by the mix technique. Also, as shown in Fig. 8, for 0 dBm local oscillator and -2 dBm optical transmitted launch power; the received constellation diagram has a very close shape to those of the back-to-back case that depicted in Fig. 6(b). According to these findings; both 0 dBm LO and -2 dBm optical launch power are selected as optimum values to preform and analyze the performance of our converged transmission WDM DP CO-OFDM proposed system. Hence, the mix compensation was chosen for the last mile link.

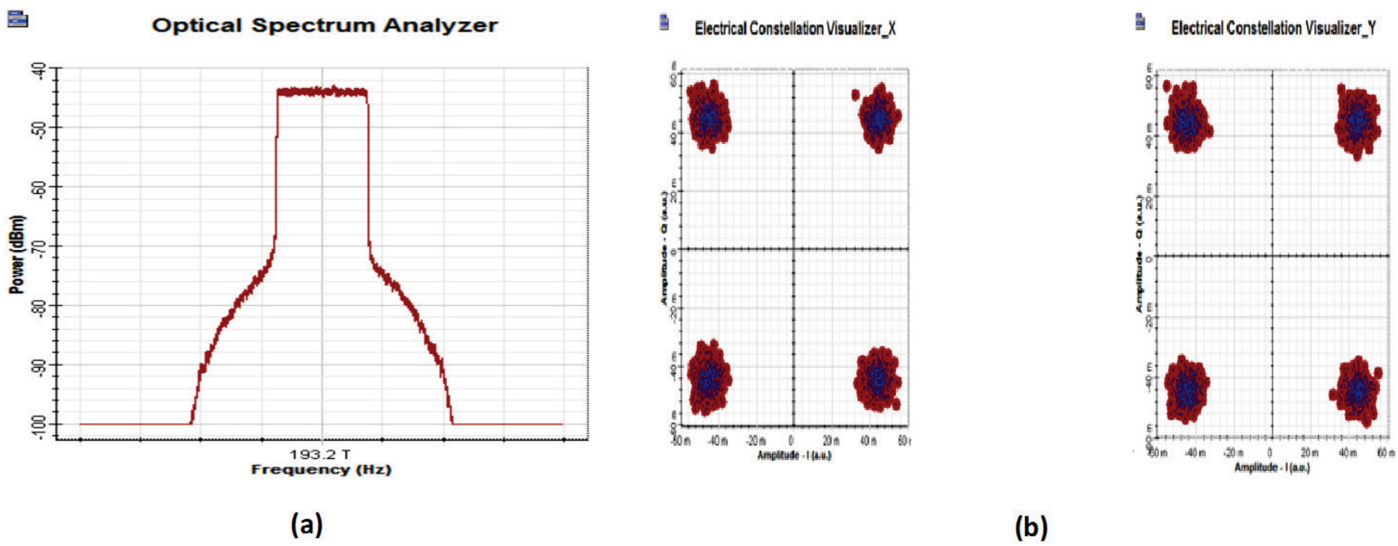


Fig. 6. The optical spectrum (a) with the received back-to-back constellation diagrams (b) of the optical OFDM signal

. Post compensation used for the last mile transmission:

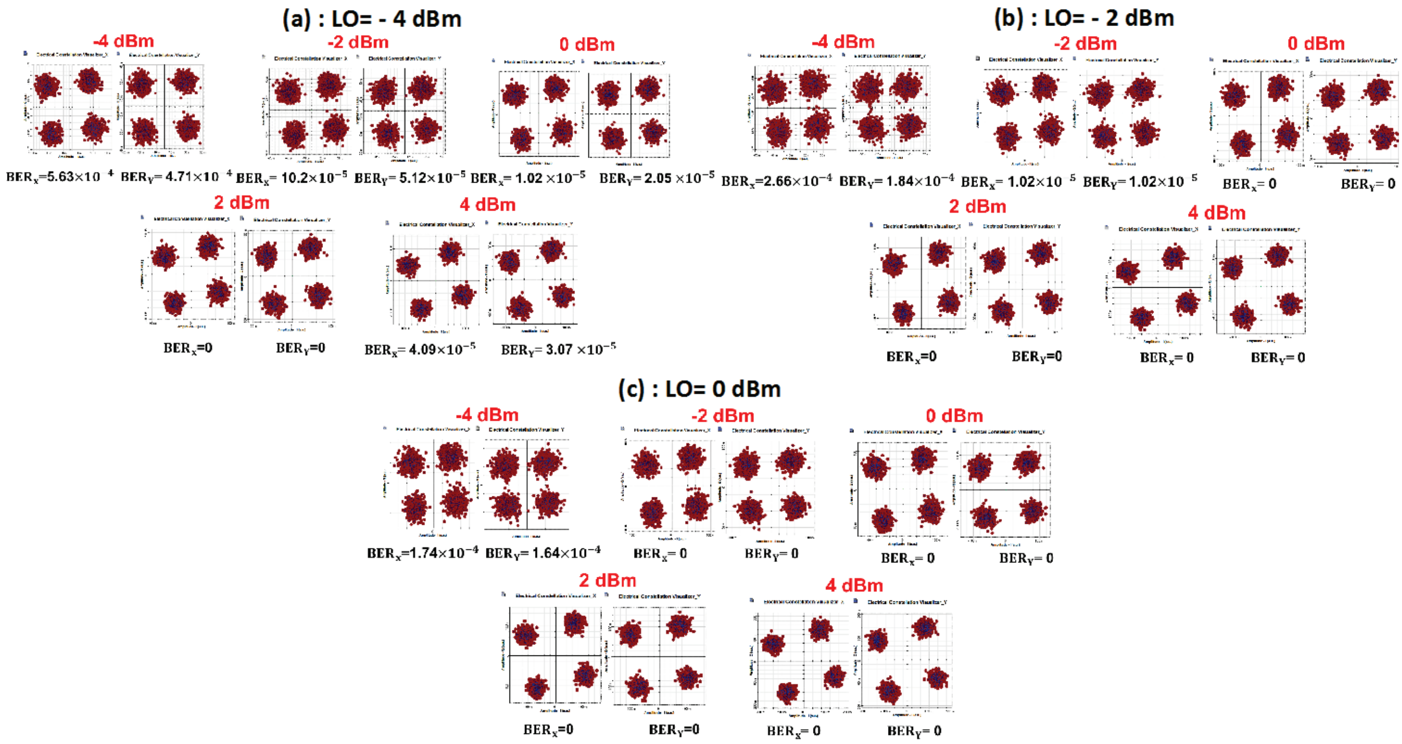


Fig. 7. Constellation diagram of post compensation at different input and LO powers

. Mix compensation used for the last mile transmission:

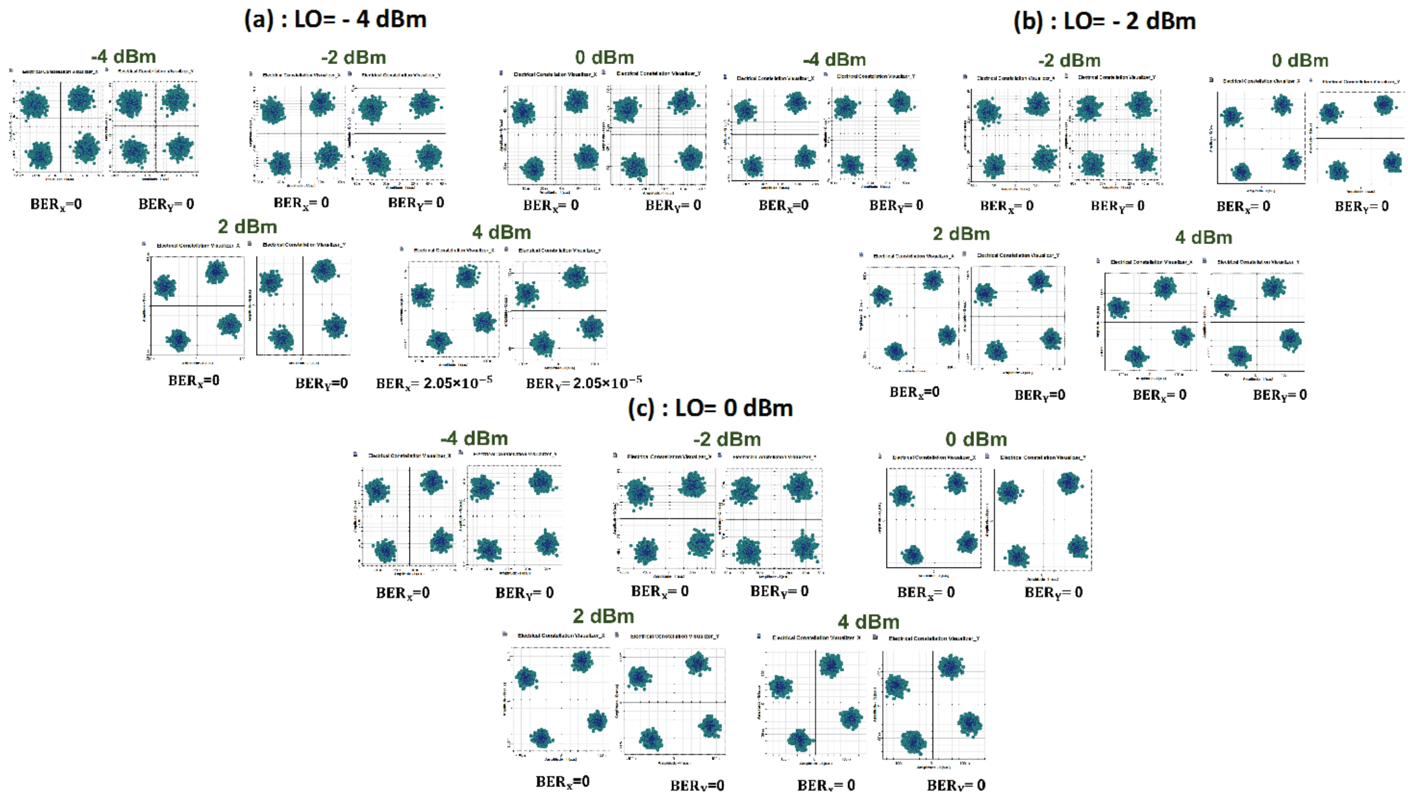


Fig. 8. Constellation diagram of mix compensation at different input and LO powers

B. Performance of Single DP CO-OFDM Channel with IRUWB Signals

In this scenario, the SP and DP IR-UWB signals at 193.1 THz are integrated with the single DP CO-OFDM channel that operate under the optimum launch powers such as -2 dBm at the transmitter and 0 dBm of the LO at the receiver. At the CO, the generated time waveform of the SP IR-UWB signal based on BPM is depicted in Fig. 9(a), while the output of the WDM multiplexer is shown in Fig. 9(b).

After the short-reach medium link (60 km), the SP IR-UWB signal is dropped and a 5 Gbps DP IR-UWB signals is inserted and transmitted with the DP CO-OFDM channel over the medium reach (120 km). Both the time waveform of IR-UWB signal based on OOK and the two integrated channels are depicted in Fig. 10 (a) and (b), respectively.

At the end of the medium reach; an optical OADM is placed to extract the DP IR-UWB signals toward the RAU. Then, the DP CO-OFDM channel is propagated alone over the last mile mix compensation long reach link up to 240 km. The IR-UWB over fiber performance is investigated in terms of BER and eye diagrams under several optical powers which are between -6 to 0 dBm to transmit SP IR-UWB, while it is from 0 dBm to 6 dBm to convey the DP IR-UWB signals. For this, we consider the hard decision-forward error correction (HD-FEC) limit is 1×10^{-9}. To show the eye diagram and its related BER values at the RAU, we connect the Butterworth filter output directly (wireless transmission is not considered) with a RF mixer and sine wave local oscillator to establish the down-conversion. The BER performance is observed as the fiber lengths combination (SMF+DCF) are 60 and 120 km of both transmitted SP IR-UWB and DP IR-UWB, respectively, as shown in Fig. 11 (a) and (b).

As we find out from the results obtained from Fig. 11 (a) and (b); the transmission performance of both SP and DP IR-UWB can be improved by increase the transmitted power. In both cases, when the input optical power increased the BER are decreased and we achieve a good opening eye diagram. For SP IR-UWB over 60 km link, the minimum launch power to achieve acceptable BER below the HD-FEC is -4 dBm, where it is 5 dBm for DP IR-UWB over 120 km. Form the graph of DP IR-UWB, the BER is not the same; this is could attribute to the polarization mode dispersion (PMD) effects. On the other hand, at the coherent detection receiver, the constellation diagram of each user was obtained with error-free transmission as shown in Fig. 12. So, this result shows that the IR-UWB signals not affect the DP CO-OFDM performance which still gives the same findings that achieved in the first scenario in both cases, B-t-B test and over 420 km (using mix compensation) without IR-UWB signals.

C. Performance of Multi–DP CO-OFDM Channel with IR-UWB Signals

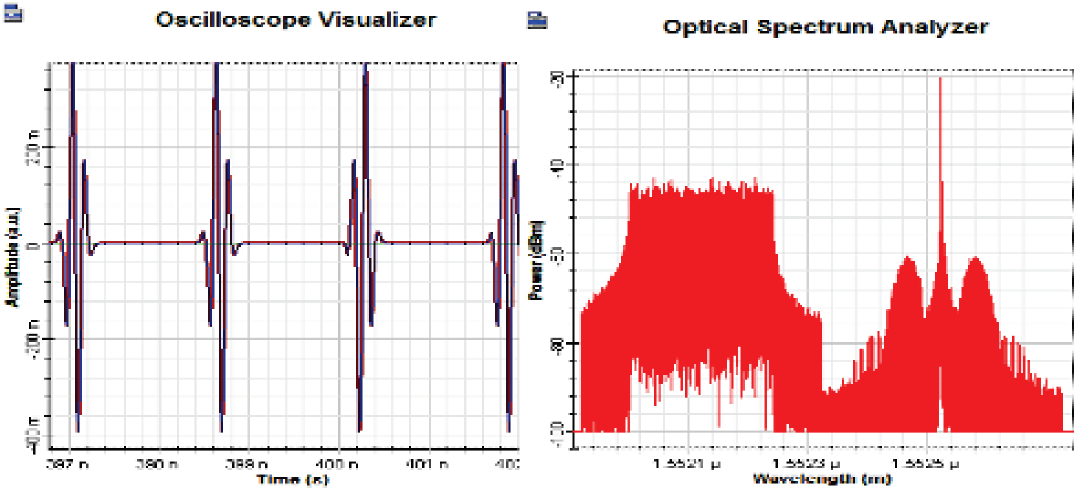
The feasibility analysis is carried finally to integrate two, four, and six PDM CO-OFDM channels with both SP and DP IR-UWB signals. From Fig. 11 (a) and (b); the optical launch power to achieve a received a BER around 10^{-12} was selected to evaluate the transmission performance of IR-UWB signals. The optical wavelengths from 193.15 THz to 194.20 THz for two DP CO-OFDM channels, 193.15 THz to 194.30 for four DP CO-OFDM channels and 193.15 THz to 194.40 for six DP CO-OFDM channels with 50 GHz channel spacing. For simplicity, the results were taken for the second coherent receiver demodulated (at 193.2 THz) instead of six channels because the performance of the rest channels is almost same. Fig. 13 shows the simulated results of the multiplexed signals after short, medium reach (on the left) and constellation diagrams (on the right) of one polarized de-multiplexed user after passed the long reach link.

It can be seen that the constellation points for all transmitted channels still maintain a good separation even though up to 420 km transmission and high data rate of 720 Gbps. We notice from the previous results depicted in Fig. 13, more we increase the DP CO-OFDM channels more constellation points are rotated from its ideal place and hence more the BER increases especially for 6 DP CO-OFDM multiplexed channels, but the 4 QAM symbols at each user still could be separately recovered because the received symbols aren't out from its quadrant in the constellation diagram, so; each constellation point could be recovered individually.

The transmission performance based on the measured BERs at the receiver of SP IR-UWB and DP IR-UWB signals they are integrated with two, four and six DP CO-OFDM are summarized in Table IV. These BER measurements clearly indicates when the number of DP CO-OFDM channels is raised a very tiny degradation of the IR-UWB signals performance has appeared. The IR-UWB signals do not affect the system performance for the transmitted DP CO-OFDM in any way. On the other hand, a long reach error-free optical OFDM transmission up to 420 km was achieved when two dual-polarization CO-OFDM channels of 240 Gbps are multiplexed with IR-UWB add/drop signals. Moreover, by considering a soft-decision forward error correction (SD-FEC) threshold of 2×10^{-2} [16] that is used in modern coherent optical communication systems; all CO-OFDM channels have BERs below this limit as shown in Table IV which greatly proves the feasibility of our results within the acceptable range.

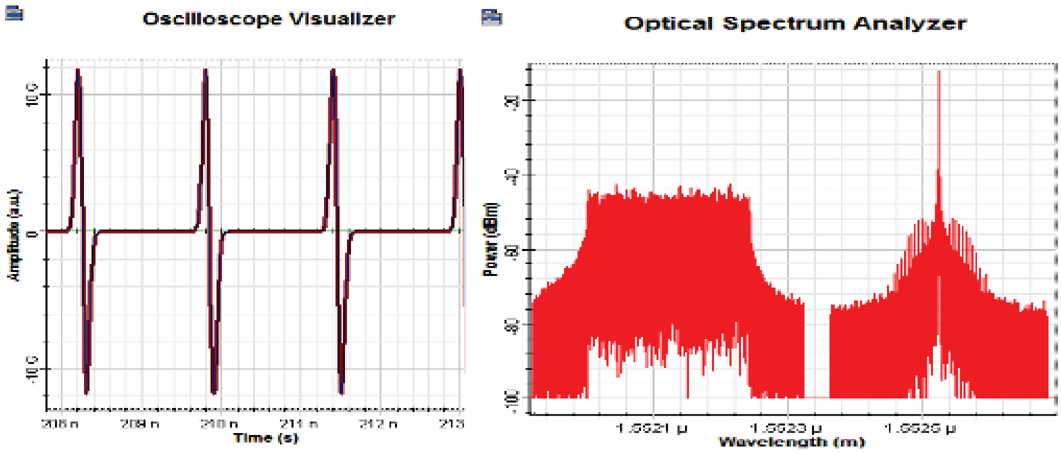
TABLE IV
BER MEASUREMENTS OF THE TRANSMITTED DP CO-OFDM/IR-UWB CHANNELS

Parameter	BER		
	Two	Four	Six
DP-OFDM	0	(2.05, 1.02) $\times10^{-5}$	(7.21,1.56) $\times10^{-3}$
SP IR-UWB	1.07×10^{-12}	1.10×10^{-12}	1.15×10^{-12}
DP IR-UWB	(2.08,2.25) $\times10^{-12}$	(2.11, 2.29) $\times10^{-12}$	(2.18, 2.35) $\times10^{-12}$



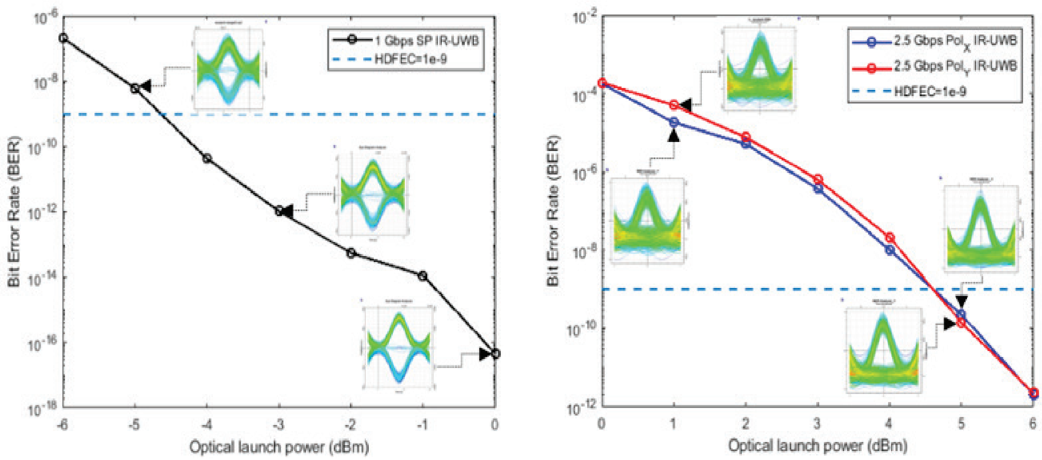
(a) (b)

Fig. 9. The time waveform of IR-UWB based on BPM (a) and the optical spectrum of the DP CO-OFDM with SP IR-UWB (b)



(a) (b)

Fig. 10. The time waveform of IR-UWB based on OOK (a) and the optical spectrum of the DP CO-OFDM with DP IR-UWB (b)



(a) (b)

Fig. 11. BER for SP IR-UWB BPM (a) and DP IR-UWB OOK (b) (Insets: corresponding eye diagrams)

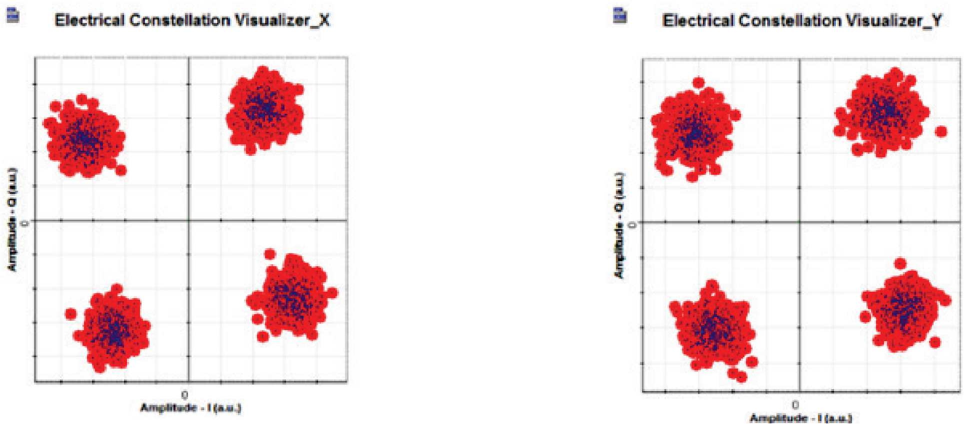


Fig. 12. The received constellation diagram at the DP CO-OFDM demodulators

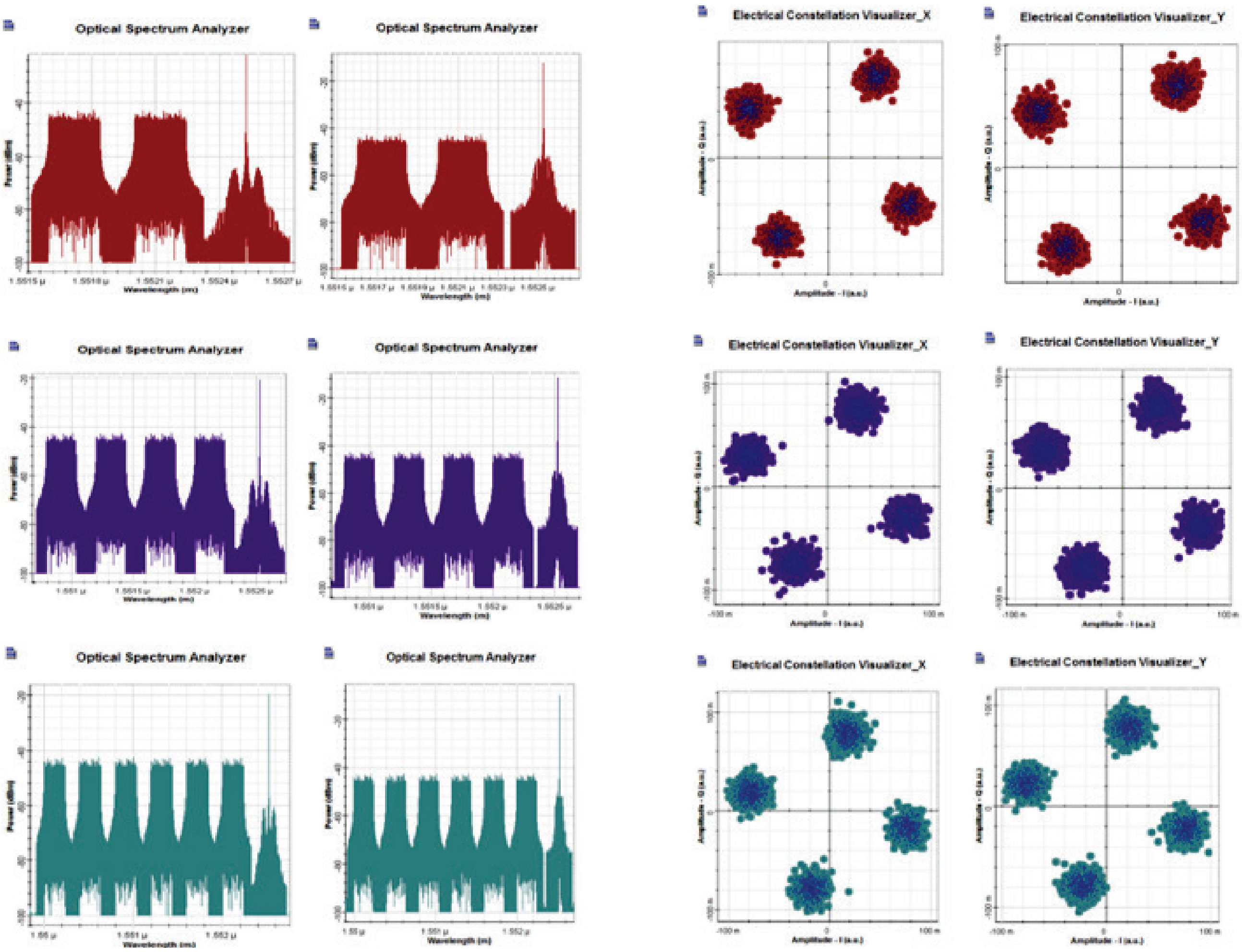


Fig. 13. Optical spectrums of two, four, and six transmitted
DP CO-OFDM channels integrated with IR-UWB and constellation diagrams of one DP channel

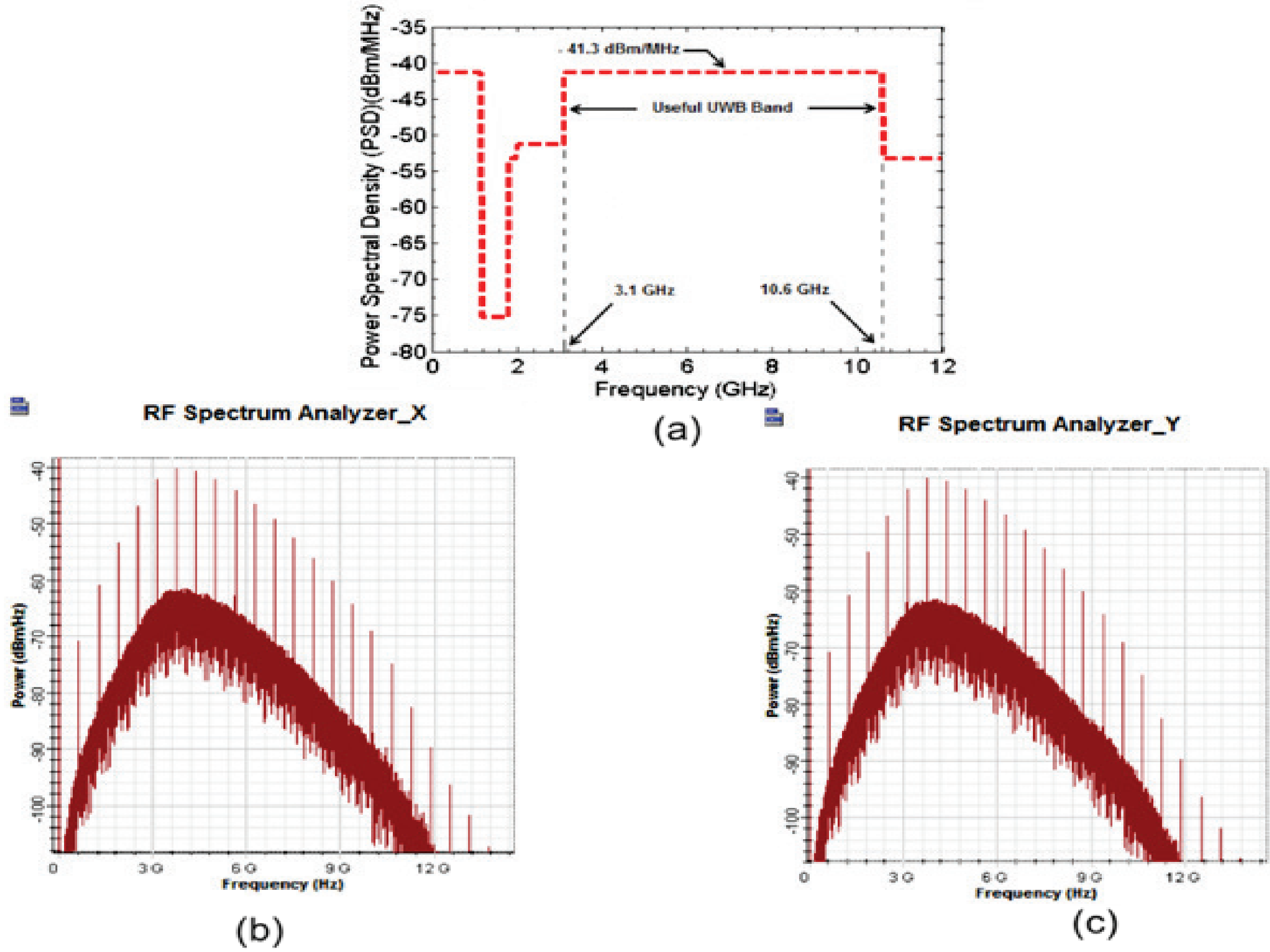


Fig. 14. Reference FCC masks UWB indoor [17] and power spectral densities of received DP IR-UWB signals

Furthermore, to demonstrate the performance of the transmitted IR-UWB signals, we have analyzed the Power Spectral Densities (PSDs) of the DP IR-UWB signals at the RAU and compared them with the standard FCC UWB used for indoor power spectrum regulation as depicted in the top of Fig. 14 (a). From the Fig. 14 (b) and (c), the power spectral densities for DP IR-UWB signals are offered favorable spectral properties that comply with the FCC UWB which is less than -41 dB/MHz along with the UWB bandwidth from 3.1 to 10.6 GHz.

V. Conclusion and Future Work

This paper studies the feasibility of the seamless provision of wired and short-range IR-UWB wireless signals over a unified radio over fiber system. The existing Optical Network Distribution (ODN) was exploited efficiently by the integration of a new cost-effective broadband UWB signals. The results indicate that the use of mix dispersion compensation technique is very promising for long-reach last mile optical fiber access transmission, it's robustness against chromatic dispersion, especially at high data rates. The proposed system operates under low and optimum optical launch powers for both DP CO-OFDM and IR-UWB services considering the future deployment of green hybrid fiber-wireless broadband access networks. As the results reviewed, the RoF system proved to have an error-free transmission for 240 Gbps DP CO-OFDM. While, a 480 Gbps (four channels) and 720 Gbps (six channels) successfully transmitted below the SD-FEC threshold of 2×10^{-2} over 420 km integrated transparently with both multi-Gbps single and dual-polarization IR-UWB signals that also received under the BER limit without severely affected.

The radio over fiber is a promising candidate using the concepts behind optical fiber-wireless based access technologies to provide ultra-high-speed transmission. Interestingly, the proposed system could suggest being implemented in the next-generation ultra-high-speed long reach PONs (LR-PONs) or 5G/6G mobile backhaul/fronthaul links that strongly comply with these requirements.

As future work, we are very interesting to develop low-cost Digital Signal Possessing (DSP) algorithms at the coherent receivers and artificial neural networks to simultaneously compensate the linear and non-linear impairments that effects the dual-polarization optical OFDM signals; to lower the cost of the whole system instead of using DCFs thorough the ODN, and then we will compare them with this reference work to show the improvement that will occur. At the same time, a full-duplex integrated wired-wireless system using optical frequency comb source will be designed instead of using array of laser sources that used to transport the IR-UWB and the DP CO-OFDM channels, and we will focus to employ high order modulation such as 16, 64, and 128 QAM for the CO-OFDM channels that are considering as the main challenge for long distances at high data rates.

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