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Optical-OFDM Detection Techniques

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***Abstract*:** Orthogonal Frequency Division Multiplexing (OFDM) is a baseband wired and wireless communication system which has proffered an effective solution to transmission impairment like nonlinearity in fiber, fading, Chromatic Dispersion (CD) which resulted in intersymbol and intercarrier interferences. The urge for a very high speed transmission has lead to a dramatic increase of interest in OFDM based optical communication system in recent years. This paper gives a tutorial overview of O-OFDM detection techniques namely; Direct Detection O-OFDM (DDO-OFDM) and Coherent O-OFDM (CO-OFDM) from the basis, outlining their similarities and differences in their performance. The only different in the conceptual diagram of DDO-OFDM and CO-OFDM is replacing MZM and PIN detector in DDO-OFDM with optical IQ modulator and coherent receiver respectively, although the DSP requirement, Cyclic Prefix (CP), DACs and ADCs design for both will depend on the choice of the designer. The building architecture of direct detection is much cheaper as compared to coherent receiver system, but with the robust implementation of DSP in the transceiver circuit as the signal volume increases, the cost of the coherent receiver will equally come down drastically.

Keywords: CO-OFDM, DDO-OFDM, DSP, FFT/IFFT, LM-DDO-OFDM, NLM-DDO-OFDM.

1. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is a Frequency Division Multiplexing (FDM) technique or scheme used as a digital multi-carrier modulation method [1]. The purpose of this format is to significantly reduce inter-carrier and inter-symbol interference. In this technique, a large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. Each sub-carrier is modulated with a conventional modulation scheme such as Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

OFDM has widely gained ground as an efficient modulation and multiplexing technique for both broadband wireless and wired communication system due to its spectrum utilization advantage and channel robustness against transmission impairments. In its generalization, OFDM belongs to a broader class of Multi-Carrier Modulation (MCM), though it forms the basis of many of several telecommunications standards in the world, counting from Digital Terrestrial Television (DTT), Wireless Local Area Networks (WLANs), digital radio broadcasting and Digital Subscribers Line (DSL) standards [2].

However, OFDM in recent years has offered so much tremendous benefits in both wired (optical) and wireless communications network. The issue of non-linearity, chromatic dispersion, inter symbol and inter carrier interferences associated with fiber communication, were eliminated using Optical-OFDM (O-OFDM) modulation technique [3]. This keen interest to develop high speed data geared toward the develop of a high capacity and robust communication network in a long-haul transmission optical network services. OFDM has taken the advantages of the Discrete Fourier Transform (DFT) and well as Inverse Discrete Fourier Transform in actualizing a high spectral efficiency and simple channel equalization in optical transmission networks [4]. Henceforth, this modulation technique has equally been applied and utilized in Wavelength Division Multiplexing (WDM) systems.

2. HISTORICAL PERSPECTIVE OF OFDM

The history of OFDM remains incomplete without mentioning the key actors in this filed. Chang in his seminal paper brought out the concept of OFDM in 1996. He proposed a method of synthesizing a band limited signals for the multichannel transmission in which signals are spaced and arranged orthogonal (90 degrees) to each other [1]. Each of these signals are transmitted simultaneously through a band limited channel overcoming transmission impairment such as inter symbol and inter carrier interference. The work of Chang was further analyzed by Salzberg in 1967, he proposed on the issue of reducing the crosstalk between adjacent channels rather than perfecting individual signals which are inevitable due to non-linear effect in fiber communications [5]. This encompasses not only in OFDM but also in Wavelength Division Multiplexing (WDM).

However, S.B Weinstein and P.M Ebert proposed the implementation of DFT and IDFT at both transmitter and receiver respectively in OFDM system . R. Peled and A. Ruiz proposed Cyclic Prefix Insertion and removal at both transmitter and receiver respectively in OFDM as well [6]. L. Cimini of Bells Labs proposed OFDM for mobile communication while Alard proposed a combination of Forward Error Correction (FEC) and OFDM. European Telecommunication Standard Institute (ETSI) in 1995 formally adopted Digital Multi-tone, a variation of OFDM Digital Subscribers Line (DSL) as well as Digital Audio/Video Broadcasting (DAB/DVB) standard. IEEE Standard adopted Wireless LAN 802.11 a(g) Wireless Fidelity (Wi-Fi), IEEE WiMax Forum equally adopted Wireless MAN standard 802.16 WiMax and finally, Third Generation Partnership Project (3GPP)/ESTI adopted Long Term Evolution (LTE)/Forth Generation (4G) and the future Fifth Generation (5G) standard. The architectures of these projects are based on OFDM modulation and detection techniques.

In a similar vein, OFDM has been incorporated into the optical domain in recent time. The pioneers in this field started with Pan and Green dated 1996 in the area of OFDM for Community Access Television (CAT) [7], You and Kahn contributed in Direct Detection Optical OFDM (DDO-OFDM), Shieh and Athaudage in the area Coherent Optical OFDM (CO-OFDM). Currently, many researches in the likes of Yang et al., succeeded in realizing up to 110 Gb/s per single channel CO-OFDM in a long-haul transmission network incorporating Orthogonal Band Multiplexing (OBM) technique into OFDM. In 2017, Zhang et al., equally realized a Real-time Optical OFDM transmissions with spectral efficiency of up to 6.93 bit/s/Hz over 50km Standard Single Mode Fiber (SSMF) Intensity Modulated Direct Detection (IMDD) systems.

In the late 2000s, long-haul transmission by optical OFDM has been investigated by a few actors. Two major research directions appeared, namely; Direct Detection Optical OFDM (DDO-OFDM) looking into a simple realization based on low-cost optical components and Coherent Optical OFDM (CO-OFDM) aiming to achieve high spectral efficiency and receiver sensitivity and incurring the cost complexity of the system [8]. Since then, the interest in optical OFDM has increased dramatically. In 2007, the world's first CO-OFDM experiment with line rate of 8-Gb/s over 1,000km was reported. This was followed by 56-Gb/s, 110Gb/s over 600-km Standard Single Mode Fiber (SSMF) using Orthogonal Band Multiplexing (OBM). Recently, up to 4-Tb/s single-channel coherent optical OFDM transmission with orthogonal-band multiplexing and subwavelength bandwidth access was successfully demonstrated [9].

2.1 The Theoretical Basics of OFDM

Frequency Division Multiplexing (FDM) is a technique where the main signal to be transmitted is divided into a set of independent signals, known as subcarriers in the frequency domain. Thus, the original data stream is divided into many parallel streams (or channels) as theoretically as possible, one for each subcarrier. Each of this subcarrier is then modulated with a conventional modulation scheme, and combined together to generates the FDM signal. Figure 1 shows a given OFDM frequency spectrum with Guard Bands, Pilot Subcarriers and User Data Subcarriers.

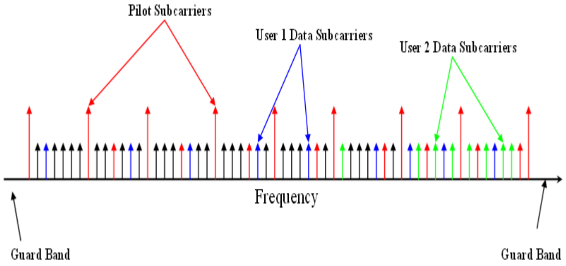

Figure 1. OFDM Subcarriers Frequency Spectrum

However, each of the subcarriers in FDM transmission is independently recovered at the receiver and therefore these signals need to fulfill certain conditions to achieve orthogonality as shown in Figure 1. For instance, they can have non-overlapping spectra so that a bank of filters tuned to each of the different subcarriers can recover each of them independently To obtain a low efficiency, there will be a guard band in-between the subcarrier bands in practical filters. If the subcarrier signals fulfill the orthogonality condition, their spectrum can overlap thereby improving the spectral efficiency. This technique is known as Orthogonal FDM or OFDM.

Then, as shown in Figure 2, an OFDM symbol spectrum consists of overlapping *sinc* functions, each one representing a subcarrier, where at the frequency of the k*th* subcarrier all other subcarriers have zeros. Note that each subcarrier is centered at f_k and separated by 1/*Ts* from its neighbours. When this happens, the orthogonality condition is being fulfilled so a great spectral efficiency for the transmission is achieved. This way, the subcarriers can be recovered at the receiver without inter-carrier interference despite strong signal spectral overlapping, by means of the orthogonality condition using a bank of oscillators and low-pass filtering for each subcarrier.

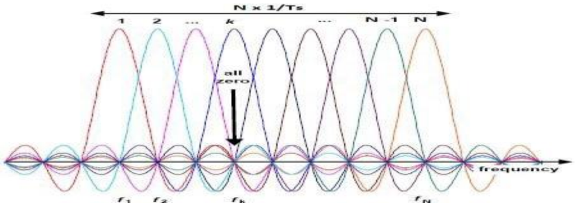

Figure. 2 Spectrum of an OFDM Symbol with Overlapping Subcarriers

2.2 Principle of Orthogonality Between OFDM Subcarriers and Subbands

The word orthogonal indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. In a normal frequency-division multiplex system, many carriers are spaced apart in such a way that the signals can be received using conventional filters and demodulators [10]. In such receivers, guard bands are introduced between the different carriers and in the frequency domain, which results in a lowering of spectrum efficiency. It is possible, however, to arrange the carriers in an OFDM signal so that the sidebands of the individual carriers overlap and the signals are still received without adjacent carrier interference. To do this, the carriers must be mathematically orthogonal to each other.

However, we can represent a Multi-Carrier Modulation (MCM) transmitted signals *s(t)* as;

$$s(t) = \sum_{i=-\infty}^{+\infty} . \sum_{k=1}^{Nsc} C_{ki} S_{ki} (t - iT_s) \qquad 1$$

$$s_k(t) = \prod(t\, e^{j2\pi fkt} \qquad 2$$

$$\prod(t) = \begin{cases} 1, & (0 < t \le T_s) \\ 0, & (t \le 0, t > T_s) \end{cases}, \qquad 3$$

where; C_{ki} represents the *ith* information symbol at the *kth* subcarrier, S_{ki} represents the waveform for the *kth* subcarrier, *Nsc* represents the number of subcarriers, *fk* represents the frequency of the subcarrier, T_s represents the symbol period and finally, $\prod(t)$ represents the pulse shaping function. However, each of the subcarrier in achieving its optimum detection could either use a filter that matches the subcarrier waveform, or a correlator that matched with the subcarrier as shown in Figure 3. In other words, the detected information symbol $C`_{ik}$ at the receiver is given as;

$$C`_{ik} = \frac{1}{T_s}\int_0^{T_s} r\,(t - iT_s) s^* k^{dt} \qquad 4$$

$$= \frac{1}{T_s}\int_0^{T_s} r\,(t - iT_s) e^{-j2\pi f k^t dt} \qquad 5$$

where; r(t) represents the received time-domain signal.

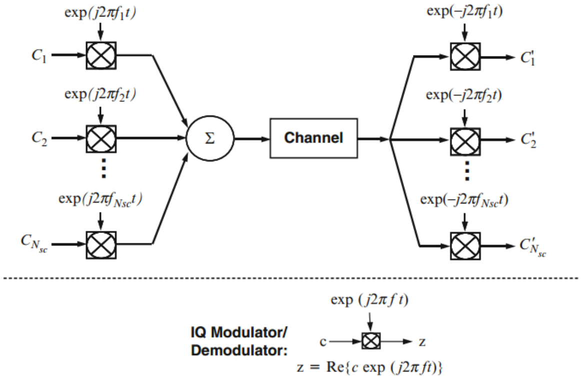

Figure 3. A Multi-Carrier Modulation System

Classically, MCM uses non-over-lapped band-limited signals, its implementation involves a bank of larger number of oscillators and filters at the transceiver. Although, with its inherent advantages, one of the major challenges of MCM is that it requires a large bandwidth. This emanates from the fact that the designed filters and oscillators are extremely cost-effective, in other words, the channel spacing has to be multiple of the symbol rate, thereby greatly reducing the spectral efficiency of the entire system. However, with the implementation of an OFDM modulation technique which employs overlapped yet orthogonal signal set, the spectral efficiency of the network improves drastically. The concept of this orthogonality originates from the idea that there exit a straightforward correlation between any two subcarriers which can be shown mathematically below;

$$\delta_{kl} = \frac{1}{T_s}\int_0^{T_s} s_k s^*_l \, dt \qquad 6$$

$$= \frac{1}{T_s}\int_0^{T_s} exp\,(j2\pi(f_k - f_l)t)dt \qquad 7$$

$$= \exp\,(j\pi(f_k - f_l)T_s)\,\frac{\sin(\pi(f_k - f_l)T_s)}{\pi\,(f_k - f_l)T_s} \qquad 8$$

we deduced from the equation 8, that if the following condition as represented below in equation 9 is satisfied,

$$f_k - f_l = \mathrm{m}\,\frac{1}{T_s} \qquad 9$$

then, we can strongly agreed that the two subcarriers are orthogonal to each other. This simply means that these orthogonal subcarrier sets, with their frequencies spaced at multiple of inverse of the symbol rate can be recovered with the matched filters as shown in equation 9 above. However, this benefit made OFDM a more robust technique because of its capability to suppress inter-symbol and inter-carrier interference in a long-haul transmission network systems in spite of strong spectral overlapping.

3. OPTICAL OFDM (O-OFDM)

Despite the use of OFDM in wireless communications, it has been applied towards optical communications in recent time [11]. OFDM has newly received a lot of interest in the fibre-optic community. The main benefit of optical OFDM is that it can deal with virtually unlimited amount of ISI as well as ICI. ISI and ICI are caused by chromatic dispersion and Polarization Mode Dispersion (PMD) in high-speed optical systems. This chromatic dispersion and polarization dispersion is a serious challenge in long-haul transmission systems.

Table 1. Comparisons between Wireless and Optical-OFDM.

	Optical OFDM (O-OFDM)	Wireless (RF) OFDM
Mathematical Model	Continuous Frequency Domain Dispersion	Multiple Discrete Time Domain Rayleigh Fading
Speed	Average	Fast for mobile environment
Non Linearity	Important and significant	None
Information carried	On optical intensity	On electrical field
Local oscillator	At receiver	At receiver
Polarity	Unipolar	Bipolar

3.1 Flavours of Optical OFDM

One of the major strengths of OFDM modulation format is its rich variation and ease of adaption to a wide range of applications. In wireless systems, OFDM has been incorporated in wireless LAN (IEEE 802. 11a/g, or better known as Wi-Fi), wireless WAN (IEEE 802.16e, or better known as WiMax), and Digital Audio/Video Broadcasting (DAB/DVB) systems adopted in most parts of the world [12]. In RF cable systems, OFDM has been incorporated in ADSL and VDSL broadband access through telephone copper wiring or power line. This rich variation has something to do with the intrinsic advantages of OFDM modulation including dispersion robustness, ease of dynamic channel estimation and mitigation, high spectral efficiency and capability of dynamic bit and power loading. Recent progress in optical OFDM is of no exception.

We have witnessed many novel proposals and demonstrations of optical OFDM systems from different areas of the applications that aim to benefit from the afore-mentioned OFDM advantages. Despite the fact that OFDM has been extensively studied in the RF domain, it is rather surprising that the first report on optical OFDM in the open literature only appeared in 1996, where they presented in-depth bit-error-rate performance analysis of light wave hybrid Adaptive Modulation OFDM (AM/OFDM) systems with comparison with AM/QAM systems in the presence of clipping impulse noise in fibre-optic systems [13]. The lack of interest in optical OFDM in the past is largely due to the fact that silicon signal processing power had not reached the point where sophisticated OFDM signal processing can be performed in a CMOS integrated circuit (IC).

Optical OFDM are mainly classified into two main categories: coherent detection and direct detection according to their underlying techniques and applications. While direct detection has been the mainstay for optical communications over the last two to three decades, the recent progress in forward-looking research has unmistakably pointed to the trend that the future of optical communications is the coherent detection because of its inherent advantages.

3.2 O-OFDM DETECTION TECHNIQUES

Basically there are two techniques in which an Optical-OFDM signal can be detected at the receiver: direct detection (DDO-OFDM) and coherent detection (CO-OFDM). All of the existing applications or designs concerning an Optical-OFDM receiver are variations of these two options. Despite the low cost benefits accrued in direct detection, coherent detection-based systems represent the best performance in receiver sensitivity, spectral efficiency and robustness against polarization dispersion, although coherent detection-based systems require the highest complexity in the transmitter design.

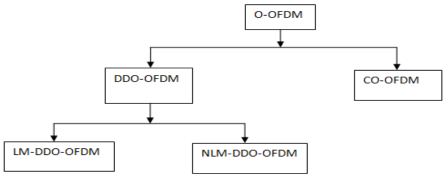

Figure 4. O-OFDM Detection Techniques Chart

3.2.1 Direct Detection O-OFDM (DDO-OFDM)

DDO-OFDM has much more variants than the coherent counterpart. This mainly stems from the broader range of applications for DDO-OFDM is due to its lower cost and effective short reach applications. According to how optical OFDM signal is being generated, DDO-OFDM is classified into two categories namely:

1. Linearly Mapped DDO-OFDM (LM-DDO-OFDM), in which the optical OFDM spectrum display a replica of baseband OFDM

2. Nonlinearly Mapped DDOOFDM (NLM-DDO-OFDM), in which the optical OFDM spectrum is not a replica of baseband OFDM [26].

For instance, the first report of the DDO-OFDM takes advantage of the fact that the OFDM signal is more immune to the impulse clipping noise in the CATV network. Other example is the single-side-band (SSB)-OFDM, which has been recently proposed by Lowery and Armstrong OFDM for dispersion compensation in a long-haul transmission network [14]. There are many publications in which different forms of direct detection methods are presented, each with some advantages over the others. However, all of them share a very important characteristic, which is the use of a simple receiver called PIN detector.

Similarly, Beyond 100Gb/s transmission over 80km SMF using Direct Detection Single Side-Band Discrete Multitone (DD-SSB-DMT) at C-band by Zhang et was proposed. The experiment was demonstrated without Chromatic Dispersion (CD) using dual-drive Mach–Zehnder Modulator-assisted SSB modulation. The experimental results show that high capacities up to 122, 110 and 105-Gb/s are achieved with bit error rate at 4.5×10^{-3} for back to back, 40- and 80-km SMF transmissions, respectively with Optical to Noise Ratio (OSNR) after 80-km SMF transmission as 34.2 dB [15]. The common feature for DDO-OFDM is of course using the direct detection at the receiver, but we classify the DDO-OFDM into two categories according to how optical OFDM signal is being generated: (1) linearly mapped DDO-OFDM (LM-DDO-OFDM), where the optical OFDM spectrum is a replica of baseband OFDM, and (2) nonlinearly mapped DDO-OFDM (NLM-DDO-OFDM), where the optical OFDM spectrum does not display a replica of baseband OFDM.

3.2.2 Coherent Optical OFDM (CO-OFDM)

CO-OFDM represents the ultimate performance in receiver sensitivity, spectral efficiency, and robustness against polarization dispersion, but yet requires the highest complexity in transceiver design. When the modulation technique of OFDM combines with coherent detection, the benefit brought by these two powerful techniques are multifold: (1) High spectral efficiency; (2) Robust to chromatic dispersion and polarization-mode dispersion; (3) High receiver sensitivity; (4) Dispersion Compensation Modules (DCM)-free operation; (5) Less DSP complexity; (6) Less oversampling factor; (7) More flexibility in spectral shaping and matched filtering.

In the open literature, CO-OFDM was first proposed by Shieh et al., and equally formalized the concept of the coherent optical MIMO-OFDM. They carried out an early CO-OFDM experiments over 1,000 km SSMF transmission at 8-Gb/s [16]. Kaneda et al., proposed a field demonstration of 100-Gb/s real-time coherent optical OFDM detection [17]. Another interesting and important development is the Sano et al., breakthrough, they proposed and demonstrated the no-guard interval CO-OFDM for 100-Gb/s long-haul Wave Length Division Multiplexing (WDM), where optical OFDM is constructed using optical subcarriers without a need for the cyclic prefix [18]. Nevertheless, the fundamental principle of CO-OFDM remain the same, which is to achieve high spectral efficiency by overlapping subcarrier spectrum yet avoiding the interference by using coherent detection and signal set orthogonality.

In the early twenty first century, the impressive record-performance experimental demonstration using a Differential-Phase-Shift-Keying (DPSK) system [19], in spite of an incoherent form of modulation by itself, reignited the interest in coherent communications. First, current coherent detection systems are heavily entrenched in silicon-based DSP for high-speed signal phase estimation and channel equalization. Second, multicarrier technology, which has emerged and thrived in the RF domain during the past decade, has gradually encroached into the optical domain [20]. Third, in contrast to the optical system that was dominated by a low-speed, point-to-point, and single-channel system a decade ago, modern optical communication systems have advanced to massive WDM and reconfigurable optical networks with a transmission speed approaching 100-Gb/s. In a nutshell, the primary aim of coherent communications has shifted toward supporting these high-speed dynamic networks by simplifying the network installation, monitoring and maintenance.

4. O-OFDM SYSTEM DESCRIPTION

The conceptual diagram of CO-OFDM system is shown in Figure 5. It contains five essential functional blocks: 1) RF-OFDM signal transmitter, 2) RF to optical (RTO) up-converter, 3) Optical fiber links, 4) optical to RF (OTR) down-converter, 5) RF-OFDM receiver. Such setup can be also used for single-carrier scheme, in which the DSP part in the transmitter and receiver needs to be modified, while all the other hardware setup remains the same.

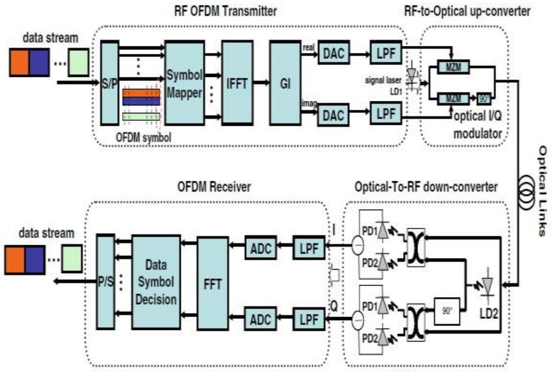

Figure 5. Coherent Optical OFDM system.

At the transmitter, data is mapped into any constellation like QAM or PSK and then passed onto an IFFT modulator to obtain the OFDM spectrum, which is directly up-converted to optical frequency. At the receiver, the down-converted RF signal is first sampled by high speed Analog-to-Digital Converter (ADC). It uses two balanced receivers for photo-detection followed by the OFDM demodulator section. Coherent requires that the state of polarization of the incoming light wave be the same as that of Local Oscillator (LO) light wave, otherwise severe performance degradation results.

4.1 O-OFDM Transceiver

At the receiver, the OFDM signal is mixed with both the component at the optical carrier frequency and the signal detected from the carrier signal mixing products. The first component which is the optical carrier frequency can either be transmitted with the OFDM signal as in direct-detection optical OFDM (DD-OOFDM) [8] or using coherent detection, where the received signal is mixed with a locally generated carrier signal as in coherent optical OFDM (CO-OFDM) [21]. Figure 6 shows DDO-OFDM transceiver

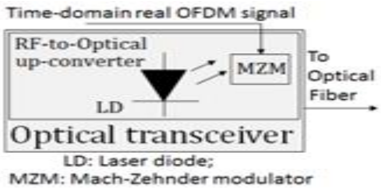

Figure 6. DDO-OFDM Transceiver Circuit

The optical coherent OFDM transmitter and receiver consists of a homodyne transmitter and receiver design circuit respectively. The component is formed by a set of 3 dB fiber couplers, a Local Oscillator (LO) laser, low-pass bessel filter and balanced detection each. Figures 7 and 8 show CO-OFDM transmitter and receiver configuration respectively.

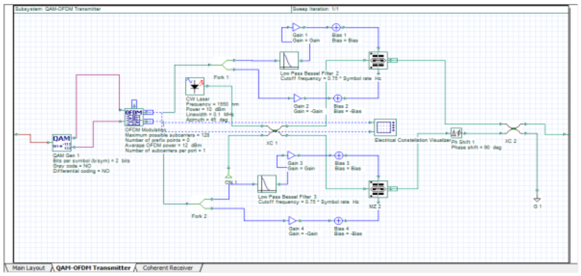
Subsystem: QAM-OFDM Transmitter
Sweep Iteration: 1/1
QAM Gen 1
Bits per symbol (b/sym) = 2 bits
Gray code = NO
Differential coding = NO
OFDM Modulation
Maximum possible subcarriers = 128
Number of prefix points = 0
Average OFDM power = 12 dBm
Number of subcarriers per port = 1
CW Laser
Frequency = 1550 nm
Power = 10 dBm
Linewidth = 0.1 MHz
Azimuth = 45 deg
Gain 1
Gain = Gain
Bias 1
Bias = Bias
Gain 2
Gain = -Gain
Bias 2
Bias = -Bias
Gain 3
Gain = Gain
Bias 3
Bias = Bias
Gain 4
Gain = -Gain
Bias 4
Bias = -Bias
Low Pass Bessel Filter 2
Cutoff frequency = 0.75 * Symbol rate Hz
Low Pass Bessel Filter 3
Cutoff frequency = 0.75 * Symbol rate Hz
Ph Shift 1
Phase shift = 90 deg

Figure 7. CO-OFDM Transmitter Circuit

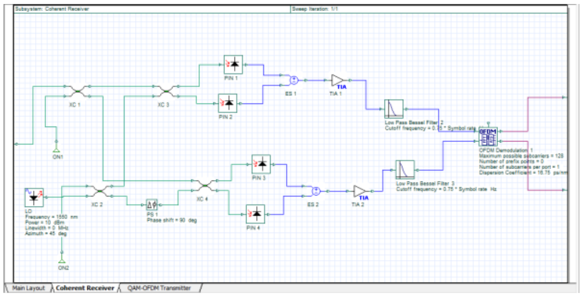

Figure 8. CO-OFDM Receiver Circuit

As earlier mentioned, the different in both circuits are replacing the Mach Zhender Modulator (MZM) and PIN detector in DDO-OFDM with optical In-Phase and Quadrature (IQ) modulator and coherent receiver respectively. However, both techniques have their own peculiar advantages and disadvantages. In DD-OOFDM the receiver is simple, but some optical frequencies must be unused if unwanted mixing products are not to cause interference. Though, this is usually achieved by inserting a guard band between the optical carrier and the OFDM subcarriers, which resulted in reducing the spectral efficiency. The shortfall of DD-OOFDM is that more transmitted optical power is required for carrier transmission. Nevertheless, CO-OFDM requires a laser at the receiver to generate the carrier locally, eventhough, it`s more sensitive to phase noise [22]. Currently, there are extensive researches into the performance of both systems and on techniques to mitigate the disadvantages of each [23] [24].

4.2 Digital Signal Processing (DSP)

The DSP requirements depend namely on two important criteria: the number of arithmetic operations, (example multiplications and addition) per bit and on the number of bits required to represent the signal at various points within the transceiver. The typical OFDM digital signal processing comprises five steps:

1. Window synchronization.
2. Frequency synchronization.
3. Discrete Fourier Transform.
4. Channel estimation.
5. Phase noise estimation.

We here briefly describe the five DSP procedures. Window synchronization aims to locate the beginning and end of an OFDM symbol correctly. One of the most popular methods was proposed by Schmidl and Cox based on cross-correlation of detected symbols with a known pattern [25]. Recently, Ma, et al., proposed an OFDM Timing Synchronization based on correlations of preamble symbol which is a cost effective DSP procedure Window synchronization [26]. A certain amount of frequency offset can be synchronized by a similar method, namely, the frequency offset can be estimated from the phase difference between two identical patterns with a known time offset. After window synchronization, OFDM signal is partitioned into blocks each containing a complete OFDM symbol. DFT is used to convert each block of OFDM signal from time domain to frequency domain [27]. Then the channel and phase noise estimation are performed in the frequency domain using training symbols and pilot subcarriers, respectively.

Very fast DSP implementations will use fixed points rather than floating point arithmetic. For instance, O-OFDM is a signal with wide dynamic range. So the choice in a fixed system of the number of bits and the signal levels which they represent is a trade-off between the largest signal values with low probability of numerical overflow and the quantization noise rounding errors [28]. These errors result from using only a few bits which always occurs in DDO-OFDM. CO-OFDM requires more complex DSP implementation than the DDO-OFDM as a result, it`s more robust against nonlinearity associated with fiber.

4.3 Digital-To-Analog Converters (DACs) and Analog-To-Digital Converters (ADCs)

The design of DACs and ADCs may as well be the most critical factor for O-OFDM. One of the advantage of DDO-OFDM systems is the fact that the DAC or ADC is required to represent only the few discrete levels of the QAM modulation. An example for this could be for a 4-QAM system, each of the In-phase and Quadrature Phase analog output from the DAC or ADC require only two levels (one bit resolution). Likewise, for 16-QAM require only four levels (two bits resolution) each. Depending on the required SNR, a DAC with six or seven bits resolution can be achievable. This means that the DDO-OFDM circuitry is simple unlike the CO-OFDM counterpart which has a complex circuitry and are heavily entrenched in silicon-based DSP for high-speed signal phase estimation and channel equalization [29].

However, other probably important aspects of DAC and ADC design will be the maximum allowable timing jitter, linearity, accuracy of the conversion and how errors in these interact with the modulation format. In general, the averaging effect of the FFT, the performance of the DDO-OFDM depends on the mean power impairments, whereas for CO-OFDM system, the peak value may be more important. Timing jitter has historically been one of the main limitations of high data rate optical systems [30].

4.4 Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT)

In an OFDM system, data are apportioned in the frequency domain of the transmitter and modulated into the time domain by using IFFT. If conjugate symmetry is imposed on the input data then, the FFT output data are guaranteed to be real-valued. At the receiver, the original data is recovered by FFT which allows proficient implementation of modulation of data onto multiple carriers [4]. This similarity of the forward and inverse transform allows the same circuitry, with minor modifications for both modulation and demodulation in transceiver.

A large number of subcarriers are required in OFDM so that the transmission channel affects each subcarrier as a flat channel, which leads to a complex architecture of OFDM system involving many filters and oscillators. Weinsten and Ebert discovered that Inverse Discrete Fourier Transform (IDFT) and Discrete Fourier Transform (DFT) can be used for OFDM modulation and demodulation [31]. IFFT/FFT blocks in an OFDM system are mathematically equivalent versions of an IDFT and a DFT of the transmitted and received OFDM signal, with the advantage of providing lower computational implementation. Because of the orthogonality property, as long as the channel is linear, the OFDM receiver will calculate the spectrum values at those points corresponding to the maximum of individual subcarriers. Then, the received subcarriers can be demodulated through an FFT operation without interference and without the need for analogue filtering to separate them, which makes OFDM not only efficient but also easy to implement in practical transmission systems.

An OFDM transmitter where subcarriers are modulated in the digital domain by means of an IFFT are shown in Figure 9. At the output s(t) of the IFFT block, the transformed symbols are then serialized and converted into an analogue signal before transmitting them to the channel.

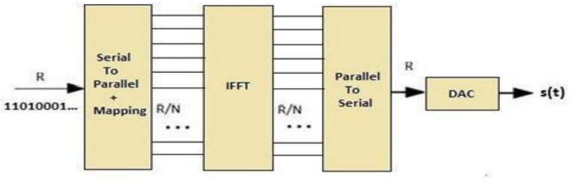

Figure 9. Basic Schematic of an IFFT Block to Modulate an OFDM Signal

In a similar vein, the subcarriers forming the received signal r(t) are demodulated by means of an FFT operation after being performed, analogue to digital (A/D) conversion and parallelized to form the FFT block inputs, as shown in Figure 10 below.

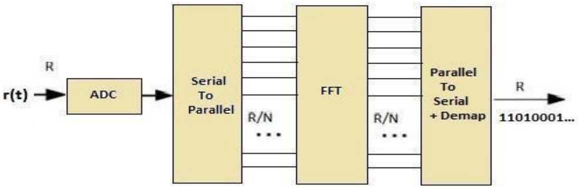

Figure 10. Basic Schematic of an FFT Block to Demodulate an OFDM Signal

In a more detailed concept, the frequencies of an OFDM signal are represented in each branch of an IFFT operation as shown in Figure 11 below. It shows a schematic of the IFFT block, where x_1,......, x_n are the input sequence symbols from subcarrier 1 to the total number of subcarriers N, and y_1......, y_n are the corresponding output sequence symbols. Moreover, the frequency domain OFDM symbol generated at the IFFT output is equally depicted as shown in Figure 11. The inverse procedure can be applied to the FFT block at the receiver end. The first output channel (y_1) is located at DC, so it is not used for modulation because carrier leakage of the modulator disturbs the quality of this channel and it would put stringent requirements on the low-pass characteristics of all electronic (and also optic) components.

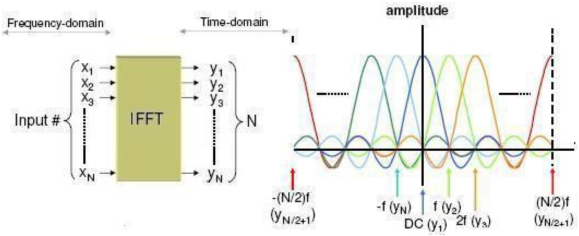

Figure. 11 Schematic of IFFT Block and Frequency Domain OFDM Symbol at its Output

Furthermore, in a complex valued IFFT the first half of the rows corresponds to the positive frequencies while the last half corresponds to negative frequencies. Thus, the so called "Nyquist channel" is located at $yNc/2+1$, which corresponds to the highest frequency that the subsequent digital-to-analogue converter can modulate: the Nyquist frequency (fN), or half the sampling frequency f_s according to the sampling theorem. FFT and IFFT implementation of OFDM provides two important advantages, they are:

1. The number of complex multiplications is reduced from N^2 to $N/2$ approximately linearly with the number of subcarriers N, due to efficient IFFT/FFT algorithm.

2. When large numbers of subcarriers are required, IFFT/FFT implementation provides simple OFDM architecture without restoring much on complicated RF oscillators and filters.

Although, DDO-OFDM shows much more variants than the coherent counterpart. Equally, DDO-OFDM has a broader range of applications due to its lower cost and takes advantage of the fact that OFDM signal is more immune to the impulse clipping noise in the CATV network. Other merit associated with DDO-OFDM is the single-side-band (SSB)-OFDM, which has been recently proposed by Lowery et al. and Djordjevic et al. for long-haul transmission which was theoretically possible to transmit data with a speed of about 52 Gb/s in an optical channel at about 1000km distance.

However, with the invention of Erbium-doped fiber amplifiers (EDFAs), coherent optical communication which has been literally abandoned since the early 1990s, can achieve sensitivity within a few decibels of coherent receivers. Recently, the impressive record-performance experimental demonstration using a combination of O-OFDM and Differential-Phase-Shift-Keying (DPSK) or Quadrature Amplitude Modulation (QAM) has shown the possibility of a reconfigurable optical networks with a transmission speed approaching 1Tb/s. This could be achieved by implementing a very fast DSP at both transmitter and receiver respectively.

4.5 Sampling Rate

Sampling rate is another criteria and an important factor for Optical-OFDM. We consider the issue of overhead in the Cyclic Prefix (CP), unused band-edge subcarriers and pilot tones mean that some oversampling is necessarily required [32]. Although, the system design will determine the exact value to be used, which necessarily will be in the range of 10-30% oversampling. Most coherent optical systems use an oversampling rate of 2 to agree with the Nyquist Sampling Theorem.

4.6 Optical Components Tolerance

In Optical-OFDM, there exist a difference or differences in the optical components tolerance. In CO-OFDM or rather in all coherent optical design systems, the sensitivity of the O-OFDM to phase noise and frequency offset do set a stringent tolerance on the line-width of the lasers, which are not likely to be so in DDO-OFDM. Although, some of these effects can be digitally compensated in the digital domain. The tolerance of O-OFDM to the fiber impairment like fiber nonlinearity and chromatic dispersion introduced by optical components and DSP algorithms, to mitigate these effects are center focus for many researchers [14].

5. CONCLUSION

In general, CO-OFDM systems give improved performance as compared to DDO-OFDM systems, although the building architecture of direct detection is much cheaper as compared to coherent receiver system. Invariably, as the signal volume increases, the cost of the coherent receiver will equally come down due to robust implementation of DSP in the transceiver circuit.

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