Next Generation of High-Speed Optical Communications Networks Using OFDM Technology

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Abstract. The usage of data transmission through Optical Fiber is highly preferred in every area where transferring of data is needed from one end to another. Moreover, nowadays the infrastructure of telecommunications is in good shape and size to handle data transmission through its optical fibers which have low attenuation and higher bandwidth. The seeking of data rate higher than 100Gbit/second and above has been increased to build it in urban and rural areas, and for long and short hauls. Consequently, the current goal is to propel this transmission system into the next appropriated level to avoid any decline of the optical infrastructure than its current capacity. To fulfill increased demand for bandwidth in Broadband services one of the most trusted technology is the Orthogonal Frequency Division Multiplexing (OFDM). The Orthogonal Frequency Division Multiplexing has been placed on-demand in optical communication, it is used in Long haul transmission Format in Direct and Coherent detection. OFDM has many features and abilities can boost the optical fiber performance by eliminating several limits of conventional Optical Fiber communication. OFDMA has polarization mode dispersion (PMD) and chromatic dispersion (CD) which are considered a big addition to the current systems. In addition to that, the easy correlation of the coherent optical OFDM with Wavelength Division Multiplexing (WDM) systems can further advantages in the transmission system such as super bandwidth, high spectral efficiency, and extra data rates. Furthermore, the WDM systems can improve data rate and capacity by using multiple wavelengths over a single fiber. This work aims to bring implementation and to perform a deep-dive study of higher data rates using Direct and Coherent Optical OFDM for long path transmissions. This research starts with a unique user and then extends to the add the OFDM - WDM system to get a data rate of 100 Gbps. Regarding the software portion, the Optisystem simulation tool was used for the design and implementation of the system. Moreover, the modulation type used is QAM for the OFDM signal, and I/Q modulation is deployed, while Coherent and Direct detection is used at the receiving portion. Q Factor, the bit error rate and eye diagram were discussed to study the System’s Performance and Quality. This work found CD-OOFDM is the best system for next generation of optical. The work compared WDM CD-OOFDM with SMF-DCF to DD and CD-OOFDM. In addition to that, it compared WDM CD-OOFDM with SMF-DCF to CD-OODFM with SMF. Therefore, the results showed that WDM CD-OOFDM with SMF-DCF achieved 25 Gbps for four channels of the WDM system at 120km channel, where the carrier frequencies were from 193.05THz to 193.2THz.

Keywords: DD-OOFDM, CD-OOFDM, Integration of CD-OOFDM with WDM for long haul high data rate transmission.

Introduction. Optical and other digital communication systems play a large role in modern communications. They lead to include the sent signals as data on optical carriers or other digital communication systems. The forms used to include data in an optical communication system are similar to the types used in radio-frequency communication systems (RFS) with phase, amplitude, and data frequencies transmitted by the optical carrier [1]. OFDM is an encouraging technology that can help meet growing demand and benefit from bandwidth in Broadband services.
OFDM technology has gained a great role in optical communication systems, especially after proposing DD-OFDM and coherent detection-OFDM techniques OOFDM, was developed to satisfy the fast-growing need for higher bandwidths in broadband services. OFDM increased the average concentration in the visual correspondence network, particularly after it was set as a nice long communication segment in consistent and direct discovery. In addition, OFDM can overcome many visual limitations of optical fibers, for example, chromatic dispersion (CD) and polarization mode dispersion (PMD). [2].

In addition, it is possible to combine OFDM systems with WDM systems, which can provide communication system with high bandwidth, high spectral efficiency, and large data rate.

WDM systems have the ability to improve capacity and data-rate by posting many wavelengths through single fiber. The increasing demand for voice, messages, and video transmission services has led to manipulate high bandwidth and data rate [3,4].

Recently, there is a great effort in the field of research and development in various research centers to meet the increasing demand in transport networks, especially in 100 Gbps Ethernet and beyond. To increase the data rate, this frequency band must be expanded to enhance spectral efficiency.

**Direct Detection -OOFDM**

Below is an illustration of the Direct Detection (DD) -OFDM system as shown in Figure (1), which begins with a DD-OOFDM transmitter. The data is transmitted to the optical fiber, which in turn carries the data to the DDOFDM receiver. Figure (1) shows the system is used for transferring one bit stream over one communication channel using one sequence of DDOFDM symbols.

![DDOOFDM Sequenced Diagram](image)

The electric sign of OFDM is produced by the OFDM transmitter, where it is transferred from the electric field to the optical domain using the electric / optical converter (E / O), which also adjusts the intensity.

The optical-fiber can be used to send the resulting of optical-sign. The loss of fiber is compensated for by using an optical amplifier. On the other side of the system, specifically at the receiver, the sign is returned from the optical field to the electrode by means of an adapter that converts the signal from optic to electric (O per E); (photodiode).

The equation below represents the electrical signal received:

\[
A_e(t) = |A_0(t)|^2 h_e(t) + w(t)
\]

As; \(A_e(t)\) is the electrical signal in the receiver; the optical OFDM sign, \(h_e(t)\) is the response of impulse; (impulse) of the electric field while the \(w(t)\) clarified the noise of the method.

After the conversion process, a decrease in the signal happens. Thus, the signal requires to be amplified again as it flits through a Low Pass Filter (L.P.F.). Then, will be sent to the receiver of OFDM. In order to obtain the initial sign [5].

**Coherent-Detection an Optical a OFDM a(OFCD-OOFDM)**

The CD-OOFDM system is illustrated in Figure (2). It is noted that the CD-OOFDM system is comparable to the DD-OOFDM system and the difference between them in is the actual per imaginary (I per Q modulator) as well as the local-oscillator (L.O.).

A local optical oscillator is can be used with an optical-coherent system to create optic signs at certain wavelengths. With reference to the local-oscillator frequency, optical coherent-detection is split into two types: homodyne
detector as well as heterodyne detector [6]. The block diagram of a basic CD-OOFDM transmitter is shown in Figure (2).

![Fig. (2) CDOOFDM Block Diagram](image)

**Heterodyne-detection**

When the L.O. does not adapt the arriving sign within the photodiode as well as whenever the two signs are combined, a new frequency is created; the Intermediate-frequency (IF.), which represents the variation between the two-frequencies. This method reduces the noise caused by the heat and the test noise, that leads to the improvement of the Signal to noise ratio (S.N.R.) execution. Anywise, the source frequency tends to deviate with the passage of time. Hence, IF must be monitored continuously. The local oscillator should also be changed in order to maintain the stability of the IF [7].

**Homodyne detection**

The L.O. frequency is identical to the received sign. Among the other components is the (modulator of I per/ Q). The (I per Q) ingredients of the digital sign are transformed into an analog sign by the (D/A) converters on the transmitter. The switching unit (I per Q) composes of two MZM units raising the converts the complex OFDM to the optical field [7,8]. The modulated sign can be formed as follows;

$$E(t) = x(t) e^{j(W_{LD1}t + \Theta_{LD1})}$$  \[1.2\]

where $x(t)$ is the transmitted electrical sign, $\Theta_{LD1}$ and $W_{LD1}$ are the phase and angular frequencies of the laserdiode respectively. The sign at the recipient is as follows;

$$E_r(t) = E(t) \otimes h(t) + w(t)$$  \[1.3\]

$h(t)$ represents the signal carrier response whereas the w(t) denotes the noise of the channel. The arriving sign is discovered by a couple of coherent detectors and optical (90˚) hybrid to execute ( I per Q ) performance. The conversion is from optic to electric.

Any detection device composed of two couplers and photodiode -type 4-digit optical outlets; The Four 90˚ Optical Hybrid Parts. It is given as follows;
\[ E_1 = \sqrt{\frac{1}{2}} [E_s + E_{LD2}] \]
\[ E_2 = \sqrt{\frac{1}{2}} [E_s + E_{LD2}] \]
\[ E_3 = \sqrt{\frac{1}{2}} [E_s + E_{LD2}] \]
\[ E_4 = \sqrt{\frac{1}{2}} [E_s + E_{LD2}] \]

Represents the signals, \( E_s \) is the incoming signal and \( E_{LD2} \) the signals of the local oscillator. On the other hand, the signal is restored The in-phase using two phase detection (PD1 and PD2) through which Photo-Current can be given in the following form;

\[ I_1 = |E_1|^2 = \frac{1}{2} \left( |E_s|^2 + |E_{LD2}|^2 + 2 \Re \{E_2 E_{LD2}\} \right) \]
\[ I_2 = |E_2|^2 = \frac{1}{2} \left( |E_s|^2 + |E_{LD2}|^2 + 2 \Re \{E_2 E_{LD2}\} \right) \]
\[ |E_s|^2 = |E_l|^2 + |n_0|^2 + 2 \Re \{E_l n_0\} \]
\[ |E_{LD2}|^2 = |I_{LD2}(I + I_{rin}(t))|^2 \]

\( I_{LD2} \) and \( I_{rin}(t) \) represent the relative intensity noise and average power of the laser-diode. Due to the stable detection, the in-phase ingredient of photo current will be as follows;

\[ I_l = 2 \Re e E_s \ E_{LD} \]

In the same way, the quadrature components can be derived from other photo detection devices as follows;

\[ I_q = 2 \Im m E_s \ E_{LD} \]

From the equations (1.6) and (1.7) the complex photo-current

\[ \tilde{I}(t) = I_l(t) + j I_q(t) = 2 E_s \ E_{LD} \]

After finalizing optical detecting, the sign is sent to the OFDM receiver to elicit the original sign [9].

**Integration of CO-OFDM with WDM for long-haul-high-data-rate transmission**

WDM is a significant factor. It is able to give more facilities and flexibles in system design and streamline network. WDM collects some of optical carrier signs in a SMF utilizing variation wave-lengths or different laser light in optic OFDM. Using WDM assists to boost system capacity and provide a huge rise in the average of information transmitted through a single-fiber. When using different wave-lengths, each wave-length constitutes a discrete channel. WDM splits the optic spectrum into least channels, that are in turn used to send and collect information at the same time. Fig. (3) Constellation Diagram of 4QAM. Figure (3) addresses the four quadrants of the I/Q constellation diagram, as mentioned.
Fig. (3) Constellation Diagram

Designing the WDM CD-OFDM System with SMF-DCF The CD-OFDM Transmitter with a 120 KM length is shown in figure (4). The CD-OFDM Transmitter is designed with P.R.B.S. Generator to create a bit series as it has been designed using 4QAM en-coder. The 4QAM sign is linked to include OFDM Modulator with the use of 512-Sub-carrier and 1024-FFT-Points. The resulting signal is sent from the OFDM to the optical (I per Q) Modulator, that composed of two Mach Zehnder modulators (MZM). The Optic Modulator modifies the sign from the electrical sign to visual sign. So as to acquire 100Gbs, there are four units of OFDM signals. The exception is the visual transmitter laser which is a wavelength that begins from 193.05THz to 193.2THz within a distance of 50GHz. The WDM composed of four channels to uphold the four bands of the Channel. Each signal of OFDM signals contains 25Gbps Bits-Rate that provides a total data-rate of 100 Gbps. Figure (4) shows the concept of RoF system Block-Diagram of WDM and CDOFDM System with SMF. -DCF of 120km.

Fig. (4) Block-Diagram of WDM. CDOFDM. System with SMF. -DCF. of 120km
The output signals from the transmitter launch WDM De-multiplexing. The four different wavelengths are integrated into a single signal sent across the visual fiber. The resulting signal is sent from the WDM via the SMF-SMF system.

The Attenuation of SMF is 0.2dB / km. Whereas, The attenuation of DCF is 0.4dB / km. The Dispersion of SMF is 16(dB / km.nm) for 100km. The dispersion of SMF is 1600ps / nm. As a result, dispersion of SMF has to be compensated for 100km where long DCF is required with 20km length with dispersion -80 ps / (km.nm), which produces -1600ps / nm, which is negative. An optical amplifier is used with a power of 20dB to amplify the signal and compensate for what it has lost. The parameters to SMF and DCF are shown in table (1).

The optical signals received from the optical connection are detached into four-wave-lengths by WDM demultiplexer. Any wavelength is discover by its receiver. Four receivers are made to sustain the similar parameter unless the center-frequency of the receiver as well as the LO that has a frequency corresponding to the laserwave length of the transmitter. In addition to that any receiver is consisting of two balanced (C-detectors) devices with L.O. to make optic I per Q conversion to electrical and omit any noise. Moreover, each of these detectors composed of two couplers and two PIN photodetectors. Any of these PINS contains a dark current of 10nA. After detecting the sign, it is sent to OFDM-demodulator which in turn contains comparable parameters.

Table (1) SMF and DCF Parameters

| Fiber Type | Length | Attenuation | Dispersion | Slope | Effective Area | Nonlinear Refractive Index $n_2$ |
|------------|--------|-------------|------------|-------|----------------|----------------------------------|
| SMF        | 100km  | 0.2dB/km    | 16ps/km.nm | 0.08ps/(nm².k) | 80μm² | 2.6x10⁻²⁰                 |
| DCF        | 20km   | 0.4dB/km    | -80ps/nm.km | -0.45ps/(nm².k) | 30 μm² | 2.6x10⁻²⁰                 |

Simulation and Result

The radio frequency spectrum (RF) of the I/Q component of CD-OOFDM WDM is located on the side of the transmitter as shown in Figure (5).

The RF-power is measured at approximately 40dB. The RF of the (I/Q) component of the CD-OOFDM WDM method is located on the side of the sender device as shown in Figure (6).

![RF Spectrum Analyzer_6](image1)
![RF Spectrum Analyzer_28](image2)

Fig. (5) RF-OFDM. Spectrum (I per Q) ingredient at the CDOFDM path
It is noted that there is a decrease of the RF power to 20 dB when it is compared to the figure (7); Figure (8) shows the four OFDM spectra following the WDM system. The four WDM paths begin with 193.05THz and up to 193.2THz. The channel spacing is 50GHz.

Fig. (6) RF-OFDM. Spectrum (I per Q) Component at the CDOFDM Receiver

Fig. (7) 4OFDM Sign after the WDM Channels
Figure (9) shows the constellation-diagram of the 4QAM in the receiver after the SMF-DCF optical connection. In this diagram, the blue dots signify the sign. The green dots signify the noise. The sign is retrieved when the CD is removed from the SMF.

Figure (9) The Constellation of 100 Gbps WDM CDOFDM System beyond 120 km
When design the completed, the Q-factor, bit-error-rate (BER), as well as eye-diagram are chosen in order to select and explore the system to identify the type of signal, shapes, and parameters are shown in figures (10), (11) and (12), respectively.

![Fig. (10) BER for 120 km of Transmission Length of SMF-DCF Optical connection](image)

![Fig. (11) Q. Factor](image)
Table (2) awards the sign information at the receiver for 100 Gbps WDM CD-OOFDM system.
Tab. (2) sign information at the receiver for 100 Gbps. Sign details at the receiver

| Max.Q-Factor   | 5.05e+049 |
|---------------|-----------|
| Min. B.E.R.   | 0         |
| Eye-Height    | 1.01      |
| Threshold     | 3.330191e-010 |

**Conclusion**

Data Rate has become a telecommunication crisis, not just in conventional systems but all over telecommunication systems such as 5G which is the fifth generation of wireless communications technologies supporting cellular data networks. Our work found a system design can fit in the front haul for the 5G systems easily. This work achieved high speed using a DD-OOFDM system which is found having the most simple to send and receive data; it is less expensive than the CD-OOFDM system and it has more protections against noise. However, it can be stated that CD-OOFDM is the next generation of optical media technology instead of DD-OOFDM as it combines all the advantages of coherent optical and OFDM systems. Besides, many restrictions that show in SMF systems including CD and PMD have been overcome. Also, combining OFDM technology with WDM technology and designing and building a system for them provides high bandwidth transmission and large data rate in addition to high spectral efficiency without growing cost or make the system more complicated.

To increase the demand in Bandwidth and data rate, it is suggested that the WDM and OFDM systems be combined. There are there effective systems have been compared. Sustainability of these systems is a key factor, so that next generation networks can adopt the best one.

In the present study, three diverse systems are designed for diverse rates utilizing DD and CD-OOFDM. The first design is based on DD-OFDM. In this system, (7.5 GHz frequency carrier) is used. The data rate is 10 Gbps. The modulator is 16-QAM, 256 subcarriers, and 512 FFT points. In addition to that, the various transmission links are checked. Moreover, as the length of the transmitter channel increases, the Q factor coefficient decreases with an increase in the worth of BER. The better worth of BER is at zero.
The second one is based on CD-OOFDM with SMF. The data rate is 40 Gbps with the embedded type 16-QAM modulation, 512 subcarriers, and 1024FFT-points. The length of the transmission connection is 150(km). After designing Simulations of this system, the best value for BER is zero.

The third and last design based on WDM CD-OOFDM with SMF-DCF. It is 120km long. The four channels of the WDM system of 25 Gbps with a built-in 4QAM transmitted the signal, as the carrier frequencies from 193.05THz to 193.2THz were channeled carrier with a 50GHz channel wideness, 512-sub-carrier and 1024FFT-points. The system is made and simulated to obtain a worth for B.E.R. that is zero.

In the DD-OOFDM system, the photodiode is utilized to convert the signal from optical to electrical. Whereas, in CD-OOFDM detection, two similar couples of stable coherent-detectors with L.O. are utilized to convert the (I per Q) the signal from optical to electrical.

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